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ORIGINAL PAPER

Improved Attribute Interval Evaluation Theory for Risk Assessment of Geological Disasters in Underground Engineering and Its Application

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Abstract Based on the theory of attribute mathematics, this paper improves on the attribute interval evaluation theory. The main feature is that the evaluation index is an interval rather than a certain value. Using single index attribute analysis of the upper and lower limits of the interval, the paper proposes two calculation methods for the multiple index synthetic attribute measure. Based on the original AIET software, we develop a new set of software packages (NEW AIET) that can automatically complete a large number of calculations in a few seconds. Via engineering application, the accuracy and feasibility of geological disaster risk assessment are verified and can be used to better evaluate engineering disaster risk.

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1 Introduction

Intrinsic risk is associated with tunnel construction because of limited a priori knowledge of the existing subsurface conditions (Sousa and Einstein 2012). Geological disasters such as landslides, water inrush, mudslides, and rock bursts often occur in underground projects, which have resulted in delays, cost overruns, and in a few cases more significant consequences such as injury and loss of life. And therefore, effective disaster prevention is an important task for geological work.

In terms of engineering risk management and evaluation research, the International Tunneling Association issued a tunnel risk management guide, which has been successfully applied in construction risk control such as landslides (Søren et al. 2004). A lot of research work has been done on domestic risk analysis and assessment. It has applied and developed in tunnel water inrush, landslide, gas outburst, etc., and prepared risk management guidelines for subway and underground construction (Ministry, 2007).

Risk assessment is the core of risk management in tunnel and underground engineering, the important link between systematic identification of engineering risks and scientific and reasonable management risks, and the basis of decision analysis. In recent years, we have researched tunnel risk assessment methods and applied the results at home and abroad, and these methods include attribute mathematics theory, analytic hierarchy process (AHP), Bayesian network (BN), fuzzy evaluation method (FMT), grey theory (GT), extension methods (EM), and others (Saaty 1980; Hwang and Lu 2007; Bukowski 2011; Song et al. 2012). In addition to the successful use of existing risk assessment methods from other engineering industries in tunnels and underground engineering, a number of risk assessment models suitable for tunnel projects have been developed based on the specific characteristics of tunnel projects.

In underground engineering, risk sources and disasters generally arise from geotechnical uncertainty (aleatory or epistemic) or error (intrinsic or implementary) (Beard 2010; Brown 2012). However, a common problem exists in the abovementioned theories and methods. In the process of geological hazard risk analysis, after establishment of the corresponding evaluation index system, the value of the index is often an exact value, which ignores the complexity of underground engineering geological conditions and the uncertainty of the risk itself. Moreover, most models can only give a risk level qualitatively or semi-quantitatively, and cannot give the probability of occurrence of the risk grade.

Therefore, based on the theory of attribute mathematics and attribute interval evaluation theory, this paper proposes an improved theory of and method for attribute interval recognition. The evaluation index is an interval rather than a certain value, and using single index attribute analysis of the upper and lower limits of the interval (with reference to the original mathematical attribute model and the idea of risk evaluation), two improved methods for comprehensive attribute measure analysis are proposed. Combined with engineering examples, we propose the adoption of the attribute recognition analysis method and demonstrate quantitative recognition of the disaster risk level (Zhou et al. 2013).

Because this paper proposes two other identification methods, an NEW AIET software package is developed to solve this problem based on the original AIET software. We verify the engineering application in different geological disasters, and the risk level obtained from the evaluation is consistent with the actual working conditions and the evaluation results of Li et al. (2013a, b), Zhou et al. (2015), Li et al. (2014), Wang et al. (2012), Chen and Li. (2008), Zhang et al. (2010) and Yang et al. (2010), thus verifying the accuracy and feasibility of the method.

2 Improved Attribute Interval Evaluation Theory

The AIET is an innovative risk assessment methodology proposed by Li et al. (2013a) based on the attribute mathematical theory (AMT). An attribute synthetic assessment system consists of three components: single index attribute measure analysis, multiple indices synthetic attribute measure analysis and attribute recognition analysis.

2.1 Single Index Attribute Measure Analysis

For a single index I_j measurement t_j, the determination of the attribute measurement $\mu_{xjk} = \mu\ (x_{ij} \in C_k)$ with attribute C_k is intended to establish its attribute measurement function. We indicate the change of the attribute measure $\mu_{xjk} = \mu\ (x_{ij} \in C_k)$ when the measured value t_j of I_j changes. The grading standards of evaluation indices are expressed in Table 1, where $a_{jk} \le b_{jk}$ should satisfy $a_{j1} < a_{j2} < \cdots < a_{jK}$, $b_{j1} < b_{j2} < \cdots < b_{jK}$ or $a_{j1} > a_{j2} > \cdots > a_{jK}$, $b_{j1} > b_{j2} > \cdots > b_{jK}$,If $a_{j1} > a_{j2} > \cdots > a_{jK}$, $b_{j1} > b_{j2} > \cdots > b_{jK}$,We take the lower limit t_{jx} single index attribute measure calculation as an example:

$$\begin{cases} \mu_{jx1} = \mu_{jx2} = \cdots = \mu_{jxK} = 0 & t_{jx} \ge a_{j1} \\ \underline{\mu}_{jx1} = \dfrac{\left|t_{jx} - a_{jl+1}\right|}{\left|a_{jl} - a_{jl+1}\right|}, \underline{\mu}_{jxk} = 0 & a_{jl+1} \le t_{jx} \le a_{jl} \\ \mu_{jxK} = 1, \mu_{jx1} = \cdots = \mu_{jxK-1} = 0 & t_{jx} \le a_{jK} \end{cases} \tag{1}$$

Among these, k < l or k > l +1.

$$\begin{cases} \mu_{jxK} = 1, \mu_{jx1} = \cdots = \mu_{jxK-1} = 0 & t_{jx} \le a_{jK} \\ \bar{\mu}_{jxl} = \dfrac{\left|t_{jx} - b_{jl+1}\right|}{\left|b_{jl} - b_{jl+1}\right|}, \mu_{jxl+1} = \dfrac{\left|t_{jx} - b_{jl}\right|}{\left|b_{jl+1} - b_{jl}\right|}, \bar{\mu}_{jxk} = 0 & b_{jl+1} \le t_{jx} \le b_{jl} \\ \bar{\mu}_{jxK} = 1, \bar{\mu}_{jx1} = \cdots = \bar{\mu}_{jxK-1} = 0 & t_{jx} \le b_{jk} \end{cases} \tag{2}$$

Among these, k < l or k > l +1.

