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Evaluation of soil erosion risks in a coal mine based on an integrated extension-cloud model

Soil and water losses have become a serious ecological and environmental problems, and how to scientifically carry out soil and water losses risk assessment on soil erosion prevention and treatment of macroeconomic decision-making are very important. Based on the concept of cloud matter element, the associated function and cloud model were used to calculate the association value, then an improved matter-element model of extension cloud combination was established, at last, the evaluation model was introduced into soil and water losses risk assessment. Through the project case in a coal mine shows that the improved evaluation model can get a reasonable risk evaluation result. In practical application, the evaluation result of the extension cloud combination model constructed by classical extension correlation function is closer to the visual statistical value.

Keywords: *Fextenics, cloud model, cloud matter element, a coal mine, soil and water losses evaluation.*

1. Introduction

Soil erosion has become a severe ecological and environmental problem, because it does not only lead to a direct drastic decline in land productivity, but also greatly increases likelihoods of disasters [1]. Hence, it is of great significance for macro-economic decision making about early warning, governance, planning and development by scientifically forecasting and evaluating soil erosion.

The results of evaluation and research can be practised in different disciplines and fields such as geologic hazard assessment, water pollution assessment, ecological assessment, land resources, performance appraisal and soil erosion. At present, many new mathematical models, including analytic hierarchy process, fuzzy mathematics and neural network models, have been introduced into assessment and research of soil erosion risks [2-6]. With great significance for being used as references, these mathematical models have rapidly promoted assessment and research of soil erosion since its introduction. However, it does not mean that all these models can achieve expected evaluation results, as some of them remain to be improved.

Put forward by Cai Wen as a new systems analysis approach, extension analysis characterizes and evaluation standard systems with classical and joint domains. During the analysis, hierarchies of evaluated objects are identified by determining correlation functions and associations. Extension analysis has been successfully performed for evaluating hazards of debris flow and rockburst intensity, but rarely carried out for assessing and exploring soil erosion risks. Cloud model, proposed by Li Deyi for qualitative concepts and quantitative descriptions as a model for transforming uncertainties, characterizes qualitative concepts based on numerical cloud-based characteristics and determines corresponding value by a cloud calculator, in order to assess trends of systems.

In this paper, extension analysis is performed in combination with features of the cloud model. Based on the concept of cloud matter element, an integrated extension and cloud model is proposed for assessing and studying soil erosion of a coal mine. By comparing it with existing evaluation methods and results, the integrated model is demonstrated to be feasible and reasonable.

2. Extension analysis and cloud model

2.1 Extension analysis

Extension analysis is one of modern methods of analysis. The matter-element extension assessment models built based on extension analysis have been widely used for risk assessment and quantitative evaluations. During an extension analysis, standard systems are characterized and evaluated with classical and joint domains. Hierarchies of objects to be evaluated are identified by determining correlation functions and associations. Specifically, a classical domain is the interval of each index in a system standard, while a joint domain is the interval of hierarchy of all indices. The matter-element to be evaluated is the value of each index of the evaluated object.

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They can be conveyed by the formula as follows:

$$R_{0i} = (N_i, C_i, V_i) = \begin{bmatrix} N_i & C_1 & V_{i1} \\ & C_2 & V_{i2} \\ & \vdots & \vdots \\ & C_n & V_{in} \end{bmatrix} =$$

$$\begin{bmatrix} N_i & C_1 & [a_{i1}, b_{i1}] \\ & C_2 & [a_{i2}, b_{i2}] \\ & \vdots & \vdots \\ & C_n & [a_{in}, b_{in}] \end{bmatrix} \quad ... \quad (1)$$

$$R_p = (P, C_i, V_p) = \begin{bmatrix} P_i & C_1 & V_{p1} \\ & C_2 & V_{p2} \\ & \vdots & \vdots \\ & C_n & V_{pn} \end{bmatrix} =$$

