Fuzzy Comprehensive Evaluation of Ecological Risk Based on Cloud Model: Taking Chengchao Iron Mine as Example

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Abstract. Aimed at the fuzziness and randomness during the evaluation process, this paper constructed a fuzzy comprehensive evaluation method based on cloud model. The evaluation index system was established based on the inherent risk, present level and control situation, which had been proved to be able to convey the main contradictions of ecological risk in mine on the macro level, and be advantageous for comparison among mines. The comment sets and membership functions improved by cloud model could reflect the uniformity of ambiguity and randomness effectively. In addition, the concept of fuzzy entropy was introduced to further characterize the fuzziness of assessments results and the complexities of ecological problems in target mine. A practical example in Chengchao Iron Mine evidenced that, the assessments results can reflect actual situations appropriately and provide a new theoretic guidance for comprehensive ecological risk evaluation of underground iron mine.

1. Introduction
The mining area belongs to the typical ecological fragile area, the ecological and environmental problems of which have aroused the concern of researchers who have made a series of studies in environmental quality, the stability and vulnerability of ecosystem, ecological civilization and ecological security [1]. In recent years, the ecological risk assessments of mining area have been transformed from special to comprehensive [2], resulting in appearing various research perspectives such as landscape [3], land destruction [4], ecological gradient [5] and ecological carrying capacity [6]. However, the ecological risk assessment of mining area still faces many problems, which are mainly manifested in the representation of uncertainty in evaluation process. The formation mechanism of mining ecological environment is complex, which leads to the ambiguity and randomness in the
process of ecological risk assessment. In order to solve the problem, a cloud model based on fuzzy comprehensive evaluation is proposed to solve fuzziness and randomness during the evaluation.

2. The Evaluation Index System
The comprehensive evaluation of ecological risk is introduced to reflect the differences of the ecological risk degree among the same types of mine. Therefore, the evaluation index system is supposed to represent the main contradiction of the production technology, technical characteristics and the ecological environment.

At present, the ecological risk evaluation generally follows the analysis framework of "risk source — risk receptor — exposure path — ecological endpoint", which is more effective for special ecological risk assessment of single risk source. It is inappropriate to adopt traditional method when comprehensive evaluation of ecological risk involves multiple sources, multiple receptors and multiple ecological endpoints. So, this paper built an index system from three aspects of inherent risk, present level and control situation to reflect the comprehensive risk degree of mines, to serve on the government decision-making management. The selected indexes are shown in table 1.

Table 1. The evaluation index system of the land ecological risk

| First-class index | Second-class index | Third-class index |
|-------------------|--------------------|------------------|
| Natural occurrence (D1) | Geology and geomorphology | D11 Climate and hydrology |
| Mining activities (D2) | Occurrence of ore | D12 |
| Geological disaster (R1) | Mining intensity | D21 Technological modernization |
| Present level (R) | Advanced level of equipment | D22 |
| Water resources (R2) | Geof risk | D23 |
| Landscape ecology (R3) | Damage | R11 Tailing risk |
| Soil environment (R4) | Water resources | R12 Waste dump risk |
| Technical means (C1) | Soil resources | R13 |
| Control situation (C) | Soil pollution | R31 Landscape fragmentation |
| Institutional policy (C2) | “Three wastes” emission | R32 |
| | Monitoring and forecasting facilities | C11 Waste stone utilization |
| | Land reclamation | C12 |

3. The Evaluation Method
As mentioned above, there are various factors influencing the ecological environment, whose mechanism and magnitude in the evolution of the ecological environment have not yet been fully revealed. Therefore, it is inappropriate to describe them as definite states. In this paper, a fuzzy comprehensive evaluation model based on cloud model is established to improve the traditional fuzzy comprehensive evaluation model which ignores the randomness.