Table 1 Grade subdivision of a single index

Evaluation indicators	Evaluation level			
	C_1	C_2	…	C_K
I_1	$[a_{11}, b_{11}]$	$[a_{12}, b_{12}]$	…	$[a_{1K}, b_{1K}]$
I_2	$[a_{21}, b_{21}]$	$[a_{22}, b_{22}]$	…	$[a_{2K}, b_{2K}]$
…	…	…	…	…
I_m	$[a_{m1}, b_{m1}]$	$[a_{m2}, b_{m2}]$	…	$[a_{mK}, b_{mK}]$

If $a_{j1} < a_{j2} < \cdots < a_{jK}$, $b_{j1} < b_{j2} < \cdots < b_{jK}$, the single index attribute measure function is not separately listed herein.

2.2 Synthetic Attribute Measure Analysis of Multiple Indices

We can calculate the comprehensive attribute measure $\mu_{j'k}$ as shown in formula (3),

$$\underline{\mu}_{j\prime k} = \sum_{j=1}^{m}\left(\omega_j \underline{\mu}_{jk}\right), \quad \bar{\mu}_{j'k} = \sum_{j=1}^{m}\left(\omega_j \bar{\mu}_{jk}\right), \quad (1 \le j \le m, \quad 1 \le k \le K) \tag{3}$$

Where ω_j is the weight of the jth indicator $\omega_j \ge 0$,

$$\sum_{j=1}^{m} \omega_j = 1 \tag{4}$$

We define the following vector

$$\underline{\mu}_{j'x} = [\underline{\mu}_{j'x1}, \underline{\mu}_{j'x1}, \ldots, \underline{\mu}_{j'x1}];$$
$$\bar{\mu}_{j'x} = [\bar{\mu}_{j'x1}, \bar{\mu}_{j'x2}, \ldots, \bar{\mu}_{j'xK}];$$
$$\underline{\mu}_{j'y} = [\underline{\mu}_{j'y1}, \underline{\mu}_{j'y1}, \ldots, \underline{\mu}_{j'y1}];$$
$$\bar{\mu}_{j'y} = [\bar{\mu}_{j'y1}, \bar{\mu}_{j'y2}, \ldots, \bar{\mu}_{j'yK}]$$

For ease of understanding, we explain the following example.

If the evaluation object takes two evaluation indicators, we can divide it into three risk levels, namely, j = 1, 2; j' = 1, 2; k = 1, 2, 3, and the evaluation index values are $[t_{1x}, t_{1'y}]$,$[t_{2x}, t_{2'y}]$.

Using formulas (1)–(2) to calculate single index attribute measure, we can obtain the vector $\underline{\mu}_{1x}$, $\bar{\mu}_{1x}$, $\underline{\mu}_{1y}$, $\bar{\mu}_{1y}$, $\underline{\mu}_{2x}$, $\bar{\mu}_{2x}$, $\underline{\mu}_{2y}$, $\bar{\mu}_{2y}$, where $\mu_{1x} = [\mu_{1x1}, \mu_{1x2}, \mu_{1x3}]$, $\underline{\mu}_{1x} = [\underline{\mu}_{1x1}, \underline{\mu}_{1x2}, \underline{\mu}_{1x3}]$, etc., and eight 2 × 3 matrices $U_{2\times3}$ can be generated. Using formula (3) to calculate the comprehensive attribute measure of the matrix $U_{2\times3}$, we obtain $\mu_{1'x}, \underline{\mu}_{1'x}, \mu_{1'y}, \underline{\mu}_{1'y}$, $\mu_{2'x}, \underline{\mu}_{2'x}, \mu_{2'y}, \underline{\mu}_{2'y}$, and subsequently conduct analysis using two types of identification methods.

2.3 Attribute Recognition Analysis

The purpose of attribute recognition is to decide which of the evaluation levels x belongs to C_k using the comprehensive attribute measure μ_{xk}. In comprehensive evaluation of attributes, the evaluation set (C_1, C_2,…, C_K) is usually an ordered set.

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

$$k_0 = \min\left\{k : \sum_{l=1}^{k} \mu_{xl} \ge \lambda \ , \quad 1 \le k \le K\right\} \tag{5}$$

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

$$k_0 = \max\left\{k : \sum_{l=k}^{K} \mu_{xl} \ge \lambda, \quad 1 \le k \le K\right\} \tag{6}$$

It is considered that x_i belongs to the C_{ki} level.where k = 1, 2,…,K; and λ is the confidence coefficient $0.5 < \lambda \le 1$. In general, λ is found in the range 0.6–0.7.

Based on the improved attribute interval recognition theory, we propose two additional calculation methods based on the two methods proposed by Zhou et al. (2013).

(1) Recognition method one: Zhou et al. (2013) uses method one in calculation of comprehensive attribute measures. It is necessary to calculate 2^m types of comprehensive attribute measures and subsequently find the corresponding average value. This method is overly complicated. In fact, we can directly average the attribute measures corresponding to each risk level:

$$\underline{\mu}_{j'xk} = \sum_{j=1}^{m}\left(\omega_j \underline{\mu}_{jxk}\right), \quad \bar{\mu}_{j'xk} = \sum_{j=1}^{m}\left(\omega_j \bar{\mu}_{jxk}\right), \tag{7}$$

$$\underline{\mu}_{j'yk} = \sum_{j=1}^{m}\left(\omega_j \underline{\mu}_{jyk}\right), \quad \bar{\mu}_{j'yk} = \sum_{j=1}^{m}\left(\omega_j \bar{\mu}_{jyk}\right), \tag{8}$$

$$\mu_{j'k} = (\underline{\mu}_{j\prime xk} + \bar{\mu}_{j\prime xk} + \underline{\mu}_{j'yk} + \bar{\mu}_{j'yk})/4, \quad (k = 1,\ 2,\ 3) \tag{9}$$

The calculation results of Eq. (9) are consistent with the calculation results of method one proposed by Zhou et al. (2013), and the calculation is simple and convenient. Therefore, we can replace the original calculation method.

