J. Cent. South Univ. (2020) 27: 517−530
DOI: https://doi.org/10.1007/s11771-020-4313-2

Springer

Risk assessment of water inrush in tunnels based on attribute interval recognition theory

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Abstract: Water inrush is one of the most serious geological hazards in underground engineering construction. In order to effectively prevent and control the occurrence of water inrush, a new attribute interval recognition theory and method is proposed to systematically evaluate the risk of water inrush in karst tunnels. Its innovation mainly includes that the value of evaluation index is an interval rather than a certain value; the single-index attribute evaluation model is improved non-linearly based on the idea of normal distribution; the synthetic attribute interval analysis method based on improved intuitionistic fuzzy theory is proposed. The TFN-AHP method is proposed to analyze the weight of evaluation index. By analyzing geological factors and engineering factors in tunnel zone, a multi-grade hierarchical index system for tunnel water inrush risk assessment is established. The proposed method is applied to ventilation incline of Xiakou tunnel, and its rationality and practicability is verified by comparison with field situation and evaluation results of other methods. In addition, the results evaluated by this method, which considers that water inrush is a complex non-linear system and the geological conditions have spatial variability, are more accurate and reliable. And it has good applicability in solving the problem of certain and uncertain problem.

Key words: water inrush; risk assessment; attribute interval recognition model; TFN-AHP

Cite this article as: WANG Sheng, LI Li-ping, CHENG Shuai, HU Hui-jiang, ZHANG Ming-guang, WEN Tao. Risk assessment of water inrush in tunnels based on attribute interval recognition theory [J]. Journal of Central South University, 2020, 27(2): 517−530. DOI: https://doi.org/10.1007/s11771-020-4313-2.

1 Introduction

With the implementation of "One Belt and Road" initiative, the construction focus in China such as highway, railway, hydraulic and hydroelectric engineering and other major projects is transferred to western karst mountainous areas with complex terrain and geological conditions [1−3]. A number of tunnel projects have emerged, and most of them show obvious characteristics of large buried depth, high stress and strong karst. Because the disaster-causing mechanism is unclear, and the geological conditions along the tunnel can't

Foundation item: Project(51722904) supported by the National Science Fund for Excellent Young Scholars, China; Project(51679131) supported by the National Natural Science Foundation of China; Project(2019JZZY010601) supported by the Shandong Provincial Key Research and Development Program (Major Scientific and Technological Innovation Project), China; Project(KJ1712304) supported by the Science and Technology Research Program of Chongqing Municipal Education Commission, China; Project(2016XJQN13) supported by the Yangtze Normal University Research Project, China
Received date: 2019-06-08; **Accepted date:** 2019-12-09
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be accurately detected, it is difficult to contain water inrush. Once water inrush occurs, it will not only lead to the machine damage and other economic loss, but also cause heavy casualties, and even be forced to change line [4−7]. In order to realize active prevention and control of water inrush, it is very important to study risk assessment theory and methods.

A number of researches on water inrush mechanism were performed based on theoretical analysis, numerical simulation and geo-mechanical model test. LI et al [8] studied the mechanism of water-rock interaction by using karst geology, engineering hydraulics and fracture mechanics, and revealed the mechanism of water inrush process. YANG et al [9] presented a fully coupled flow-stress-damage model based on porous media flow and damage mechanics, and simulated the evolution of water inrush channels. ZHAO et al [10] proposed a seepage-stress coupling method based on 3D digital models, and explored the change law of seepage field, stress field and displacement in the process of water inrush. LI et al [11] and YANG et al [12] carried out a large-scale true triaxial geo-mechanical model test to study the evolution law of multivariate physical information, and then analyzed the mechanism of water inrush.

However, many scholars have conducted quite a few researchers regarding risk management and risk assessment of underground engineering, which is an effective method to predict the occurrence of water inrush. The International Tunnelling Association promulgated "Guidelines for Tunneling Risk Management" to manage and avoid risks in tunnel construction [13]. BUKOWSKI [14] developed a risk assessment system of water flowing considering inflow intensity, suspended material, shaft condition and the mine history. ZHANG et al [15] proposed a quantitative evaluation method of water inrush and a four-color mechanism of disaster warning for high-risk karst tunnels. XU et al [16] analyzed the key influencing factors of water or mud inrush and calculated their weight based on AHP, and then put forward a three-stage risk assessment method in karst tunnels. LI et al [4, 17] established two-stage attribute synthetic evaluation system, which is applied in design stage and construction stage; and then put forward an attribute interval evaluation methodology. In addition, a lot of evaluation models were established to evaluate the water inrush risk in tunnels, such as attribute model [3, 4, 6, 18], cloud model [19], fuzzy model [20, 21], unascertained measure model [5], grey theory [22]. With the development of computer technology, LI et al [23] studied the risk assessment system based on GIS to predict dynamically the water inrush risk in the karst tunnel. LI et al [24, 25] developed risk evaluation software for water inrush, which improved the efficiency of risk management in tunnel construction. But the variability of factors measure values, nonlinearity of evaluation models and the uncertainty of factor weights are not comprehensively considered.

The paper aims to propose a new method to predict the water inrush risk in karst tunnels. The multi-grade hierarchical index system for tunnel water inrush risk assessment is established, and an interval rather than a certain value is used to quantify the evaluation indices. The traditional attribute evaluation model is improved nonlinearly by introducing the idea of normal distribution, and improved intuitionistic fuzzy sets theory is adopted to calculate attribute measure interval. Meanwhile, the weights of multi-grade indices are determined by TFN-AHP. The theory and method realizes the quantitative identification of disaster risk level and provides an effective approach for risk assessment of water inrush in karst tunnels.

2 Improved attribute interval recognition theory

Let X be evaluation object space, and $X=\{x_1, \cdots, x_i, \cdots, x_n\}$. The object x_i has m evaluation indexes I_j (j=1, 2, ⋯, m). Each evaluation index I_j has K risk grades C_k (k=1, 2, ⋯, K). In the work, the attribute space C is defined as risk level of water inrush in karst tunnels, and $C=\{C_1, C_2, C_3, C_4\}$={very high risk, high risk, medium risk, low risk}.

2.1 Single-index attribute measure analysis

According to the measured value t_j of evaluation index I_j, the single-index attribute measure function is used to compute the single-index attribute measure μ_{ijk} which can determine t_j belonging to risk level C_k. In general, the single-index attribute measure function is determined according to grade form and grading standard presented in Table 1.