$$\begin{bmatrix} P_i & C_1 & [a_{p1}, b_{p1}] \\ & C_2 & [a_{p2}, b_{p2}] \\ & \vdots & \vdots \\ & C_n & [a_{pn}, b_{pn}] \end{bmatrix} \quad ... \quad (2)$$

$$R = (p, C_i, v_i) = \begin{bmatrix} p & C_1 & v_1 \\ & C_2 & v_2 \\ & \vdots & \vdots \\ & C_n & v_n \end{bmatrix} \quad ... \quad (3)$$

where, R_{0i} is a matter-element; N_i is the ith type of evaluation; C_i is the ith evaluation indicator; V_i - C_i is the predetermined range of value; P is the type of general evaluation; and V_{pi} is C_i the range of value. The correlation functions between indexes of matter-elements to be evaluated and corresponding hierarchies are determined by Formula (4).

$$K_j(v_i) = \begin{cases} \dfrac{-\rho(v_i, V_{ij})}{|V_{ij}|} & v_i \in V_{ij} \\ \dfrac{\rho(v_i, V_{ij})}{\rho(v_i, V_{pi}) - \rho(v_i, V_{ij})} & v_i \notin V_{ij} \end{cases} \quad ... \quad (4)$$

$$\rho(v_i, V_{ij}) = \left| v_i - \frac{a_{ij} + b_{ij}}{2} \right| - \frac{b_{ij} - a_{ij}}{2} \quad ... \quad (5a)$$

$$|V_{ij}| = |b_{ij} - a_{ij}| \quad ... \quad (5b)$$

$$\rho(v_i, V_{pi}) = \left| v_i - \frac{a_{pi} + b_{pi}}{2} \right| - \frac{b_{pi} - a_{pi}}{2} \quad ... \quad (5c)$$

The correlations are measured based on numerical values of the correlation functions, and hierarchies of the matter-elements are identified. The correlations are calculated by Formula (6).

$$K_j(p) = \sum_{i=1}^{n} w_i K_j(v_i) \quad ... \quad (6)$$

where, w_i is the weight of the ith index. The hierarchies of matter-elements to be evaluated are judged according to following rules: Provided that K_{j0} (p) = max K_j (p), the hierarchy of the corresponding object shall be j_0 in the evaluation system.

2.2. Cloud model

Having developed as a new mathematical model over the past years, cloud model has been applied in the fields like risk evaluation. In general, this model is advantageous in its fuzziness and randomness. It depicts a qualitative concept through three numerical characteristics, including expectation *Ex*, entropy *En* and hyper entropy *He*. In this model, uncertainties are converted between certain qualitative concepts and quantitative representations by a corresponding cloud generator. This model organically integrates conceptual fuzziness and randomness [7-8]. Normal cloud generators are used most extensively in practices. The normal cloud is defined as follows:

Supposing that Z is a quantitative discourse domain, C shall be a qualitative concept of Z. Assuming that the quantitative value $x \in Z$, x is a random realization of the qualitative concept C, Formula (7) is satisfied and u is the degree to which x is certain about C, the normal cloud shall be defined to as distribution of x on Z.

$$u(x) = \exp\left(-\frac{(x - Ex)^2}{2En'^2} \right) \quad ... \quad (7a)$$

$$x \sim N(Ex, En'^2) \quad ... \quad (7b)$$

$$En' \sim N(En, He^2) \quad ... \quad (7c)$$

In a multi-attribute assessment, expectation *Ex*, entropy *En* and hyper entropy *He* are calculated according to Formulas (8) to (10).

$$Ex = \frac{C_{\max} + C_{\min}}{2} \quad ... \quad (8)$$

$$En = \frac{C_{\max} - C_{\min}}{6} \quad ... \quad (9)$$

$$He = k \quad ... \quad (10)$$

where, $C_{\max}$ and $C_{\min}$ are maximum and minimum values of hierarchies; k is a constant.

