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A new quantitative method for risk assessment of geological disasters in underground engineering: Attribute Interval Evaluation Theory (AIET)

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ABSTRACT

A new quantitative method named Attribute Interval Evaluation Theory (AIET) is proposed for risk assessment of geological disasters in underground engineering in the present study. The AIET not only can quantitatively evaluate and prioritize risks by combining consequences and probability of occurrence, but also can make an analysis of the reliability of evaluation results. The values of evaluation indices are taken as intervals rather than unique values, which is more reasonable because of geotechnical complexity and uncertainty. A simple and practical software package is developed so that the risk assessment process which is subjected to a large number of calculations can be completed automatically in a few seconds. Engineering applications to different geological disasters and results comparison indicate that the AIET can be successful in evaluating and prioritizing risks in most cases. The confidence coefficient value has a big impact on the reliability of evaluation results. The reasonable confidence coefficient value for an evaluation result with a reliability index of no less than 80% is found to be in the range of 0.60–0.63, and its maximum value can reach 0.66 for most of the engineering practices.

1. Introduction

A geological disaster in underground engineering is generally induced by one of several types of adverse geological conditions and has a big impact on engineering constructions, resulting in damages or loss of lives and property. These disasters, such as water inrushes, rock bursts, gas explosions, large deformations and collapses, sometimes are instigated through careless constructions and can be avoidable or preventable to some extent. Risk assessment, which is composed of risk identification, risk analysis and risk evaluation, followed by mitigation and control strategies, is a practical and effective approach to predicting and preventing such disasters.

Risk assessment consists of an objective evaluation of risk in which assumptions and uncertainties are clearly considered and may be qualitative, semi-quantitative or quantitative. Quantitative risk assessment should be in consideration of both possible adverse consequences and probability of occurrence (Brown, 2012). Various methods and methodologies have been proposed for risk assessment of geological disasters over the past few decades, such as the *fault tree analysis* (*FTA*), the *event tree analysis* (*ETA*), the *accident tree analysis* (*ATA*), the *Delphi method* (*DM*), the *analytic hierarchy process* (*AHP*), the *Bayesian network* (*BN*), the *fuzzy mathematics theory* (*FMT*), the *grey theory* (*GT*), the *extension method* (*EM*) and so on (Saaty, 1980; Corotis et al., 1981; Einstein, 1996; Choi et al., 2004; Beard, 2010; Sousa and Einstein, 2012), and an overview of risk assessment methods that are commonly used in underground rock engineering was provided by Brown (2012).

In underground engineering, risk sources and disasters generally arise from geotechnical uncertainty (aleatory or epistemic) or error (intrinsic or implementary) (Baecher and Christian, 2003; Brown, 2007; Hadjigeorgiou and Harrison, 2011). However, for most of current commonly used risk assessment methods, the value of each evaluation index is taken as a unique value, which ignores consideration of geotechnical uncertainty and natural variability. Additionally, most of them evaluate and prioritize risks by combining consequences and probability of occurrence, but fail to analyze the reliability of evaluation results.

Therefore, an effective and practical method named Attribute Interval Evaluation Theory (AIET) is put forward in the present study, which not only can quantitatively evaluate and prioritize risks by combining consequences and probability of occurrence, but also can make an analysis of the reliability of evaluation results. The values of evaluation indices used for risk assessment are taken as intervals rather than unique values, which is more reasonable than other methods because of geotechnical uncertainty.

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As it is subjected to a large number of calculations, a simple and practical software is developed to overcome this disadvantage. Engineering applications to different geological disasters are also carried out to verify its accuracy and feasibility for risk assessment.

2. Attribute Interval Evaluation Theory (AIET)

The AIET is an innovative risk assessment methodology proposed by Li et al. (2013a) based on the *attribute mathematical theory* (AMT). Both of them have three sub-systems, but differ in computational methods. In the AIET, a new method is proposed for multiple indices synthetic attribute measure analysis and two new methods are put forward for attribute recognition analysis. The AIET and its advantages are summarized as follows.