Table 1 Grade subdivision of single index

Index	Risk level			
	C_1	C_2	···	C_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	$a_{m0}-a_{m1}$	$a_{m1}-a_{m2}$	···	$a_{m(k-1)}-a_{mk}$

$$b_{jk}=\frac{a_{jk-1}+a_{jk}}{2},\quad k=1,\ 2,\ \cdots,\ K \tag{1}$$

$$d_{jk}=\min\left\{\left|b_{jk}-a_{jk}\right|,\left|b_{jk+1}-a_{jk}\right|\right\},\quad k=1,\ 2,\ \cdots,\ K-1 \tag{2}$$

The common single-index attribute measure function is shown in Figure 1. It can be seen from Figure 1 that the traditional single-index attribute measure function is linear; that is, the attribute measure value exhibits linear change along with measured value of influencing factor. A large

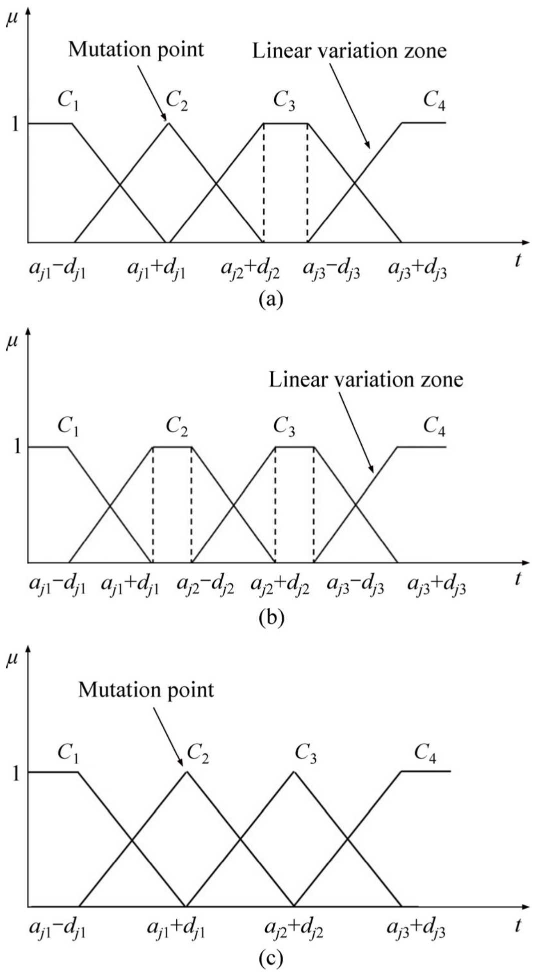

Figure 1 Linear attribute measurement functions: (a) Index with regular grading and large interval; (b) Index with regular grading and small interval; (c) Index with irregular grading

number of project experiences show that water inrush in tunnels is a non-linear complex system affected by many factors. Therefore, the non-linear improvement is conducted (Figure 2).

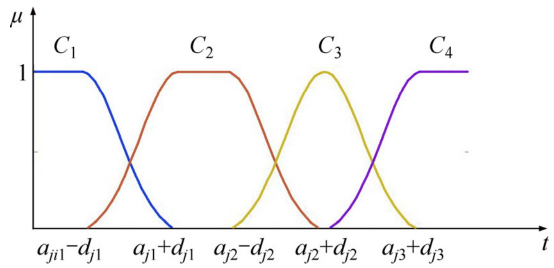

Figure 2 Non-linear attribute measurement function

The formula of normal distribution (μ, σ^2) is as follows:

$$f_{jk}(x)=\frac{1}{\sqrt{2\pi}\sigma_{jk}}\exp\left[-\frac{(x_j-\mu_{jk})^2}{2\sigma_{jk}{}^2}\right] \tag{3}$$

where $f_{jk}(x)$ is single-index attribute measure value of the j-th evaluation index belonging to risk level C_k; μ_{jk} is the mutation point value of the j-th evaluation index belonging to risk level C_k; σ_{jk} is equilibrium coefficient of the j-th evaluation index belonging to risk level C_k. And f_{jk} meets:

$$\max\left\{f_{jk}(x)\right\}=1,\quad \text{that is}\ \frac{1}{\sqrt{2\pi}\sigma_{jk}}=1.$$

Formula is transformed as follows:

$$\sigma_{jk}=\frac{1}{\sqrt{2\pi}}.$$

Formula (3) is simplified by substituting Eq. (4):

$$f_{jk}(x)=\exp\left[-\pi(x_j-\mu_{jk})^2\right] \tag{4}$$

From the above equation, when x=−∞ or +∞, $f_{ij}(x)$→0; and $f_{ij}(x_a)$=exp[−π]=0.043, approaching to zero. Therefore, let $(x_j-u_{jk})\in[0,\ 1]$ while let $f_{ij}(x)\in[0,\ 1]$.

When $a_{j0}<a_{j1}<\cdots<a_{jk}$,

$$\mu_{ij1}(t_j)=\begin{cases}1,\ t_j<a_{j1}-d_{j1}\\ \dfrac{\exp\left[-\pi\left(\dfrac{t_j-a_{j1}+d_{j1}}{2d_{j1}}\right)^2\right]-e^{-\pi}}{1-e^{-\pi}},\\ \quad a_{j1}-d_{j1}\le t_j\le a_{j1}+d_{j1}\\ 0,\ t_j>a_{j1}+d_{j1}\end{cases} \tag{5}$$

$$\mu_{ijk}(t_j)=\begin{cases}0,\ t_j<a_{jk-1}-d_{jk-1}\\ \dfrac{\exp\left[-\pi\left(\dfrac{t_j-a_{jk-1}-d_{jk-1}}{2d_{jk-1}}\right)^2\right]-e^{-\pi}}{1-e^{-\pi}},\\ \quad a_{jk-1}-d_{jk-1}\le t_j\le a_{jk-1}+d_{jk-1}\\ 1,\ a_{jk-1}+d_{jk-1}<t_j<a_{jk}-d_{jk}\\ \dfrac{\exp\left[-\pi\left(\dfrac{t_j-a_{jk}+d_{jk}}{2d_{jk}}\right)^2\right]-e^{-\pi}}{1-e^{-\pi}},\\ \quad a_{jk}-d_{jk}\le t_j\le a_{jk}+d_{jk}\\ 0,\ t_j>a_{jk}+d_{jk}\end{cases} \tag{6}$$

$$\mu_{ijK}(t_j)=\begin{cases}0,\ t_j<a_{jK-1}-d_{jK-1}\\ \dfrac{\exp\left[-\pi\left(\dfrac{t_j-a_{jK-1}-d_{jK-1}}{2d_{jK-1}}\right)^2\right]-e^{-\pi}}{1-e^{-\pi}},\\ \quad a_{jK-1}-d_{jK-1}\le t_j\le a_{jK-1}+d_{jK-1}\\ 1,\ t_j>a_{jK-1}+d_{jK-1}\end{cases} \tag{7}$$