(2) Recognition method two: First, we obtain the average $\mu_{j'x}$ and $\mu_{j'y}$ matrices via the comprehensive attribute measure corresponding to the risk levels of $\underline{\mu}_{j'x}$ and $\bar{\mu}_{j'x}$, $\underline{\mu}_{j'y}$ and $\bar{\mu}_{j'y}$ respectively.

$$\mu_{j'x} = (\underline{\mu}_{j'x} + \overline{\mu}_{j'x})/2, \quad \mu_{j'y} = (\underline{\mu}_{j'y} + \overline{\mu}_{j'y})/2 \tag{10}$$

After orderly combination of $\mu_{j'x}$ and $\mu_{j'y}$, we use method 2 proposed by Zhou et al. (2013) for attribute interval evaluation.

The matrix $U_{m\times K}$ constructed using this method contains 2^m types of combinations for each, and the attribute measurement corresponding to $U_{m\times K}$ can be calculated by the following formula (11):

$$\mu_k = \omega_j \mu_{kn} = [\omega_1, \omega_2, \cdots, \omega_m][\mu_{k1}, \mu_{k2}, \cdots, \mu_{km}]^{\mathrm{T}} \tag{11}$$

where ω_j is a weight vector $[\omega_1, \omega_2, \ldots, \omega_1]_{1\times m}$; $[\mu_{k1}, \mu_{k2}, \ldots, \mu_{km}]^{\mathrm{T}}_{m\times 1}$.

We build two sets of $m \times K$ order matrices: $\underline{\mu}_{j'x}$ and $\bar{\mu}_{j'x}$ $\bar{\mu}_{j'x}$ is a group, $\underline{\mu}_{j'y}$ and $\bar{\mu}_{j'y}$ is a group. By analysing 2^m values of k_0, we can obtain the ratios at which the risk levels can occur.

3 Development of NEW AIET Software Package

The risk assessment process of improved AIET can be considered as a series of matrix operations and requires a large number of calculations because 2^m types of combinations of measures exist for the comprehensive attributes. Different methods are applied to determine the risk level, and thus we propose two other identification methods in this paper and develop a new software package (NEW AIET) based on the original AIET software to solve this problem. The newly developed software consists of several panels, as shown in Fig. 1.

The Grading Standards of Evaluation Indices panel is primarily used to obtain the single attribute measure functions based on the grading standards of the evaluation indices. We first import the threshold limits of grading standards a_{ij} and subsequently calculate the variables b_{ij} and d_{ij} automatically. Finally, we derive the single index attribute functions from Fig. 1 and display them in a pop-up window. We use the Evaluation Indices Values panel to import the lower and upper limit values of the evaluation indices. LLV and ULV refer to the lower and upper limit values, respectively. We use the Evaluation Weights panel to import the weights of the evaluation indices. We use the Confidence Coefficient and Recognition Method panels to assign the value of k and select the recognition method, respectively (Li et al. 2016).

We can complete all operations in a few seconds, and we display the operation results in the specific blanks in the Multiple Indices Synthetic Attribute Measure and Attribute Recognition panel. In addition, using selected important information, we can also display information such as U^{l}_{ij};$U^{\mathrm{u}}_{\mathrm{ij}}$;$\overline{\mu}_j$ and $N_{k=j}$ in several pop-up windows.

4 Engineering Applications in Different Geological Disasters

In recent years, many risk theories have been introduced and studied in domestic academic circles. Based on previous studies, risk assessments of several types of geological disasters, including water inrush, floor water inrush, rock burst and gas outburst, are carried out in the present study.

It should be noted that the evaluation indices for risk assessment of each geological disaster and their grading standards proposed by previous researchers and presented in the literatures are adopted and used in the present study. Analogously, the weights of evaluation indices are also obtained from the values presented in the literatures.