2.1. AIET sub-systems and fundamentals

2.1.1. Single index attribute measure analysis

The method used for single index attribute measure analysis in the AIET is same to that in the AMT. The grading standards of evaluation indices can be expressed as

$$A=\begin{bmatrix} U_i\setminus C_j & C_1 & C_2 & \cdots & C_n \\ U_1 & a_{10}\sim a_{11} & a_{11}\sim a_{12} & \cdots & a_{1(n-1)}\sim a_{1n} \\ U_2 & a_{20}\sim a_{21} & a_{21}\sim a_{22} & \cdots & a_{2(n-1)}\sim a_{2n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ U_m & a_{m0}\sim a_{m1} & a_{m1}\sim a_{m2} & \cdots & a_{m(n-1)}\sim a_{mn} \end{bmatrix} \tag{1}$$

where a_{ij} ($i = 1, 2, \ldots, m$; and $j = 0, 1, 2, \ldots, n$) are the threshold limits and should satisfy either $a_{i0} < a_{i1} < \cdots < a_{in}$ or $a_{i0} > a_{i1} > \cdots > a_{in}$. m and n are the number of evaluation indices (U_i) and risk grades (C_j), respectively.

The single index attribute measures can be expressed as follows:

$$\mathbf{U}_{ij}=\begin{bmatrix}\boldsymbol{u}_{1j}\\ \boldsymbol{u}_{2j}\\ \vdots\\ \boldsymbol{u}_{ij}\\ \vdots\\ \boldsymbol{u}_{mj}\end{bmatrix}=\begin{bmatrix} u_{11} & u_{12} & \cdots & u_{1j} & \cdots & u_{1n}\\ u_{21} & u_{22} & \cdots & u_{2j} & \cdots & u_{2n}\\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots\\ u_{i1} & u_{i2} & \cdots & u_{ij} & \cdots & u_{in}\\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots\\ u_{m1} & u_{m2} & \cdots & u_{mj} & \cdots & u_{mn}\end{bmatrix} \tag{2}$$

where u_{ij} can be derived from Fig. 1. The boundaries marked with ellipses in Fig. 1 should satisfy

$$\text{For Fig.1(a)}:\ a_{i(j-1)}+d_{i(j-1)} \leqslant a_{ij}-d_{ij} \quad (j=2,\ 3,\ n-1) \tag{3}$$

$$\text{For Fig.1(b)}:\ a_{i(j-1)}-d_{i(j-1)} \leqslant a_{ij}+d_{ij} \quad (j=2,\ 3,\ n-1) \tag{4}$$

in which

$$d_{ij}=\min\{|b_{ij}-a_{ij}|,\quad |b_{i(j+1)}-a_{ij}|\} \quad (j=1,\ 2,\ \ldots,\ n-1) \tag{5}$$

and

$$b_{ij}=\frac{a_{i(j-1)}+a_{ij}}{2} \quad (j=1,\ 2,\ \ldots,\ n) \tag{6}$$

It should be noted that the values of evaluation indices in the AIET are taken as intervals rather than unique values. The upper and lower limit values should be calculated separately and two single index attribute measure matrixes can be obtained and expressed as