When $a_{j0}> a_{j1}>\cdots>a_{jK}$

$$\mu_{ij1}(t_j)=\begin{cases}0,\ t_j<a_{j1}-d_{j1}\\ \dfrac{\exp\left[-\pi\left(\dfrac{t_j-a_{j1}-d_{j1}}{2d_{j1}}\right)^2\right]-e^{-\pi}}{1-e^{-\pi}},\\ \quad a_{j1}-d_{j1}\le t_j\le a_{j1}+d_{j1}\\ 1,\ t_j>a_{j1}+d_{j1}\end{cases} \tag{8}$$

$$\mu_{ijk}(t_j)=\begin{cases}0,\ t_j<a_{jk}-d_{jk}\\ \dfrac{\exp\left[-\pi\left(\dfrac{t_j-a_{jk}-d_{jk}}{2d_{jk}}\right)^2\right]-e^{-\pi}}{1-e^{-\pi}},\\ \quad a_{jk}-d_{jk}\le t_j\le a_{jk}+d_{jk}\\ 1,\ a_{jk}+d_{jk}<t_j<a_{jk-1}-d_{jk-1}\\ \dfrac{\exp\left[-\pi\left(\dfrac{t_j-a_{jk-1}+d_{jk-1}}{2d_{jk-1}}\right)^2\right]-e^{-\pi}}{1-e^{-\pi}},\\ \quad a_{jk-1}-d_{jk-1}\le t_j\le a_{jk-1}+d_{jk-1}\\ 0,\ t_j>a_{jk-1}+d_{jk-1}\end{cases} \tag{9}$$

$$\mu_{ijK}(t_j)=\begin{cases}1,\ t_j<a_{jK-1}-d_{jK-1}\\ \dfrac{\exp\left[-\pi\left(\dfrac{t_j-a_{jK-1}+d_{jK-1}}{2d_{jK-1}}\right)^2\right]-e^{-\pi}}{1-e^{-\pi}},\\ \quad a_{jK-1}-d_{jK-1}\le t_j\le a_{jK-1}+d_{jK-1}\\ 0,\ t_j>a_{jK-1}+d_{jK-1}\end{cases} \tag{10}$$

where j=1, 2, ⋯, m; k=1, 2, ⋯, K.

2.2 Attribute interval recognition based on intuitionistic fuzzy sets

1) Basic concept of intuitionistic fuzzy sets

Definition 1: concept. For a given universe X, let a intuitionistic fuzzy set $A=\{<x, u_A(x), v_A(x)>|x\in X\}$ of X, where $u_A(x)$ and $v_A(x)$ represent respectively the membership degree and the non-membership degree of x to A, and $u_A(x)$: $X\rightarrow[0, 1]$, $v_A(x)$: $X\rightarrow[0, 1]$. For any $x\in X$, $0\le u_A(x)+v_A(x)\le 1$. The $\pi_A(x)=1-u_A(x)-v_A(x)$ is defined as hesitancy degree of element x in the universe X to A. The membership degree $A(x)$, non-membership degree $v_A(x)$ and hesitancy degree $\pi_A(x)$ denote respectively support degree, opposing degree and neutral degree of element x belonging to intuitionistic fuzzy set A [26, 27].

Definition 2: score function. The score function not only reflects the size of intuitionistic fuzzy number well, but also accurately expresses support degree for decision-making. Therefore, whether score function is reasonable or not is particularly important. Let $\alpha=(u_\alpha, v_\alpha)$ be intuitionistic fuzzy value, where (u_α, v_α) is intuitionistic fuzzy number. Formula (11) is the traditional score function [28, 29], but the value S is often equal, for example (0.6, 0.1) and (0.7, 0.2). Therefore, the score function is improved in Formula (12).

$$S(\alpha)=u_\alpha-v_\alpha \tag{11}$$

$$S(\alpha)=\frac{1-v_\alpha}{2-u_\alpha-v_\alpha} \tag{12}$$

2) Attribute interval recognition

The discontinuity and heterogeneity of rock mass medium in the underground space complicate the geological conditions. The more complicated the geological conditions that underground engineering passes through are, the more easily the geological disasters are induced. Therefore, for accurately quantifying the geological parameters, the measured value of evaluation index I_j is quantified in the form of interval $[t_{jx}, t_{jy}]$ considering the complexity and variability of geological conditions. Then the single-index attribute measure matrices of t_{jx} and t_{jy} are respectively calculated by formulae (5)−(10), as follows:

$$U_{jxk}=\begin{pmatrix}\mu_{1x1} & \mu_{1x2} & \cdots & \mu_{1xK}\\ \mu_{2x1} & \mu_{2x2} & \cdots & \mu_{2xK}\\ \vdots & \vdots & \ddots & \vdots\\ \mu_{mx1} & \mu_{mx2} & \cdots & \mu_{mxK}\end{pmatrix},$$

$$U_{jyk}=\begin{pmatrix}\mu_{1y1} & \mu_{1y2} & \cdots & \mu_{1yK}\\ \mu_{2y1} & \mu_{2y2} & \cdots & \mu_{2yK}\\ \vdots & \vdots & \ddots & \vdots\\ \mu_{my1} & \mu_{my2} & \cdots & \mu_{myK}\end{pmatrix}.$$

Let membership degree u_{jk}=min{μ_{jxk}, μ_{jyk}}, hesitancy degree π_{jk}=max{μ_{jxk}, μ_{jyk}}−min{μ_{jxk}, μ_{jyk}}, non-membership degree v_{jk}=1−max{μ_{jxk}, μ_{jyk}} in the intuitionistic fuzzy set. The intuitionistic fuzzy decision matrix $D=(d_{jk})_{m\times K}$ is constructed.

$$D=\begin{matrix} & C_1 & C_2 & \cdots & C_K\\ F_1 & (u_{11},v_{11}) & (u_{12},v_{12}) & \cdots & (u_{1K},v_{1K})\\ F_2 & (u_{21},v_{21}) & (u_{22},v_{22}) & \cdots & (u_{2K},v_{1K})\\ \vdots & \vdots & \vdots & \ddots & \vdots\\ F_m & (u_{m1},v_{m1}) & (u_{m2},v_{m2}) & \cdots & (u_{mK},v_{mK})\end{matrix} \tag{13}$$

The score matrix $S=(s_{jk})_{m\times K}$ is obtained based on score function (12).