The ideas of applying the cloud model in a comprehensive evaluation may be summarized as follows [9]: The membership of each hierarchy of cloud to which certain index belongs to is firstly determined by a cloud model. Next, weights of factors are calculated by certain weight method and integrated with the degree of membership to measure the comprehensiveness. Thus, Formula (11) is obtained. On the basis of maximizing comprehensiveness, the hierarchies of evaluated objects are evaluated.

$$U = \sum_{i=1}^{m} uw_i \quad \text{...} \quad (11)$$

In Formula (11), u is the degree of certainty about the evaluated index i, which is considered as cloud droplets; w_i is the weight of the index.

3. Integrated extension-cloud evaluation model

3.1 Cloud matter-elements

Provided that a hierarchy of certain index is reckoned as a qualitative concept in a multi-index assessment, it may be denoted by numerical characteristics of cloud in place of the fixed interval of the matter-element extension evaluation. These characteristics are referred to as cloud matter elements. For instance, the cloud matter element of a classical domain is as follows:

$$R_{0i} = \left(N_i, C_i, V_i\right) = \begin{bmatrix} N_i & C_1 & V_{i1} \\ & C_2 & V_{i2} \\ & \vdots & \vdots \\ & C_n & V_{in} \end{bmatrix} =$$

$$\begin{bmatrix} N_i & C_1 & \left[Ex_1, En_1, He\right] \\ & C_2 & \left[Ex_2, En_2, He\right] \\ & \vdots & \vdots \\ & C_n & \left[Ex_n, En_n, He\right] \end{bmatrix} \quad \text{...} \quad (12)$$

The cloud matter elements of joint and classical domains shall be consistently represented.

3.2 Improved Model for Cloud Matter Elements

After classical and joint domains of the extension theory are represented by cloud matter elements based on their concepts, correlation functions can be calculated according to those in extenics. At last, hierarchies of evaluated objects can be determined by measuring the correlations.

The specific steps of calculations are as follows:

Firstly, numerical characteristics of classical and joint domains are measured according to formulas (8) and (9).

Secondly, each interval of the classical and joint domains is represented by numerical characteristics of cloud to generate cloud matter elements. In addition, maximum and minimum values are statistically determined for each interval of cloud matter elements.

Thirdly, numerical values of correlation functions are calculated in line with Formula (4).

Fourthly, input weights of all indexes in the evaluation system and measure correlations pursuant to Formula (6).

At last, repeat above steps for N times and calculate the mean of correlations among hierarchies, so as to confirm hierarchies of evaluated objects.

4. Application of integrated extension-cloud model in evaluating soil erosion risks

4.1 Establishment of an evaluation system for soil erosion

Certain mine that is located in a heavily eroded area of Loess Plateau in the west of China is exemplified. It is one of the areas with the most severe soil erosion in China and even over the world. In this area, the annual erosion modulus is as high as over 13,000t/km^2. This coalfield is 65km long from the south to the north and 21km wide from the east to the west, covering a total area of 1,365m^2. The geological reserves of coal reach 26.760 billion tonnes, including 1.498 billion tonnes of recoverable raw coal reserves explored in an opencast coal mine in the early period. Assuming that the annual production capacity is 12,000,000t, the service life of the coal mine will be as long as 115 years. More than 7 years were spent in the Phase 1 engineering construction of this coal mine, including mine exploitation, factory construction, road repair and other supporting engineering construction. In this phase, more than 0.1 billion m^3 earth, stone and sand were disturbed in total. The construction of such a large-scale and integrated project of “coal, electricity and road” imposed significant and serious environmental impacts upon this coal mine that had become ecologically vulnerable with heavy soil erosion, so it has aroused great concerns[10]. This paper is based on measured data about evaluation of soil erosion risks on side slopes of the mine. The data are compared to existing mature evaluations to verify whether the integrated extension-cloud evaluation model is feasible and suitable. Side slope (C1), vegetation coverage (C2), rainfall intensity (C3), soil properties (C4), water erosion modulus (C5), soil thickness (C6) and permeability (C7) are chosen as evaluation indexes. The evaluation standards for soil erosion are listed in Table 1. The risks are evaluated by the model proposed in this paper according to measured evaluation indexes for soil erosion of certain area in the coal mine. Table 2 shows the measured indexes for soil erosion of the representative area.