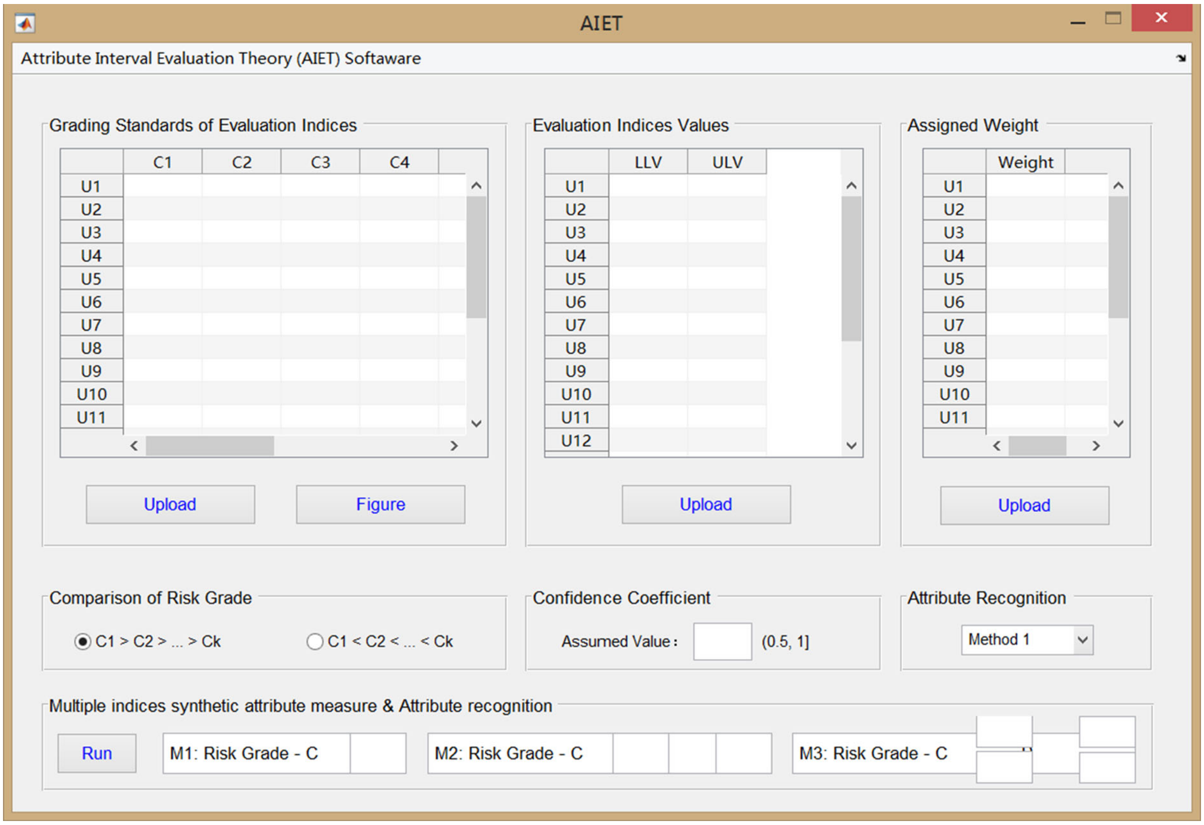

Fig. 1 Main interface of New AIET software package

4.1 Risk Assessment of Water Inrush in Karst Tunnels

We often encounter karst disaster sources such as karst cavity and karst cracking in tunnel construction. The risk of water and mud inrush in a karst tunnel seriously threatens the safety and construction of the tunnel. The karst water inrush has become one of the main geological disasters for tunnel construction in karst regions. According to the karst hydrogeology and engineering geological conditions of the tunnel area, we select seven influence factors as the evaluation indices, including formation lithology, unfavourable geological conditions, groundwater level, landform and physiognomy, attitude of rock formation, contact zones of dissolvable and insoluble rock, and layer and interlayer fissures. In combination with the case of attribute recognition and analysis by Li et al. (2013a), we use the water inrush disasters at *Jigongling tunnel* and *Xiakou tunnel* for engineering applications. The grading standards and value intervals of the evaluation indices are shown in Tables 1 and 2. We take the weights of evaluation indices as 0.167, 0.349, 0.176, 0.097, 0.049, 0.114 and 0.048. The confidence coefficient value is taken as 0.65 in Table 3. According to the evaluation results shown in Table 4, we use two methods to analyse and compare case W①:

Recognition method 1: According to Sect. 2.2, we obtain the property measure from Eqs. (7) to (9):

$$\mu_k = [0.5159, 0.3161, 0.1377, 0.0303] \quad (12)$$

In assessing the risk level, the degree of confidence $\lambda = 0.65$ with available $k_0 = 1$ means that the risk of water inrush from the tunnel is C_1.

Recognition method 2: The combinatorial arrangement of $\mu_{j'x}$ and $\mu_{j'y}$ is used to analyse the comprehensive attribute measures of 128 combinations. The analysis results show that 116 cases exist for which $k_0 = 1$ in the combination of $\mu_{j'x}$ and $\mu_{j'y}$, and the corresponding risk level is C_1. Additionally, we have

Table 2 Grading standards of water inrush evaluation indices (Li et al. 2013a, b; Zhou et al. 2015)

Indices		C_1(I) a_{i0}~a_{i1}	C_2(II) a_{i1}~a_{i2}	C_3(III) a_{i2}~a_{i3}	C_4(IV) a_{i3}~a_{i4}	
		a_{i0}	a_{i1}	a_{i2}	a_{i3}	a_{i4}
U_1 Formation lithology		100	85	70	60	50
		0.404	0.254	0.104	0.042	0
U_2 Unfavourable geological conditions		100	85	70	60	50
U_3 Groundwater level (m)		90	60	30	10	0
U_4 Landform and physiognomy		80	60	40	20	0
U_5 Attitude of rock formation	For $\varphi^* > 45°$	45	25	10	0	-
	For $\varphi < 45°$	45	25	10	-	0
U_6 Contact zones of dissolvable and insoluble rock		100	85	70	60	50
U_7 Layer and interlayer fissures		100	85	70	60	50

*φ: dip angle of rock stratum

Table 3 ULV and LLV of water inrush evaluation indices (Li et al. 2013a)

Case no.	Values	U_1	U_2	U_3	U_4	U_5	U_6	U_7
W①	ULV	80	95	75	30	40	75	90
	LLV	75	90	75	25	40	70	85
W②	ULV	0.075	85	75	42	16	70	80
	LLV	0.067	80	75	37	13	65	75

Table 4 Evaluation results of water inrush risks (k = 0.65)

Case	Method 1						Method 2	Risk*
	C_1	C_2	C_3	C_4	k	Risk		
W①	0.5159	0.3161	0.1377	0.0303	1	I	$N_1 = 118$ & $P(C_1) = 91\%$	–
W②	0.2992	0.3937	0.2448	0.0623	2	II	$N_2 = 128$ & $P(C_2) = 100\%$	II

*Risk results derived from AMT (Li et al. 2013b) and GT (Zhou et al. 2015)

10 combinations for which $k_0 = 2$. We can conclude that the probability of water inrush at C_1 level is 91%, such that the probability of water inrush at C_2 level is 7.5% and that of 1.5% is between C_1 and C_2.

4.2 Risk Assessment of Floor Water Inrush in Coal Mines

Floor water inrush refers to the phenomenon of a sudden and exponential increase of water inrush in a short period of time. We usually divide inrush water into five categories: fault, surface, floor, collapse columns, and goaf seeper. China is a country that has experienced multiple mine water inrush accidents. According to the statistics, water inrush accidents in coal mine floors account for approximately 1/4 of the total number of various types of water inrush accidents in China, and such water inrushes often cause major catastrophic losses. Four influence factors are selected by Wang et al. (2012) and Li et al. (2014) as the evaluation indices: ① Geological structure index, including fault density, fault-water transmitting ability and fracture development degree; ② Hydrogeology index, which consists of confined water pressure, aquifer water property, karst development degree and water supply condition; ③ Floor aquifuge index, including aquifuge thickness, aquifuge strength and aquifuge integrity; and ④ Mining condition index, consisting of mining thickness, mining depth and inclined length of the mining face. As shown in Table 5, six cases introduced in Wang et al. (2012) and Li et al. (2014) are studied in this work. The value intervals of evaluation indices are shown in Table 6. We take the weights of evaluation indices as 0.109, 0.180, 0.143, 0.058, 0.042, 0.071, 0.049, 0.082, 0.059, 0.069, 0.026, 0.047 and 0.066. The confidence coefficient value is taken as 0.65. The evaluation results and comparison are shown in Table 7.