2.3 Attribute recognition analysis

After m single-index attribute measure values of evaluation object x_i are obtained, the comprehensive attribute measure values μ_{ik} belonging to every risk grade are calculated as follows:

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

$$\mu_{ik}=\mu'_{ik}\Big/\sum_{k=1}^{K}\mu'_{ik} \tag{15}$$

where ω_j is the weight of the jth index, s.t., $0\le\omega_j\le1$ and $\sum_{j=1}^{m}\omega_j=1$.

In the attribute recognition model, attribute space F={C_1, C_2, C_3, C_4} is an ordered segmentation comment set. On the basis of comprehensive attribute measure matrix, confidence criterion is adopted to identify which risk grade C_k is preferred by the evaluation object x_i. The confidence criterion: let an ordered comment set F={C_1, C_2, ⋯, C_K}, the confidence $\lambda\in(0.5, 1]$, usually between 0.6−0.7.

When $C_1< C_2<\cdots<C_K$, if

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

x belongs to C_{k0}.

When $C_1> C_2>\cdots>C_K$, if

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

x belongs to C_{k0}.

3 Risk evaluation method of water inrush in tunnels

3.1 Attribute recognition analysis

For a complex dynamic disaster, water inrush in tunnels is caused by the instability of groundwater storage system or groundwater movement system disturbed by outside forces. The occurrence mechanism for a water inrush disaster is very complex and influenced by multiple factors. If selecting too many factors as evaluation indices will weaken the contribution degree of key control factors, thus the accuracy of evaluation results is affected. If fewer factors are selected as evaluation indices, the applicability is limited. In order to resolve the above problem, the multi-grade hierarchical index system for water inrush in tunnels is established. By systematically summarizing and analyzing over 100 cases of water inrush in Chinese tunnels[4, 17, 30], the index system consists of 5 first-grade evaluation indices, which are geology and tectonic I_1, ground water I_2, topography and geomorphology I_3, construction situation I_4, climate condition I_5. The first-grade indices are divided into 15 second-grade evaluation indices, as shown in Figure 3.

3.2 Grading standards of water inrush risk in tunnels

According to existing management achievement and literature material of water inrush risk in tunnels [3−5, 17, 31], combining with rich field construction experience, each evaluation index is divided into 4 risk levels. The evaluation space is {C_1, C_2, C_3, C_4}, i.e., C_1={very high risk}, C_2={high risk}, C_3={medium risk}, C_4={low risk}, as shown in Table 2.

Since the evaluation indices such as unfavorable geology I_{13}, crack growth degree I_{15}, rich aquifer I_{23}, surface karst I_{32}, forecast and monitoring technology I_{41}, construction and management level I_{42} and rainfall season

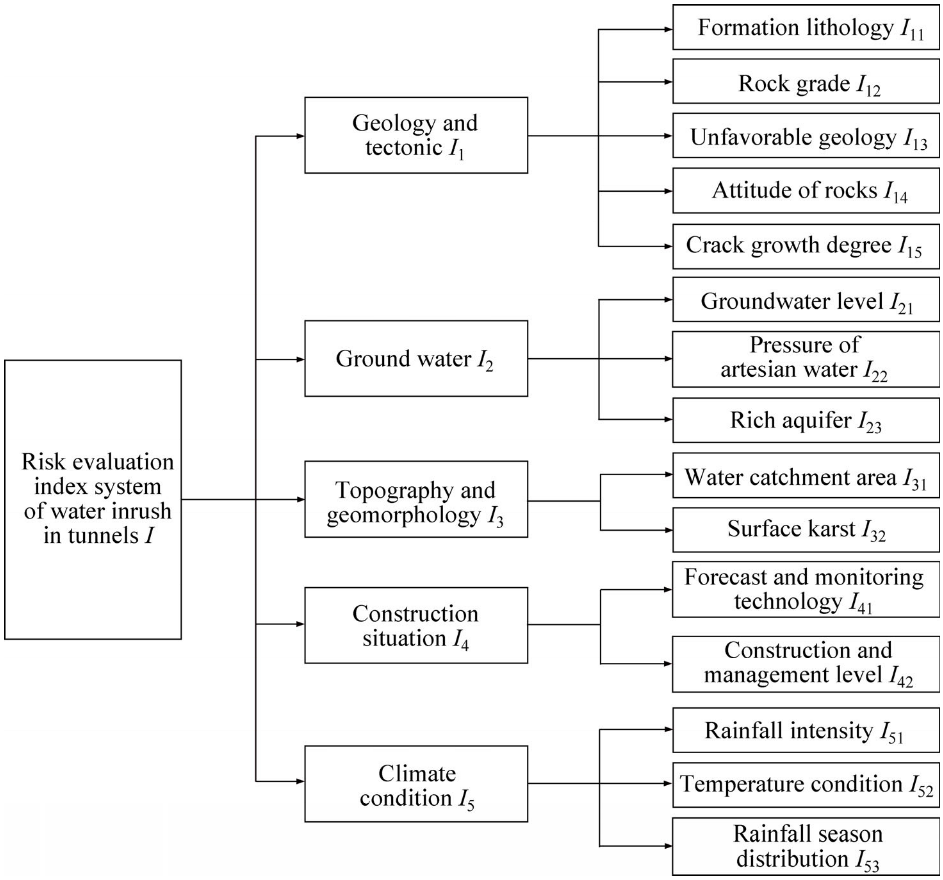

Figure 3 Risk evaluation index system of water inrush in tunnels

distribution I_{53}, which are mainly of qualitative analysis, are difficultly quantified, the expert evaluation method is used for quantitative grading. The surrounding rock grade is discontinuous and cannot meet the continuous form of data in Table 1. The method of the rock grade is proposed as shown in Table 2. And the values are only taken as integers. The formation lithology can be graded by expert evaluation method or rock layer solubility [4, 6, 17]. According to Ref. [30], the single-index attribute measure of attitude of rocks is represented by 0 or 1. The other evaluation indices can use formulae (5)−(10) to construct single-index attribute measure function.

