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A principal component analysis/fuzzy comprehensive evaluation model for coal burst liability assessment

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1. Introduction

Rock bursts, as a natural hazard induced by the rapid and violent release of elastic strain energy from rock mass failure, pose a serious threat to the safety of underground mining. In addition to the destructive and dynamic natural of a rock burst event, the catastrophic failure of rock/coal may also disturb mine ventilation and result in secondary hazards such as gas outbursts or dust explosion. The coal burst liability (CBL) arises with the increase of stored strain energy in coal seams, which ultimately results in rock burst failure. Strain energy, which is one of the built-in attributes of rock, is the internal cause and an essential condition for the occurrence of rock bursts.[1,2] Researchers around the world have proposed various burst liability indices based on energy, failure duration, deformation, stiffness, and strength, etc. Accordingly, the current approaches to evaluate CBL focus on measuring the uniaxial compressive strength,[3–5] elastic strain energy,[1] bursting energy,[6,7] dynamic failure duration,[8] energy release speed,[9,10] surplus energy,[11,12] modified brittleness,[13] microcrystalline parameter,[14] and energy dissipation indices.[15]

The CBL indices currently used in China are the uniaxial compressive strength (R_C), elastic strain energy (W_{ET}), bursting energy (K_E), and dynamic failure duration (D_T).[16] These all play an important role in evaluating rock burst hazards in coal seams. However, they still present some drawbacks. One of them is that the CBL is affected simultaneously by compressive strength, time, and energy.[17] But the four indices above merely evaluate the intensity of CBL from one aspect. This leads to inconsistent results when the four indices are adopted along with each other. Another drawback is that the fuzziness, which is inevitably contained in the classification of any CBL magnitude and the gradual transition between different grades of rock burst hazard, are not taken into account.

In order to address above challenges, a number of researchers have conducted comprehensive assessments of rock burst risks using computational intelligence methods. These methods include the application of the support vector machine,[18] knowledge-based and data-driven fuzzy modeling,[19] cloud model,[20] statistical method,[21] principal component analysis (PCA),[22] fuzzy comprehensive evaluation (FCE),[23,24] Mahalanobis-Taguchi system,[25] and fuzzy matter-element model.[26] The Chinese standard to assess the CBL, the GB/T 25217.2–2010[16] (hereinafter simply referred to as 'GB'), clearly stipulates that the four indices should be reevaluated by the FCE method or other probability statistic methods when their evaluation results are contradictory. Although inconsistency in the results obtained using different indices can be somewhat addressed according to the GB recommendation, the following aspects are worth reconsidering (see Appendix A):

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(1) The weights of the four indices in GB are constant and selected subjectively, which may induce bias in the selection process and overlook the information conveyed by the test data.
(2) There are eight terms among the 81 test results corresponding to the four indices in GB which cannot be comprehensively evaluated.
(3) Due to the heterogeneity of coal or rock, the test results are different even when the samples are collected from the same sampling sites. Moreover, the GB does not present treatment methods to evaluate the CBL of the entire mining face in a coal seam, for instance, multiple test groups from different sampling sites are required when different test results have been observed.
(4) The existing data processing methods, e.g., using the mean value of multiple test groups' results for the CBL evaluation, ignore the weight of each test group and the highly discrete nature of the coal specimen tests. This is especially troublesome as the high discreteness of the test data greatly reduces the reliability of the evaluation results.

Considering these shortcomings, in this study we use the loading factor and the EPDE model, derived from the PCA method, to determine the objective weight of each CBL index and each test group, respectively. Then, the obtained objective weights were combined with the subjective weights normally used in the Chinese standard, and the comprehensive value of each index are calculated. Finally, the CBL of each test group and the entire mining face are comprehensively evaluated using the maximum membership degree method (MMDM) in the FCE. This paper improves upon the existing CBL evaluation methods, and provides a new approach to comprehensively assess the CBL of a complete mining face, which can also be extended to the coal seam scale.