The evaluation results of cases F① and F⑥ agree well with those derived from AMT (Li et al. 2014) and FMT (Wang et al. 2012), whereas the improved AIET performs conservatively again for cases F③ and F⑤. However, the cases of F① and F④ are deemed as high risk in the current study but are considered as medium risk in Wang et al. (2012) and Li et al. (2014).

4.3 Risk Assessment of Rock Burst in Deep-Buried Tunnels

Rock burst is a common dynamic failure phenomenon in construction of deeply buried underground engineering. Rock burst often causes serious damage to the excavation face as well as equipment damage and casualties and has become a worldwide problem in the field of rock underground engineering and rock mechanics. Chen and Li (2008) refer to eight influence factors as the evaluation indices for risk assessment in the current study, including brittleness coefficient, stress coefficient, liability index, linear elastic energy, surrounding rock classification, T criterion, RQD index and stress index, as shown in Table 8. This article primarily studies the engineering practice introduced in Chen and Li (2008). We take the weights of evaluation indices as 0.0774, 0.2437, 0.2322, 0.0774, 0.0808, 0.1063, 0.0892 and 0.0930. The confidence coefficient value is taken as 0.65. The value intervals of evaluation indices are shown in Table 9, and the risk results are shown in Table 10.

The evaluation results and comparisons shown in Table 9 indicate that the improved AIET is only successful in evaluating the risks of sections S①, S④, S⑤ and S⑨. The evaluation results of sections S②, S⑥and S⑧ derived from the improved AIET are slightly conservative, and the results of sections S③ and S⑦ are too conservative. The improved AIET performs conservatively for half of the rock burst cases in the current study. Figure 2 shows the statistical analysis chart of each evaluation result. The combinatorial arrangement of $\mu_{j'x}$ and $\mu_{j'y}$ is used to analyse the comprehensive attribute measure of 128

Table 5 Grading standards of floor water inrush evaluation indices (Wang et al. 2012; Li et al. 2014)

Indices	C_1(I) a_{i0}~ a_{i1}	C_2(II) a_{i1}~ a_{i2}	C_3(III) a_{i2}~ a_{i3}	C_4(IV) a_{i3}~ a_{i4}	C_5(V) a_{i4}~ a_{i5}	
	a_{i0}	a_{i1}	a_{i2}	a_{i3}	a_{i4}	a_{i5}
U_1 Fault density (lip/km^2)	3.3	2.9	2.5	2.1	1.6	1.1
U_2 Fault-water transmitting ability	5.5	4.5	3.5	2.5	1.5	0.5
U_3 Fracture development degree	5.5	4.5	3.5	2.5	1.5	0.5
U_4 Confined water pressure (MPa)	4.4	3.7	3	2	1.2	0.4
U_5 Aquifer water property	5.5	4.5	3.5	2.5	1.5	0.5
U_6 Karst development degree	5.5	4.5	3.5	2.5	1.5	0.5
U_7 Water supply condition	5.5	4.5	3.5	2.5	1.5	0.5
U_8 Aquifuge thickness (m)	13	31	49	74	93	112
U_9 Aquifuge strength (MPa)	1.1	1.4	1.7	2.1	2.4	2.7
U_{10} Aquifuge integrity	0.5	1.5	2.5	3.5	4.5	5.5
U_{11} Mining thickness (m)	2.6	2.1	1.6	1.4	1.2	1
U_{12} Mining depth (m)	850	750	650	550	450	350
U_{13} Inclined length of the mining face (m)	222	177	132	87	45	3

Table 6 ULV and LLV of floor water inrush evaluation indices (Wang et al. 2012; Li et al. 2014)

Case no.	Values	U_1	U_2	U_3	U_4	U_5	U_6	U_7	U_8	U_9	U_{10}	U_{11}	U_{12}	U_{13}
F①	ULV	3.54	5.1	5.1	3.21	4.1	4.1	4.1	57.5	1.43	3.1	2.85	460	145
	LLV	3.46	4.9	4.9	3.07	3.9	3.9	3.9	52.5	1.37	2.9	2.75	440	135
F②	ULV	1.59	3.1	5.1	1.98	5.1	5.1	4.1	30.3	2.13	4.1	5.55	560	150
	LLV	1.49	2.9	4.9	1.82	4.9	4.9	3.9	26.7	2.07	3.9	5.45	540	140
F③	ULV	0.35	1.1	3.1	10.1	5.1	2.1	1.1	132	2.43	2.1	9.05	1110	185
	LLV	0.25	0.9	2.9	9.93	4.9	1.9	0.9	128	2.37	1.9	8.95	1090	175
F④	ULV	3.56	4.1	3.1	0.68	5.1	2.1	2.1	9.18	1.63	2.1	1.34	110	64
	LLV	3.48	3.9	2.9	0.52	4.9	1.9	1.9	8.82	1.57	1.9	1.3	90	56
F⑤	ULV	0.65	1.1	2.1	3.97	5.1	5.1	5.1	59.5	1.94	1.1	1.45	365	205
	LLV	0.55	0.9	1.9	3.83	4.9	4.9	4.9	55.5	1.86	0.9	1.41	345	195
F⑥	ULV	2.6	4.1	5.1	2.95	4.1	4.1	5.1	31.4	2.63	2.1	1.52	290	160
	LLV	2.52	3.9	4.9	2.75	3.9	3.9	4.9	27.8	2.57	1.9	1.48	270	150