3.3 Weight method based on TFN-AHP

The weight reflects the importance of each evaluation index to evaluation object. Whether the weight is accurate or not directly affects the evaluation results. At present, the common weight methods can be divided into subjective weighting method and objective weighting method. The subjective weighting method is to calculate the weight by constructing judgement matrix, which is obtained by comparing the importance of each risk factor in pairs, such as AHP [6, 32, 33], expert grade method. This method can give full play to experts' experience, but it is easy to be influenced by decision maker's experience, thinking mode and individual preference. Therefore, the weight is subjectively random. The objective weighting method is to calculate the weight by the difference of evaluation index data, such as entropy method and variation coefficient method. This method avoids the bias caused by human factors, but has high requirements for the evaluation index data, and the importance degree of evaluation index in the actual situation is neglected. In order to overcome the shortcoming of the above methods, the triangular fuzzy number theory is used to optimize the judgment matrix [34]. Meanwhile, possibility degree matrix is introduced to solve consistency check of judgment matrix and calculation difficulty of factor weight in the traditional AHP.

3.3.1 Preparative knowledge of triangular fuzzy number theory

Let fuzzy number $M=(l, m, u)$, s.t., $l\leq m\leq u$ and $l>0$. The l, m and u are minimum possible value,

Table 2 Indices and criteria for risk assessment of water inrush

First-grade evaluation index	Second-grade evaluation index		Risk level			
			C_4 (Low risk)	C_3 (Medium risk)	C_2 (High risk)	C_1 (Very high risk)
I_1	I_{11}	Formation solubility	>0.254	0.104−0.254	0.042−0.104	0−0.042
		Expert evaluation	0−60	60−70	70−85	85−100
	I_{12}	Description	I, II	III	IV	V, VI
		Expert evaluation	(0, 3)	[3, 4)	[4, 5)	[5, 6]
	I_{13}		0−60	60−70	70−85	85−100
	I_{14}		0°−10°	80°−90°	10°−25° or 65°−80°	25°−45° or 45°−65°
	I_{15}	Description	Poor developed	Well developed	Developed	Very developed
		Expert evaluation	0−60	60−70	70−85	85−100
I_2	I_{21}	h/m	h<10	10≤h<30	30≤h<60	h≥60
	I_{22}	p/MPa	p <0.5	0.5≤p<1.0	1.0≤p<1.5	p≥1.5
	I_{23}	Description	Low	Medium	Relatively rich	rich
		Expert evaluation	0−60	60−70	70−85	85−100
I_3	I_{31}	Proportion of negative landform area	<20%	20%−40%	40%−60%	>60%
	I_{32}	Description	Complete slope	Relatively complete slope	Steep slope terrace, trough valley	Peak cluster, ponor, peak forest, dissolution plain, gently slope terrace
		Expert evaluation	0−60	60−70	70−85	85−100
I_4	I_{41}	Description	Better	Good	General	Bad
		Expert evaluation	0−60	60−70	70−85	85−100
	I_{42}	Description	Better	Good	General	Bad
		Expert evaluation	0−60	60−70	70−85	85−100
I_5	I_{51}/mm		<400	400−800	800−1200	>1200
	I_{52}/°C		<5	5−10	10−20	>20
	I_{53}	Description	Uniform	Relatively uniform	Concentrated in summer	Very concentrated in summer
		Expert evaluation	0−60	60−70	70−85	85−100

middle value and maximum possible value of M respectively, which called a triangular fuzzy number of M. The operational rule is determined by arbitrarily selecting two triangular fuzzy numbers $M_1=(l_1, m_1, u_1)$ and $M_2=(l_2, m_2, u_2)$.

1) $M_1 \oplus M_2 = (l_1 + l_2, m_1 + m_2, u_1 + u_2)$;

2) $M_1 \otimes M_2 = (l_1 l_2, m_1 m_2, u_1 u_2)$;

3) $\lambda M_1 = (\lambda l_1, \lambda m_1, \lambda u_1), \lambda \ge 0$;

4) $M_1^{\lambda} = (l_1^{\lambda}, m_1^{\lambda}, u_1^{\lambda}), \lambda \ge 0$;

5) $M_1^{-1} = (1/l_1, 1/m_1, 1/u_1)$.

3.3.2 Weight method

Step 1: According to $\tilde{1}-\tilde{9}$ triangular fuzzy scale method (Table 3), the judgment matrix $M=(d_{ij})_{n\times n}$ is constructed by experts.

$$d_{ji}=(d_{ij})^{-1} \tag{18}$$

where d_{ij} is importance degree of I_i relative to I_j, and is also a triangular fuzzy number.

Table 3 Scale method of triangular fuzzy linguistic variables

Scale	Triangular number	Linguistic scale for importance
$\tilde{9}$	(8, 9, 9)	Absolutely more important
$\tilde{7}$	(6, 7, 8)	Strongly more important
$\tilde{5}$	(4, 5, 6)	More important
$\tilde{3}$	(2, 3, 4)	Weakly more important
$\tilde{1}$	(1, 1, 2)	Equally important
$\tilde{2}$, $\tilde{4}$, $\tilde{6}$, $\tilde{8}$	(3, 4, 5), (5, 6, 7), (7, 8, 9)	Middle value of upper and lower scales respectively

Step 2: The comprehensive fuzzy number of evaluation index I_i is calculated. Then the comprehensive triangular fuzzy number M_i is determined.

$$M_i=\sum_{j=1}^{n}d_{ij}\otimes\left(\sum_{i=1}^{n}\sum_{j=1}^{n}d_{ij}\right)^{-1} \tag{19}$$

where i and j=1, 2, ⋯, n.

Step 3: The defuzzification of comprehensive triangular fuzzy number M_i is conducted. Let $M_i=(l_i, m_i, u_i)$ and $M_j=(l_j, m_j, u_j)$, possibility degree of $M_i \geq M_j$ is

$$v(M_i \geq M_j)=\begin{cases}1, \ m_i \geq m_j \\ \dfrac{l_j-u_i}{(m_i-u_i)-(m_j-l_j)}, \ m_i<m_j, u_i \geq l_j \\ 0, \ \text{other}\end{cases} \tag{20}$$

Step 4: Let $\omega_i'=\min v(M_i \geq M_1, M_2, \cdots, M_{i-1}, M_{i+1}, \cdots, M_n)$, i=1, 2, ⋯, n. The $W'=(\omega_1', \omega_2', \cdots, \omega_n')$ is obtained. Then W' is made normalized processing. Finally, weight vector of evaluation index is determined as follows:

$$W=(\omega_1, \omega_2, \cdots, \omega_n)^{\mathrm{T}} \tag{21}$$

3.4 Water inrush risk assessment procedure in tunnels

The risk evaluation procedure of water inrush in tunnels based on improved attribute interval recognition model is as follows:

1) A multi-grade hierarchical index system for water inrush in tunnels is established. Index set I={ I_1, I_2, I_3, I_4, I_5} can be divided into 5 index subsets according to some attribute. For example, I_l={ I_{11}, I_{12}, I_{13}, I_{14}, I_{15}}.