2. The PCA–FCE method

2.1. Principal component analysis

PCA was first proposed by Hotelling in 1933. The basic idea is to achieve dimension reduction of the problem while retaining the information of the original parameters as much as possible. By doing this, the complexity of the problem is further simplified and the main contradiction is captured. Geometrically, PCA can be illustrated by the rotation of the coordinate system. The principal components are described by the conversion relations between the new coordinate system and the original coordinate system. In the new coordinate system, the axis direction is the direction of the largest variation of the original data.[27]

The detailed steps in the analysis are as follows:

(1) Establish the original variable matrix **x**. It is assumed that there are n samples, one of which has p variables to be observed. Thus, the matrix **x** can be expressed as $\mathbf{x} = (x_{ij})_{n \times p}$, where x_{ij} is the jth index value of sample i.
(2) Normalize the data. Due to the large differences in the dimensions, sizes, and evaluation standards of the factors, the comparability of these factors is poor. Therefore, the factors need to be normalized to achieve good comparability. Herein, we adopt the range normalization:

$$X_{ij} = \frac{x_{ij} - \bar{x}_j}{R_j}, \cdot i = 1, 2, 3, \cdots, n, \cdot j = 1, 2, 3, \cdots, p \tag{1}$$

where $R_j = \max\{x_{ij}\} - \min\{x_{ij}\}$ and $\bar{x}_j = \frac{1}{n}\sum_{i=1}^{n} x_{ij}$ is the mean value of the jth index.
(3) Calculate the correlation coefficient matrix **R** of the normalized data.
(4) Solve for the eigenvalues and eigenvectors of the matrix **R**.
(5) Establish the equations of principal components and calculate their values.
(6) Calculate the objective information weight for each factor.

2.2. Fuzzy comprehensive evaluation

FCE is divided into two main steps: separate evaluation using each factor, and comprehensive evaluation using all factors.[28]

(1) Establish the factor set. The factor set is a common set composed of all the factors determining the evaluation object. It is expressed using the vector U, i.e. $U = \{u_1, u_2, \cdots, u_p\}$.
(2) Build the weight set. The importance of each factor is generally different. Therefore, the factors cannot be treated equally. To reflect the importance of each factor, the factors need to be given corresponding weights. The set of weights, $A = \{a_1, a_2, \cdots, a_p\}$, is called the weight set. Each weight should satisfy normalization and the non-negative conditions:

$$\sum_{i=1}^{p} a_i = 1, \cdot a_i \geq 0 \cdot (i = 1, 2, \ldots, p) \tag{2}$$

(3) Establish the alternative set. The alternative set is an ensemble of all possible evaluation sets which are obtained by evaluating target objects. It is represented by $V = \{v_1, v_2, \cdots, v_p\}$ where v_i are the various possible evaluation results.
(4) Single-factor fuzzy evaluation. Each single influencing factor is individually evaluated in this step to determine the degree of membership of the evaluated object to the alternative set factor. Assuming that the evaluated object is evaluated by the ith factor u_i, and the membership degree of the jth factor v_j is γ_{ij}, the evaluation result for u_i can be expressed as $\mathbf{R}_i = \{\gamma_{i1}, \gamma_{i2}, \cdots, \gamma_{in}\}$. By arranging the degree of membership of each factor evaluation set in rows, the single-factor evaluation matrix can be constructed:

$$\mathbf{R} = \begin{bmatrix} \gamma_{11} & \gamma_{12} & \cdots & \gamma_{1n} \\ \gamma_{21} & \gamma_{22} & \cdots & \gamma_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ \gamma_{m1} & \gamma_{m2} & \cdots & \gamma_{mn} \end{bmatrix} \tag{3}$$

(5) All factor fuzzy evaluation. The single-factor fuzzy evaluation only reflects the influence of the single-factor on the evaluated object. The aim of FCE is to comprehensively consider the influences of *all* factors. The FCE set for all factors can be expressed in the form: $\mathbf{B} = \mathbf{A} \cdot \mathbf{R} = (b_1, b_2, \cdots, b_m)$, where b_j is defined as the degree of membership of the evaluated object to the jth factor in the alternative set when considering the influence of all factors.
(6) Locate the evaluation index using the MMDM. After obtaining the evaluation index b_j, the component v_L in the alternative set corresponding to the largest evaluation index, $\max_j(b_j)$, is taken as the evaluation result:

$$V = \left\{ v_L \middle| v_L \to \max_j \left(b_j \right) \right\} \tag{4}$$

3. A case study

3.1. Site description

LW 250205 is located in the Yanbei coal mine of Gansu Province, China. It is the first mining face in the mining district of No. 2502, adjacent to the anticline axis in the south and the west wing of a syncline in the north. The panel is fairly deep at about 505 m underground. The coal seam thickness ranges from 22.7 m to