Table 7 Evaluation results of floor water inrush risks (k = 0.65)

Case	Method 1							Method 2	Risk*
	C_1	C_2	C_3	C_4	C_5	k	Risk		
F①	0.4589	0.3002	0.1690	0.0494	0.0235	1	I	N_1 = 8192 and $P(C_1)$ = 100%	I
F②	0.2865	0.2041	0.2187	0.2072	0.0846	1	I	N_2 = 8192 and $P(C_1)$ = 100%	II
F③	0.2150	0.1108	0.1087	0.1565	0.4100	5	V	N_3 = 8192 and $P(C_5)$ = 100%	III
F④	0.2946	0.2002	0.2030	0.1490	0.1542	1	I	N_4 = 8192 and $P(C_1)$ = 100%	II
F⑤	0.2604	0.1384	0.1193	0.1580	0.3250	5	V	N_5 = 8192 and $P(C_5)$ = 100%	III
F⑥	0.3037	0.3850	0.1954	0.0207	0.0962	2	II	N_6 = 8192 and $P(C_2)$ = 100%	II

*Risk results derived from AMT (Li et al. 2014) and FMT (Wang et al. 2012)

Table 8 Grading standards of rock burst evaluation indices (Chen and Li 2008)

Indices	C_1(I) a_{i0}~ a_{i1}	C_2(II) a_{i1}~ a_{i2}	C_3(III) a_{i2}~ a_{i3}	C_4(IV) a_{i3}~ a_{i4}	
	a_{i0}	a_{i1}	a_{i2}	a_{i3}	a_{i4}
U_1 Brittleness coefficient (σ_c*/σ_t*)	53.3	40	26.7	14.5	2.3
U_2 Stress coefficient (σ_θ*/σ_c)	0.1	0.3	0.5	0.7	0.9
U_3 Liability index (W_{et})	0.5	2	3.5	5	6.5
U_4 Linear elastic energy (kJ/m^3)	0	40	100	200	300
U_5 Surrounding rock classification	4	3	2	1	0
U_6 Turchaninov criterion (σ_θ+σ_l*/σ_c)	0.1	0.3	0.5	0.8	1.1
U_7 Rock quality designation (RQD)	0	0.25	0.5	0.7	0.9
U_8 Stress index (σ_{max}*/σ_c)	0.1	0.15	0.2	0.25	0.3

*σ_c, uniaxial compressive strength; σ_t, uniaxial tensile strength; σ_θ, uniaxial tangential stress; σ_l, axial stress; σ_{max}, maximum in situ stress

Table 9 ULV and LLV of rock burst evaluation indices (Chen and Li 2008)

Case no.	Values	U_1	U_2	U_3	U_4	U_5	U_6	U_7	U_8
S①	ULV	22.9	0.26	1.65	132	3.1	0.3	0.78	0.205
	LLV	20.5	0.22	1.35	112	2.9	0.26	0.74	0.195
S①	ULV	20.2	0.65	2.55	111	2.6	0.7	0.81	0.455
	LLV	17.8	0.61	2.25	95	2.4	0.64	0.77	0.445
S③	ULV	21.2	0.86	2.45	119	2.6	0.91	0.87	0.575
	LLV	18.8	0.82	2.15	99	2.4	0.85	0.83	0.565
S④	ULV	16.7	0.95	3.55	96	2.1	1	0.4	0.715
	LLV	14.3	0.91	3.25	84	1.9	0.94	0.9	0.705
S⑤	ULV	18.9	1.1	3.35	113	2.1	1	0.94	0.745
	LLV	16.5	1.06	3.05	97	1.9	0.94	0.9	0.735
S⑥	ULV	18.9	1.15	3.35	113	2.1	1.02	0.94	0.715
	LLV	16.5	1.11	3.05	97	1.9	0.96	0.9	0.705
S⑦	ULV	17.9	0.88	3.35	97	2.6	0.97	0.91	0.625
	LLV	15.5	0.84	3.05	85	2.4	0.91	0.87	0.615
S⑧	ULV	17.2	0.64	3.15	82.6	2.6	0.79	0.81	0.485
	LLV	14.8	0.6	2.85	70.6	2.4	0.73	0.77	0.475
S⑨	ULV	16.1	0.33	2.65	4.47	3.1	0.49	0.74	0.355
	LLV	13.7	0.29	2.35	0	2.9	0.45	0.7	0.345

Table 10 Evaluation results of rock burst risks (cases S①–S⑨) (k = 0.65)

Case	Method 1						Method 2	Risk*
	C_1	C_2	C_3	C_4	k	Risk		
S①	0.4144	0.3461	0.1548	0.0847	1	I	$N_1 = 252$ & $P(C_1) = 98\%$	I
S②	0.1070	0.2730	0.3265	0.2935	3	III	$N_2 = 240$ & $P(C_3) = 94\%$	II-III
S③	0.1134	0.2090	0.2072	0.4704	4	IV	$N_3 = 256$ & $P(C_4) = 100\%$	III
S④	0.0181	0.1947	0.2385	0.5487	4	IV	$N_4 = 256$ & $P(C_4) = 100\%$	IV
S⑤	0.0262	0.2008	0.2307	0.5423	4	IV	$N_5 = 256$ & $P(C_4) = 100\%$	IV
S⑥	0.0262	0.2008	0.2272	0.5458	4	IV	$N_6 = 256$ & $P(C_4) = 100\%$	III-IV
S⑦	0.0492	0.2022	0.2407	0.5079	4	IV	$N_7 = 256$ & $P(C_4) = 100\%$	III
S⑧	0.0740	0.2558	0.3594	0.3108	3	III	$N_8 = 254$ & $P(C_3) = 99\%$	II-III
S⑨	0.3168	0.3311	0.1726	0.1795	2	II	$N_9 = 188$ & $P(C_2) = 92\%$	II

*Risk results derived from AHP-FUZZY (Chen and Li 2008)

combinations. The analysis result of S② shows that there are 240 cases for which $k_0 = 3$ in the combination of $\mu_{j'x}$ and $\mu_{j'y}$, the corresponding risk level is C_3. There are 16 combinations for which $k_0 = 4$, and the corresponding risk level is C_4. We can conclude that the probability of rock burst at the C_3 level is 93.75%, and the probability of rock burst at the C_4 level is 6.25%. The analysis result of S⑧ shows that there are 254 cases in which $k_0 = 3$ in the combination of $\mu_{j'x}$ and $\mu_{j'y}$, and the corresponding risk level is C_3. There are 2 combinations with $k_0 = 4$, and the corresponding risk level is C_4. We can conclude that the probability of rock burst at the C_3 level is 99.2%, and the probability of rock burst at the C_4 level is 0.8%. For case S③, S⑥ and S⑦, the reliability index values are all 100%.