4.2 Comparisons of results

Weights of all evaluation indexes are determined through analytic hierarchy process. They are 0.3874, 0.2376, 0.1471, w = [0.1056, 0.0599, 0.0368, 0.0256] . The measured data listed in Table 2 are assessed by the integrated extension-cloud model of this paper, which is compared to existing methods. The results of comparisons are shown in Table 3. From Table 3, it may be observed that conclusions usually differ among various evaluation methods. However, this does not mean that the method and theory proposed in this paper are wrong. Comparatively, the integrated model put forward in this paper

TABLE 1: EVALUATION STANDARDS OF SOIL EROSION

Index	Unit	Grade				
		I	II	III	IV	V
C1	º	0~10	10~20	20~30	30~40	40~45
C2	%	75~90	60~75	40~60	25~40	0~25
C3	mm	421~500	500~580	580~620	620~660	660~696
C4	$g.cm^{-3}$	1.9~2.1	1.6~1.9	1.3~1.6	1.1~1.3	0~1.1
C5	$t.km^{-2}.a^{-1}$	200~1000	1000~2500	2500~5000	5000~7000	7000~8000
C6	mm	40~50	30~40	20~30	10~20	0~10
C7	mm	0.002~0.075	0.075~0.2	0.2~2	2~5	5~10

TABLE 2: EVALUATION FACTORS

Number	C1	C2	C3	C4	C5	C6	C7
1	30	65	695.7	1.42	1350	34	0.122
2	38	22	594.4	1.5	1000	41	0.085
3	31	28	607.9	1.36	1200	28	0.076
4	23	32	594.4	1.44	2300	32	0.052
5	29	25	695.7	1.56	1800	19	0.142
6	36	58	695.7	1.45	2000	33	0.185
7	16	40	637.8	1.39	2500	29	0.212
8	30	58	594.4	1.29	1500	31	0.108

TABLE 3: COMPARATIVE RESULTS

Number	Soil erosion intensity classification standard	Extension model	Cloud model	Extension-cloud combination model
1	III	III	II	III
2	IV	IV	IV	IV
3	IV	IV	IV	IV
4	III	IV	III	III
5	III	II	III	IV
6	IV	IV	IV	IV
7	III	III	II	III
8	III	III	III	III

Remark: Soil erosion intensity classification standard refers to the Chinese Ministry of Water Resources Standards.

best meets the gradation standards for soil erosion established by the Ministry of Water Resources of the People's Republic of China. In addition, it is in more accordance with intuitive statistics.

5. Conclusions

(1) Classical matter-elements of extenics and numerical characteristics of the cloud model are included in cloud matter elements, which are thus more applicable. Trends of a field may be evaluated from certain perspective by mathematical models in combination with Matlab.

(2) An integrated extension-cloud model is put forward in this paper, where specific steps and methods of calculations are clarified. The soil erosion of certain coal mine in the west of China is evaluated. The integrated model of this paper is compared to other methods to make further comparisons with measured data. The results suggest that the evaluations of the integrated extension-cloud model are consistent with the practical situation, and the model is acceptable compared to other mature methods.

(3) An evaluation of soil erosion in a coal mine is impacted by multiple factors. Thus, it is necessary to establish a more complete system for evaluating soil erosion. The system shall be integrated with GIS to visualize the evaluation results, which will be a focus of subsequent research.

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TIME AND MOTION STUDY OF DUMPERS AND SHOVEL DEPLOYED AT A SHALLOW DEPTH MINE

Continued from page 7

understand the operational statistics of excavator and these probability distributions diagrams may be used for improving operational efficiency of the excavator.

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