3.1. Fuzzy Comprehensive Evaluation Model
Fuzzy mathematics based on the "fuzzy set" theory is a kind of quantification method for dealing with
uncertain and imprecise problems. It is applied in many fields such as fuzzy control, fuzzy recognition, fuzzy decision, information retrieval and fuzzy evaluation. And fuzzy comprehensive evaluation model is the most commonly used to evaluate fuzzy problems for better evaluation results. For the three-level evaluation index system involved in this study, the multilevel fuzzy comprehensive evaluation model can be used to evaluate, the general expression is:

$$P = \left( \begin{array}{cccc}
v_1 & v_2 & \ldots & v_j \\
p_{i1} & p_{i2} & \ldots & p_{ij} \\
p_{21} & p_{22} & \ldots & p_{2j} \\
\vdots & \vdots & \ddots & \vdots \\
u_i & p_{i1} & \ldots & p_{ij} \\
\end{array} \right)$$

$$Y = \bigoplus_{i=1}^{m} a_i \bigotimes p_i$$  \hspace{1cm} (1)

In which \{u_1, u_2, \ldots, u_i\} and \{v_1, v_2, \ldots, v_j\} are the evaluation factors set and comment set, respectively, \(P\) is relation matrix, \(p_{ij}\) is the membership of participation factors \(u_i\) in comment \(v_j\), \(Y\) is evaluation result. The symbols \(\bigoplus\) and \(\bigotimes\) are fuzzy operators, which stands for cyclic addition and cyclic multiplication, respectively.

Among them, constructing a reasonable membership function is the key to fuzzy evaluation. But the membership used in most of the existing methods is given by subjective value or empirical formula. Once the membership function is determined, the fuzzy problem is replaced by the precise mathematics, which can not express the randomness.

### 3.2. Cloud Model Improvement Process

Cloud model firstly proposed by Academician Li D Y [7] is an uncertainty conversion model between qualitative concepts and quantitative expression, which has been proved to be universally applicable.

The cloud model includes three digital features: expected value (Ex), entropy (En) and hyper entropy (He). Among them, Ex is the most representative point of a concept in the theoretical domain; En is used to measure the ambiguity and probability of the qualitative concept; He expresses the uncertainty of En, its value can be described by the dispersion and thickness of cloud.

The process of fuzzy comprehensive evaluation of ecological risk based on cloud model includes:

#### 3.2.1. Determining the Weights of the Evaluation Indexes

Analytic hierarchy process (AHP) is a hierarchical and systematic analysis method; it can solve the complicated fuzzy problems effectively and conveniently. Therefore, AHP was introduced to determine the weights of evaluation indexes in this paper.

#### 3.2.2. Setting Comment Sets and Benchmark Cloud

In this paper, ecological risk of underground iron mine was divided into four levels: high risk, medium risk, low risk and slight risk, whose evaluation scores are set to [0, 2.5], [2.5, 5], [5, 7.5] and [7.5, 10] correspondingly. And the normal cloud model is introduced to describe the risk status of these four levels respectively to form benchmark cloud.

The parameters of the benchmark cloud are determined by the formulas under bilateral constraints.

\[
\begin{align*}
E_x &= \frac{(B_{\text{max}} + B_{\text{min}})}{2} \\
E_c &= \frac{(B_{\text{max}} - B_{\text{min}})}{6} \\
H_c &= k
\end{align*}
\]  \hspace{1cm} (2)
In the above equations $B_{\text{max}}$ and $B_{\text{min}}$ are the upper and lower limits of the quantitative interval respectively, $k$ is a constant, adjusted according to the fuzzy threshold of the variable itself. Since $k$ equals 0, the model degenerates into the membership function. Referencing to the relevant research, $k$ equals 1 in this paper.

3.2.3. Generating the Cloud Model. This paper set up scoring basis and created descriptions firstly. Then, experts were invited and informed of scoring rules that scores from 0-10 indicate that the degree of risk is getting lower and lower. According to the principle of inverse cloud generator, taking each score as cloud droplet generates membership clouds of 4 risk grade, then combined as the membership cloud model of each evaluation index. The parameters are calculated as follows:

\[
\begin{align*}
E_x &= \tau = \sum_{j=1}^{n} x_j \\
E_n &= \frac{1}{\sqrt{2}} \times \frac{1}{n} \times \sum_{j=1}^{n} |x_j - E_x| \\
H_n &= \sqrt{S^2 - E_n^2} = \frac{1}{\sqrt{n-1}} \times \sum_{j=1}^{n} (x_j - \tau) - E_n^2
\end{align*}
\]  

(3)

In equation (3) $x_j$ is the score assigned by the j-th expert to the description. Using the three characteristics (Ex, En, He) of cloud, we can express the randomness between the evaluation index and the membership of risk grade. When the membership model is established, the more the number of experts are, the higher the accuracy of the model will have.