In addition, Zhang et al. (2010) also proposed an evaluation index system consisting of six influence factors, including uniaxial compressive strength, strength-stress ratio, brittleness coefficient, stress coefficient, liability index, and integrity index, as shown in Table 11. Combined with the case of

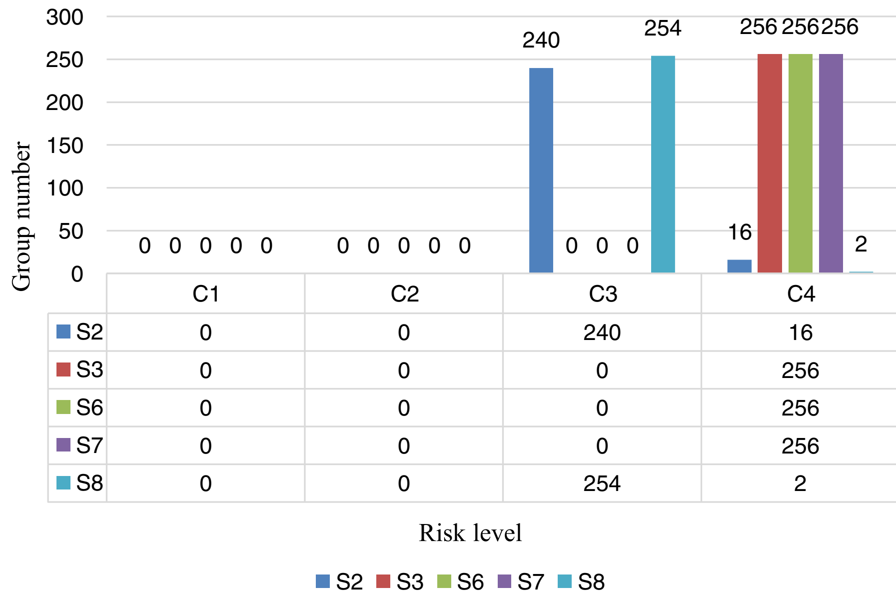

Fig. 2 Risk assessment result of rock burst in deep-buried tunnels

Table 11 Grading standards of rock burst evaluation indices (Zhang et al. 2010)

Indices	C_1(I) a_{i0}~ a_{i1}	C_2(II) a_{i1}~ a_{i2}	C_3(III) a_{i2}~ a_{i3}	C_4(IV) a_{i3}~ a_{i4}	
	a_{i0}	a_{i1}	a_{i2}	a_{i3}	a_{i4}
U_1 Uniaxial compressive strength (σ_c)	40	80	120	180	240
U_2 Strength-stress ratio (σ_c/σ_{max}*)	23.5	14.5	5.5	2.5	0
U_3 Brittleness coefficient (σ_c/σ_t*)	53.3	40	26.7	14.5	2.3
U_4 Stress coefficient (σ_θ*/σ_c)	0.1	0.3	0.5	0.7	0.9
U_5 Liability index (W_{et})	0.5	2	3.5	5	6.5
U_6 Intactness index (K_v)	0.45	0.55	0.65	0.75	0.85

*σ_t: uniaxial tensile strength; σ_θ: maximum tangential stress; σ_{max}: maximum in situ stress

attribute recognition analysis suggested by Zhang et al. (2010), the value intervals of the evaluation indices are shown in Table 12, and the risk results are shown in Table 13. The results are in good agreement with those derived from EM (Zhang et al. 2010).

4.4 Risk Assessment of Gas Outburst in Coal Mines

Coal and gas outburst is a powerful natural disaster in underground coal mining and is a serious threat to the safe production of coal mines. Because coal and gas outbursts can instantaneously explode large amounts of coal and gas streams into the working face of the excavation surface, these events cause severe destruction of the roadway facilities and the ventilation system. These events also fill wells in the nearby area with gas and pulverized coal, causing gas suffocation or coal flow that can bury people and might even cause coal dust and gas explosion and other serious consequences. The evaluation indices suggested by Wu and Yang (2011) and Yang et al. (2010), including mining depth, coal thickness, soft layer thickness change, coal seam inclination angle change, geological structure,

Table 12 ULV and LLV of rock burst evaluation indices (Zhang et al. 2010)

Case no.	Values	U_1	U_2	U_3	U_4	U_5	U_6
R①	ULV	151.63	2.42	11.96	0.56	6.12	0.78
	LLV	163.63	3.02	14.4	0.6	6.42	0.8
R②	ULV	142.38	3.88	16.31	0.43	4.93	0.67
	LLV	154.38	4.48	18.75	0.47	5.23	0.69
R③	ULV	126.05	4.56	19.64	0.37	4.48	0.64
	LLV	138.05	5.16	22.08	0.41	4.78	0.66
R④	ULV	121.93	5.05	27.57	0.26	3.52	0.59
	LLV	133.93	5.65	30.23	0.3	3.82	0.61
R⑤	ULV	103.52	7.91	34.71	0.18	2.14	0.49
	LLV	111.52	9.71	37.37	0.22	2.44	0.51
R⑥	ULV	92.41	10.17	46.6	0.17	1.72	0.42
	LLV	100.41	11.97	49.26	0.21	2.02	0.44
R⑦	ULV	161.19	1.66	11.98	0.64	6.68	0.81
	LLV	173.19	2.16	14.42	0.68	6.98	0.83
R⑧	ULV	114.46	5.35	32.42	0.2	2.74	0.53
	LLV	123.46	6.94	35.08	0.24	3.04	0.55