2) The judgment matrix M is constructed based on $\tilde{1}-\tilde{9}$ triangular fuzzy scale method. The weight vector W of first-grade evaluation indices and the weight vector W_j (j=1, 2, ⋯, 5) of second-grade evaluation indices are calculated according to formulae (18)−(20).

3) The measured interval value $[t_{jrx}, t_{jry}]$ of second-grade evaluation indices belonging to I_j (j=1, 2, ⋯, 5) is determined by experienced experts based on detailed data of geological survey and construction information. The single-index attribute measures of t_{jrx} and t_{jry} are respectively calculated by formulae (5)−(10). The single-index attribute measure matrices U_{jx} and U_{jy} of I_j are formed.

4) The intuitionistic fuzzy decision matrix is constructed. The score matrix is obtained according to formula (12). The comprehensive attribute measure vector is calculated according to formulae (14)−(15). Finally, the risk grade of water inrush in tunnels is determined according to formulae (16)−(17).

4 Engineering applications

4.1 Engineering background of Xiakou tunnel

The Xiakou tunnel is a dominant engineering of the expressway from Yichang to Badong, located in Xiakou Town, Xingshan County, Hubei Province. It passes through a south-north mountain and has two separate lanes, with the left line length 6456.0 m and right line length 6487.0 m. The Xiakou tunnel is a deep and extra-long with a maximum burial depth of 1500 m. The geomorphic unit of tunnel area belongs to low semi mountainous gorge area with layered monoclinic of structural denudation and corrosion. The mountain strata is composed of the carbonate rock intercalated with clastic rock from Cambrian to Triassic period, in which the carbonate rock is soluble rock. The surface karst forms such as karst marsh land, funnels and falling water holes are well developed in combination. The geological conditions and the karst hydrologic conditions are extremely complex, especially in the section from K107+800 to K109+700 of Xiakou tunnel. The engineering geological profile of tunnel section K107+800−K109+700 is shown in Figure 4.

There is a ventilation incline on the left line of Xiakou tunnel. The dip of ventilation incline is 24.5° and its overall length is 780.95 m. The spatial relationship of ventilation incline and Xiakou tunnel is presented in Figure 5. In Figure 5, “K108+⋯” represents the distance numbers of Xiakou tunnel, while “XJK0+⋯” represents the distance numbers of ventilation incline. In this paper, the water inrush risk for XJK0+110−XJK0+060 section of ventilation incline is evaluated by attribute interval recognition theory proposed.

4.2 Risk assessment of water inrush

4.2.1 Determination of weights with TFN-AHP

The experienced tunnel expert is invited to construct fuzzy judgment matrixes of evaluation indices by $\tilde{1}-\tilde{9}$ triangular fuzzy scale method. Then, the weight vectors are determined according to Eqs. (18)−(20).

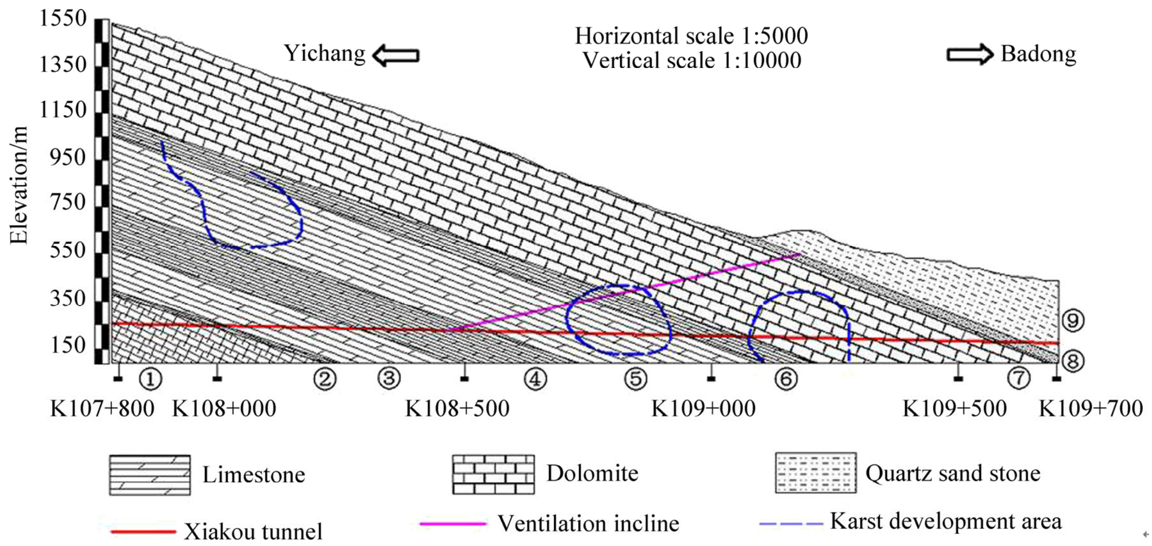

Figure 4 Engineering geological profile of Xiakou tunnel [17, 19] (① carbonaceous bituminous limestone and chert limestone intercalated with carbonaceous shale of Permian Qixia Formation (P_1q); ② bottom silico-manganese shale and carbonaceous shale of Permian Maokou Formation(P_1m); ③ slightly weathered grey massive limestone and flint-banded limestone of Permian Maokou Formation (P_1m); ④ slightly weathered thin limestone coupled with shale of lower member of Triassic Daye Formation (T_1d^1); ⑤ slightly weathered middle-thick limestone and thin-middle thick limestone of middle member of Triassic Daye Formation (T_1d^2); ⑥ slightly weathered thin mud-banded limestone of upper member of Triassic Daye Formation (T_1d^3); ⑦ platy dolomite and dolomitic breccia, grey massive limestone and middle-thick mud-banded limestone of Triassic Jialingjiang Formation($T_{1\text{-}2}j$); ⑧ shale intercalated with fine sandstone and aubergine siltstone intercalated with shale of lower member of Triassic Dongba Formation(T_2b^1); ⑨ thin siltstone, clay rock intercalated with carbonaceous shale and coal seam of Triassic Shaximiao Formation(T_3s))