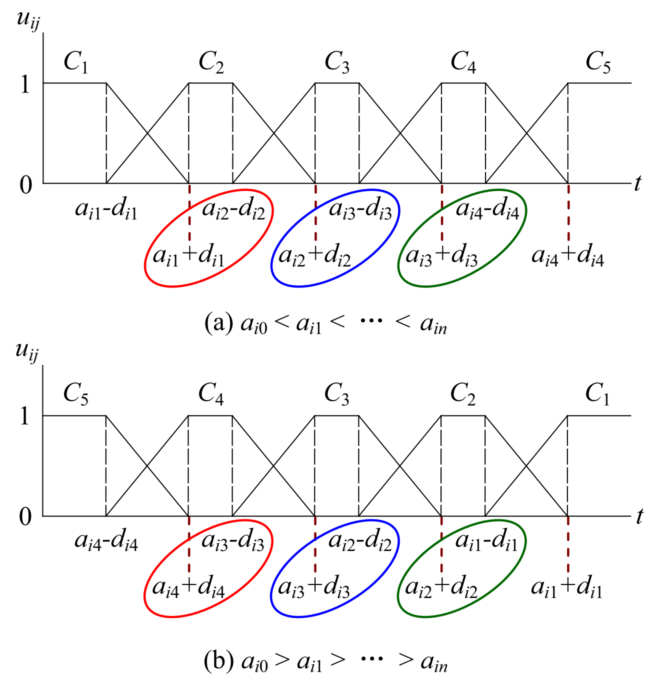

Fig. 1. Illustration of single attribute measure functions ($n = 5$).

$$\mathbf{U}^u_{ij}=\begin{bmatrix}\boldsymbol{u}^u_{1j}\\ \boldsymbol{u}^u_{2j}\\ \vdots\\ \boldsymbol{u}^u_{ij}\\ \vdots\\ \boldsymbol{u}^u_{mj}\end{bmatrix}=\begin{bmatrix} u^u_{11} & u^u_{12} & \cdots & u^u_{1j} & \cdots & u^u_{1n}\\ u^u_{21} & u^u_{22} & \cdots & u^u_{2j} & \cdots & u^u_{2n}\\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots\\ u^u_{i1} & u^u_{i2} & \cdots & u^u_{ij} & \cdots & u^u_{in}\\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots\\ u^u_{m1} & u^u_{m2} & \cdots & u^u_{mj} & \cdots & u^u_{mn}\end{bmatrix} \tag{7}$$

$$\mathbf{U}^l_{ij}=\begin{bmatrix}\boldsymbol{u}^l_{1j}\\ \boldsymbol{u}^l_{2j}\\ \vdots\\ \boldsymbol{u}^l_{ij}\\ \vdots\\ \boldsymbol{u}^l_{mj}\end{bmatrix}=\begin{bmatrix} u^l_{11} & u^l_{12} & \cdots & u^l_{1j} & \cdots & u^l_{1n}\\ u^l_{21} & u^l_{22} & \cdots & u^l_{2j} & \cdots & u^l_{2n}\\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots\\ u^l_{i1} & u^l_{i2} & \cdots & u^l_{ij} & \cdots & u^l_{in}\\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots\\ u^l_{m1} & u^l_{m2} & \cdots & u^l_{mj} & \cdots & u^l_{mn}\end{bmatrix} \tag{8}$$

where $\boldsymbol{u}^u_{ij}$ and $\boldsymbol{u}^l_{ij}$ are two n-dimensional row vectors, in which u and l denote the upper and lower limit values, respectively.

2.1.2. Multiple indices synthetic attribute measure analysis

An $m \times n$ order matrix can be obtained from

$$\mathbf{U}'_{ij}=\begin{bmatrix} C^1_2\left(\boldsymbol{u}^u_{1j}\quad \boldsymbol{u}^l_{1j}\right)\\ C^1_2\left(\boldsymbol{u}^u_{2j}\quad \boldsymbol{u}^l_{2j}\right)\\ \vdots\\ C^1_2\left(\boldsymbol{u}^u_{ij}\quad \boldsymbol{u}^l_{ij}\right)\\ \vdots\\ C^1_2\left(\boldsymbol{u}^u_{mj}\quad \boldsymbol{u}^l_{mj}\right)\end{bmatrix} \tag{9}$$

where $C^1_2\left(\boldsymbol{u}^u_{ij}\quad \boldsymbol{u}^l_{ij}\right)$ means to select one from $\boldsymbol{u}^u_{ij}$ and $\boldsymbol{u}^l_{ij}$. The total number of $\mathbf{U}'_{ij}$ is 2^m. Eq. (9) also can be expressed as