Table 13 Evaluation results of rock burst risks (cases R①–R⑧) (k = 0.65)

Case	Method 1						Method 2	Risk*
	C_1	C_2	C_3	C_4	k	Risk		
R①	0	0.0867	0.3637	0.5487	4	IV	$N_1 = 64$ & $P(C_4) = 100\%$	IV
R②	0.0151	0.2222	0.4751	0.2866	3	III	$N_2 = 64$ & $P(C_3) = 100\%$	III
R③	0.0363	0.3317	0.4632	0.1678	3	III	$N_3 = 64$ & $P(C_3) = 100\%$	III
R④	0.1099	0.4592	0.3957	0.0342	2	II	$N_4 = 64$ & $P(C_2) = 100\%$	II
R⑤	0.3925	0.4390	0.1675	0	2	II	$N_5 = 61$ & $P(C_2) = 95\%$	II
R⑥	0.5764	0.3491	0.0735	0	1	I	$N_6 = 64$ & $P(C_1) = 100\%$	I
R⑦	0	0.0379	0.3138	0.6473	4	IV	$N_7 = 64$ & $P(C_4) = 100\%$	IV
R⑧	0.2540	0.4642	0.2758	0.0050	2	II	$N_8 = 64$ & $P(C_2) = 100\%$	II

*Risk results derived from EM (Zhang et al. 2010)

sturdiness coefficient, maximum gas outburst initial velocity, dynamic phenomena and maximum gas pressure, are selected as the evaluation indices for risk assessment in the current study, as shown in Table 14. Combining the four cases introduced in Wu and Yang (2011) and Yang et al. (2010), we take the weights of evaluation indices as 0.152, 0.102, 0.081, 0.06, 0.015, 0.064, 0.247, 0.021 and 0.258. The confidence coefficient value is taken as 0.65. The value intervals of evaluation indices are shown in Table 15, and the risk results are shown in Table 16.

The evaluation results and comparisons shown in Table 16 indicate that the evaluation results are generally in good agreement with those derived from the EM. For case G④, the reliability index value is 99%, and the values of the other three cases are all 100%.

5 Conclusions

- We propose a new comprehensive attribute measurement analysis method and attribute identification method. The novel characteristic of attribute interval evaluation theory is that the values of the evaluation indices are taken as intervals rather than

Table 14 Grading standards of coal and gas outburst evaluation indices (Yang et al. 2010)

Indices	C_1(I) $a_{i0}\sim a_{i1}$	C_2(II) $a_{i1}\sim a_{i2}$		C_3(III) $a_{i2}\sim a_{i3}$
	a_{i0}	a_{i1}	a_{i2}	a_{i3}
U_1 Mining depth (m)	1200	500	200	100
U_2 Thickness of coal seam (m)	10	5	3	1
U_3 Thickness variation of soft layer	10	8	4	1
U_4 Dip angle variation of coal seam	10	8	4	1
U_5 Geological structure	10	8	4	1
U_6 Solidity coefficient	0	0.2	0.3	1.5
U_7 Maximum initial velocity of gas emission (L/min)	18	10	5	1
U_8 Dynamic phenomenon	10	8	4	1
U_9 Maximum gas pressure (MPa)	6	3	1.1	0.3

Table 15 ULV and LLV of coal and gas outburst evaluation indices (Yang et al. 2010)

Case no.	Values	U_1	U_2	U_3	U_4	U_5	U_6	U_7	U_8	U_9
G①	ULV	520	3.5	8.7	6.5	8.8	0.2	4.3	7.7	3.03
	LLV	460	3.1	8.3	5.7	8.4	0.16	3.5	6.9	2.65
G②	ULV	607	3.6	7.2	7.9	9.4	0.26	3.9	8.8	1.64
	LLV	507	3.2	6.4	7.1	9	0.24	3.1	8.4	1.26
G③	ULV	476	5.5	5.8	9.5	9.1	0.22	1.9	9.3	4.25
	LLV	416	4.8	5	9.1	8.7	0.2	1.1	8.9	3.65
G④	ULV	890	5.7	8.9	9.1	7.8	0.29	3.9	9.6	3.53
	LLV	790	4.9	8.5	8.7	7	0.27	3.1	9.2	2.93

Table 16 Evaluation results of coal and gas outburst risks (k = 0.65)

Case.	Method 1					Method 2	Risk*
	C_1	C_2	C_3	k	Risk		
G①	0.3174	0.4487	0.2338	2	II	$N_1 = 512$ & $P(C_2) = 100\%$	II
G②	0.2124	0.4398	0.3477	2	II	$N_2 = 512$ & $P(C_2) = 100\%$	II
G③	0.4028	0.3199	0.2773	1	I	$N_3 = 512$ & $P(C_1) = 100\%$	I
G④	0.4330	0.3668	0.2002	1	I	$N_4 = 505$ & $P(C_1) = 99\%$	I

*Risk results derived from EM (Yang et al. 2010)

unique values, and the single index attribute measure of the upper and lower limits is calculated separately. With further exploration and application of the evaluation method, we propose two calculation methods of the multiple index attribute measure. This method considers the complexity of underground engineering geological conditions and the uncertainty of risk and thus can better evaluate the project disaster risk.

- The risk assessment process of the improved AIET requires a large amount of calculations. Therefore, based on the original AIET software package, we develop new simple and practical NEW AIET software to overcome this shortcoming. We can complete the risk assessment process in a few seconds using the developed software.
- Engineering applications have been carried out to verify the accuracy and feasibility of the improved AIET for risk assessment of geological disasters, including water inrush, floor water inrush, rock burst and coal and gas outburst. Taking Jigongling Tunnel, Xiakou Tunnel and others as examples, the risk assessment of geological disasters in underground engineering was carried out. The evaluation results are consistent with the analysis results of other methods, which is consistent with the actual engineering excavation. Engineering application and verification show that the two multi-attribute attribute measurement analysis and identification method determination results can be analysed and evaluated for actual projects, and multiple methods can be used in comprehensive analysis in the evaluation process.

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