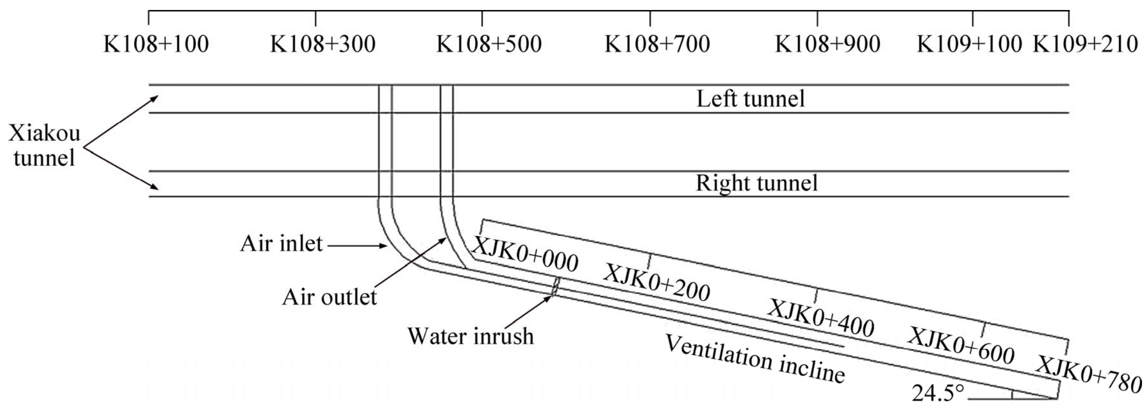

Figure 5 Spatial relationship of ventilation incline and Xiakou tunnel [17, 19]

Table 4 Fuzzy judgment matrix of evaluation index I_1

I_1	I_{11}	I_{12}	I_{13}	I_{14}	I_{15}
I_{11}	(1, 1, 2)	(2, 3, 4)	(1/3, 1/2, 1)	(1, 2, 3)	(1, 2, 3)
I_{12}	(1/4, 1/3, 1/2)	(1, 1, 2)	(1/6, 1/5, 1/4)	(1/3, 1/2, 1)	(1/3, 1/2, 1)
I_{13}	(1, 2, 3)	(4, 5, 6)	(1, 1, 2)	(2, 3, 4)	(2, 3, 4)
I_{14}	(1/3, 1/2, 1)	(1, 2, 3)	(1/4, 1/3, 1/2)	(1, 1, 2)	(1, 1, 2)
I_{15}	(1/3, 1/2, 1)	(1, 2, 3)	(1/4, 1/3, 1/2)	(1, 1, 2)	(1, 1, 2)
Weight vector	W_1=(0.278, 0.009, 0.407, 0.153, 0.153)^T				

Table 5 Fuzzy judgment matrix of evaluation index I_2

I_2	I_{21}	I_{22}	I_{23}
I_{21}	(1, 1, 2)	(1/4, 1/3, 1/2)	(1/3, 1/2, 1)
I_{22}	(2, 3, 4)	(1, 1, 2)	(1, 2, 3)
I_{23}	(1, 2, 3)	(1/3, 1/2, 1)	(1, 1, 2)
Weight vector	W_2=(0.182, 0.478, 0.340)^T		

4.2.2 Risk assessment analysis of water inrush

By comprehensive analysis of geological investigation data, geological sketch and advanced geological prediction, the indices value of geology

Table 6 Fuzzy judgement matrix of evaluation index I_5

I_5	I_{51}	I_{52}	I_{53}
I_{51}	(1/4, 1/3, 1/2)	(2, 3, 4)	(1, 2, 3)
I_{52}	(2, 3, 4)	(1, 1, 2)	(1, 2, 3)
I_{53}	(1/3, 1/2, 1)	(1/3, 1/2, 1)	(1, 1, 2)
Weight vector	W_5=(0.472, 0.316, 0.212)^T		

Table 7 Fuzzy judgement matrix of first-grade evaluation index I

I	I_1	I_2	I_3	I_4	I_5
I_1	(1, 1, 2)	(1/3, 1/2, 1)	(1, 2, 3)	(2, 3, 4)	(1, 2, 3)
I_2	(1, 2, 3)	(1, 1, 2)	(2, 3, 4)	(3, 4, 5)	(2, 3, 4)
I_3	(1/3, 1/2, 1)	(1/4, 1/3, 1/2)	(1, 1, 2)	(2, 3, 4)	(1, 1, 2)
I_4	(1/4, 1/3, 1/2)	(1/5, 1/4, 1/3)	(1/4, 1/3, 1/2)	(1, 1, 2)	(1/3, 1/2, 1)
I_5	(1/3, 1/2, 1)	(1/4, 1/3, 1/2)	(1, 1, 2)	(1, 2, 3)	(1, 1, 2)
Weight vector	W_1=(0.272, 0.370, 0.190, 0.009, 0.159)^T				

and tectonic I_1 and ground water I_2 are determined. According to geological survey combining with locale exploration, topography and geomorphology I_3 is quantified. The values of construction situation I_4 are obtained based on the construction and management level of the unit and the implementation situation of monitoring and forecast. The values of climate condition I_5 are obtained based on meteorological and climatic data from the location of the tunnel.

According to single-index attribute measure function in this paper, the attribute measure value of measured interval value [t_{jx}, t_{jy}] for evaluation indices is calculated. Based on intuitionistic fuzzy sets theory, single-index attribute measure intervals are determined, as shown in Table 8.

The improved score function (10) in this paper is used to calculate the single-index attribute measure intervals of second-grade evaluation indices, and then the support degrees that can accurately describe the single index belonging to each risk level are obtained, as shown in Table 9.

According to formula (12), the comprehensive attribute measure values of second-grade indices and first-grade indices are calculated respectively. It is worth mentioning that the comprehensive attribute measure values of second-grade indices are taken as single-index attribute measure values of first-grade indices. The initial comprehensive attribute measure values are normalized by formula (16), and the final comprehensive attribute measure value can be obtained, as shown in Table 10.