3.2.4. Comprehensive Evaluation of Ecological Risk. The experts graded each index according to the scoring basis. Substituting the experts’ scores into the membership cloud model can obtain $C_{e_i}$ which represents the membership of evaluation index to each risk level respectively. Eventually the cloud model can be obtained by assigning the membership cloud a weight under each risk level. The weighted synthesis method of cloud model is as follows [8]:

\[
(E_x, E_n, H_n) = (E_{n_1}, E_{n_2}, H_{n_2}) \oplus (E_{n_2}, E_{n_3}, H_{n_3}) \oplus \cdots \oplus (E_{n_i}, E_{n_{i+1}}, H_{n_{i+1}})
\]  

(4)

\[
\begin{align*}
E_x &= \sum_{i=1}^{m} E_{n_i} \times \omega_i \\
E_n &= \sqrt{\sum_{i=1}^{m} E_{n_i}^2 \times \omega_i} \\
H_n &= \sum_{i=1}^{m} H_{n_i} \times \omega_i
\end{align*}
\]  

(5)

In which $\omega_i$ is the weight, $i$ is the number of evaluation indexes, $\oplus$ represents the weighted composition of the cloud.

3.2.5. Characterization of Fuzzy Degree of Evaluation Results. It is difficult for single grade evaluation results to reflect the details of the ecological risk degree of underground iron mine because of the hierarchical distribution inconsistency of each evaluation index. So the De Luca-Trimini
definition of fuzzy entropy is used to characterize the ambiguity of the evaluation result of the cloud model.

\[
E = -k_2 \sum_{j=1}^{n} [C_{e_j} \ln C_{e_j} + (1-C_{e_j}) \ln(1-C_{e_j})]
\]

(6)

\[
k_2 = -\ln(\frac{1}{n}) - (n-1)\ln\frac{n-1}{n}
\]

(7)

In the above equations \(E\) is fuzzy entropy, characterizing the fuzzy degree of evaluation results; \(C_{e_i}\) is \(i\)-th element of the vector \(Ce\) for cloud model’s certainty under different risk grade, setting \(\ln 0 = 0\); and \(k_2\) is the standard coefficient. The relations are [0, 0.25], [0.25, 0.5], [0.5, 0.75], [0.75, 1] corresponding to "significant", "less significant", "less fuzzy" and "fuzzy" respectively.

4. Instance Verification and Result Analysis

4.1. Overview of the Study Area

Located in Ezhou City, Hubei Province, Chengchao Iron Ore has the most abundant resources and the largest mining scale of underground iron in Central South Region of China. The main geological structure is affected by the two tectonic systems, the Huaiyang epsilon structural system and the Neocathaysian structural system. Faults and fractures are extremely developed. Marble is the main aquifer with zonal distribution. There is no bulk surface water, and ground water is replenished by the infiltration of precipitation. The mining area is located in the subtropical monsoon climate zone, whose annual average temperature and rainfall are 17.2 degrees and 1306mm respectively.

4.2. Evaluation Results and Analysis

Referring to the geological report, statistical report, environmental quality monitoring report and relevant studies in Chengchao Iron Ore, ten experts are invited to score each index according to comment sets and scoring rules. Then, according to the fuzzy comprehensive evaluation method based on cloud model, the ecological risk assessments are carried out under the Matlab 7.0 environment. The results are shown as figure 1.

The ecological risk degree in Chengchao Iron Ore is between "medium risk" and "low risk". It can be further determined as "medium risk" by the expected value of evaluation cloud which equals 0.476. Substituting the scores into the membership cloud model can obtain the membership’s certainty of evaluation index to each risk level. By the formulas (6), (7), the fuzzy entropy of evaluation results is 0.481, which points to "less significant".

The ecological risk in Chengchao Iron Ore can be expressed as [medium risk, less significant]. In order to further examine the reliability of evaluation results, we carried out the fuzzy comprehensive evaluation of the 20 experts scoring results and the membership of four comments determined by using the trapezoidal distribution function. The evaluation results are (0.158, 0.385, 0.354, 0.103), which points to “medium risk”, the same as the cloud model.
5. Conclusions
The establishment of comprehensive evaluation index system based on the inherent risk, present level and control situation is able to convey the main contradictions of ecological risk in mine and it is also beneficial to the comparison between different mines.

The empirical study of Chengchao iron ore shows that the fuzzy comprehensive evaluation model which is improved by cloud can reflect the actual situation of ecological risk better.

The introduction of cloud model can express the fuzziness and randomness during the evaluation process, but whether it will bring more uncertainty is still needed further researches.

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