The higher the risk of water inrush, the lower the probability of occurrence. So, let the ordered set

Table 8 Single-index attribute measure intervals

Index		Single-index attribute measure interval			
First-grade index	Second-grade index	C_4	C_3	C_2	C_1
I_1 (0.272)	I_{11} (0.278)	0	0	(0.913, 1)	(0, 0.073)
	I_{12} (0.009)	0	0.431	0.431	0
	I_{13} (0.407)	0	0	(0, 0.073)	(0.913, 1)
	I_{14} (0.153)	0	0	0	1
	I_{15} (0.153)	0	0	(0.073, 0.431)	(0.431, 0.913)
I_2 (0.370)	I_{21} (0.182)	0	0	0	1
	I_{22} (0.478)	0	(0.431, 0.968)	(0.037, 0.431)	0
	I_{23} (0.340)	0	0	(0.073, 0.431)	(0.431, 0.913)
I_3 (0.190)	I_{31} (0.500)	(0, 0.133)	(0.814, 1)	0	0
	I_{32} (0.500)	0	(0.431, 1)	(0, 0.431)	0
I_4 (0.009)	I_{41} (0.500)	(0, 0.431)	(0.431, 1)	0	0
	I_{42} (0.500)	(0, 0.431)	(0.431, 1)	0	0
I_5 (0.159)	I_{51} (0.472)	0	(0, 0.133)	(0.431, 0.814)	(0, 0.431)
	I_{52} (0.316)	0	0	0.997	0.009
	I_{53} (0.212)	0	0	(0.431, 0.913)	(0.073, 0.431)

Table 9 Single-index attribute measure of second-grade indices

Index		Single-index attribute measure value			
First-grade index	Second-grade indices	C_4	C_3	C_2	C_1
I_1 (0.272)	I_{11} (0.278)	0	0	0.920	0.068
	I_{12} (0.009)	0	0.431	0.431	0
	I_{13} (0.407)	0	0	0.068	0.920
	I_{14} (0.153)	0	0	0	1
	I_{15} (0.153)	0	0	0.317	0.616
I_2 (0.370)	I_{21} (0.182)	0	0	0	1
	I_{22} (0.478)	0	0.630	0.309	0
	I_{23} (0.340)	0	0	0.317	0.616
I_3 (0.190)	I_{31} (0.500)	0.117	0.843	0	0
	I_{32} (0.500)	0	0.637	0.301	0
I_4 (0.009)	I_{41} (0.500)	0.301	0.637	0	0
	I_{42} (0.500)	0.301	0.637	0	0
I_5 (0.159)	I_{51} (0.472)	0	0.117	0.589	0.301
	I_{52} (0.316)	0	0	0.997	0.009
	I_{53} (0.212)	0	0	0.616	0.317

Table 10 Attribute measure calculation of multi-grade evaluation indices

Index	C_4	C_3	C_2	C_1	Weight
I_1	0	0.004	0.336	0.641	0.272
I_2	0	0.301	0.255	0.391	0.370
I_3	0.059	0.740	0.151	0	0.190
I_4	0.301	0.637	0	0	0.009
I_5	0	0.055	0.724	0.212	0.159
u	0.014	0.278	0.342	0.366	

(C_1, C_2, C_3, C_4) meet $C_1<C_2<C_3<C_4$. According to the confidence criterion, the confidence degree λ is generally between 0.6 and 0.7. In this paper, the confidence degree λ is 0.65. Formula (14) is simplified as follows:

$$k_0 = \max\left\{k : \sum_{l=k}^{4} u_{xl} \geq 0.65, 1 \leq k \leq 4\right\}.$$

If k=2, $\sum_{l=2}^{4} u_{xl} =$ 0.342+0.278+0.014=0.634< 0.65, the inequality doesn't hold.

If and only if k=1, $\sum_{l=1}^{4} u_{xl} = 0.366+0.342+$ 0.278+0.014=1>0.65, the inequality holds. Therefore, the risk level of water inrush in the section XJK0+110−XJK0+060 is C_1. That is very high risk. According to the previous studies, the risk level was evaluated as C_1 (very high risk) based on the attribute mathematical theory [17] and the novel cloud model [19]. The evaluation result in this paper shows good agreement with the former results. Furthermore, the prediction result obtained by using attribute interval recognition theory in this paper coincides with the actual condition. On August 7, 2011, water inrush occurred from blast holes in the left side of ventilation incline face XJK0+101; the jet distance was approximately 4 m; and the inflow of water was 64 m^3/h, as shown in Figure 6(a). Until August 30, 2011, the total inflow of water was about 28000 m^3, as shown in Figure 6(b). The attribute interval recognition theory is verified to be useful for the risk assessment of water inrush. Moreover, the method can provide better accuracy and satisfy the requirement for practical projects.

5 Conclusions

1) A new attribute interval recognition theory and method is proposed based on improved attribute evaluation model and intuitionistic fuzzy sets theory. The measure value of evaluation index is an interval rather than a certain value. The index

Figure 6 Verification by excavation result [17, 19]: (a) Water inrush from the side wall XJK0+097; (b) Water inrush in the face XJK0+101

weights are determined by improved TFN-AHP. The methodology solves the variability of geological condition, nonlinearity of evaluation model and the uncertainty of weight.

2) Based on the information of water inrush examples in karst tunnels, geology and tectonic I_1, ground water I_2, topography and geomorphology I_3, construction situation I_4, climate condition I_5 are selected as risk evaluation indices. Five first-grade evaluation indices are divided into 15 second-grade evaluation indices. Therefore, a multi-grade hierarchical index system for tunnel water inrush risk assessment is established, which fully considers the influencing factors, and does not affect the accuracy of evaluation results.

3) This new theory and method in the paper is successfully applied to ventilation incline XJK0+110−XJK0+060 section of Xiakou tunnel. The evaluation result is not only consistent with the results of attribute mathematical theory and the novel cloud model, but only shows good agreement with the actual situation, which provides a new way for water inrush risk evaluation method in karst tunnels.

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(Edited by YANG Hua)

中文导读

基于改进属性区间辨识模型的隧道突涌水灾害风险评价方法

摘要：突涌水灾害是地下工程建设过程中最严重的地质灾害之一。为了实现突涌水灾害的有效主动防控，提出了一种新的属性区间辨识模型来系统地评价岩溶隧道突涌水风险。其创新主要在于评价指标的取值是一个区间，而不是一个确定值；引入正态分布理念对传统属性综合评价模型进行非线性改进，提出基于改进直觉模糊理论的综合属性区间测度分析方法；并采用 TFN-AHP 法进行突涌水评价指标权重分析。同时，通过分析岩溶隧道突涌水灾害的地质影响因素和工程影响因素，建立了一个多层次突涌水风险评价指标体系。将建立的评价方法应用于峡口隧道斜井某段的突涌水风险分析，通过与现场情况和其他方法的评估结果对比，验证了该方法的合理性与实用性。此外，本方法考虑了突涌水这一复杂非线性系统与围岩的空间变异性，评价结果更准确、可靠；且在解决确定与不确定问题方面具有较好的适用性。

关键词：突涌水灾害；风险评价；属性区间辨识模型；三角模糊层次分析法