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Research Article

Grading Evaluation of Goaf Stability Based on Entropy and Normal Cloud Model

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Aiming at the fuzziness and randomness of goaf stability classification, to obtain goaf stability classification more objectively, an entropy weight-normal cloud model for goaf stability classification is proposed. Based on the geological conditions and engineering conditions, 14 indexes that affect the stability of a goaf are selected to establish an evaluation index system, and the weight of each index is determined using the entropy weight method, which makes the weight distribution more objective. Based on the cloud model theory, the cloud numerical characteristics of each evaluation index belonging to goaf stability level are calculated, and a corresponding cloud model is generated. Combined with the entropy weight, the comprehensive certainty degree is calculated, and the evaluation results are obtained. Taking 25 mined-out areas in Xishan mine of Shandong Gold Mining and the Dabaoshan mine as examples, the model is used for stability evaluation, and the evaluation results are basically consistent with the actual situation, which proves the feasibility of the method and provides a new and effective method for stability evaluation of mined-out areas.

1. Introduction

With the rapid development of the economy, the demand for mineral resources is increasing. This demand can only be met by increasing the mining volume of mineral resources. Currently, the main way to obtain mineral resources is through underground mining. This process will inevitably lead to mined-out areas [1], and most shallow resources will be close to depletion after long-term mining. The depth of underground mining is increasing [2], and the stability of goafs is becoming an increasingly prominent problem. Accidents such as goaf collapse, surface collapse, and roof caving often occur [3] and have become one of the main hazard sources of underground mines. Therefore, correctly evaluating the stability of a goaf is very important for safe mine production.

Much research has been performed on the stability of goafs, and results related to accurate detection [4, 5] and stability evaluation have been achieved. There are mainly two methods used for research on the stability evaluation of goafs: numerical simulations and mathematical statistics. In terms of numerical simulations, Li and Lu [6] initiated the use of ANSYS for goaf stability evaluation, and the evaluation results were mostly consistent with the actual situation. Luo et al. [7] used Surpac to build a three-dimensional model of a mine and Phase2 software to analyse the stability of the goaf, and good results were achieved. Du et al. [3] used GTS-MADIS software to model and analyse the goaf in the Laoyachao Mine. The results were compared with the evaluation results of matter-element analysis and were similar. Kou et al. [8] accurately obtained the spatial shape information of a goaf using CMS and successfully simulated the stability of a goaf using Dimine-FLAC3D. Zhang et al. [9] used Midas-GTS to establish a four-dimensional model, simulated the stability of complex goaf groups based on the improved FLAC3D software, and achieved good results.

Some results have been achieved using the above methods, but a numerical simulation is often limited by assumptions, and the influencing factors of goaf stability are uncertain and complex. Therefore, many researchers have begun to use mathematical statistics to evaluate goaf stability. Based on the unascertained measurement theory, Gong [10] et al. established a goaf risk grade evaluation model, and the evaluation results were consistent with engineering practice. Wang et al. [11] evaluated the stability of a goaf based on the principle of fuzzy mathematics, and the results were consistent with engineering practice. Wang et al. [12] established a support vector machine mining area stability evaluation model, and the grading results were highly consistent with the results of the unconfirmed measurement method. Wang et al. [13] applied the theory of physical element analysis to establish an improved physical element topologizable model for the evaluation of the stability of a mining area and obtained more accurate evaluation results. Tang et al. [14] constructed a neural network model applicable to the evaluation of the stability of a mining area, and the evaluation results obtained were consistent with the actual situation. Jiang et al. [15] established an improved grey target model for the evaluation of the stability of a mining area, considering the influence of the evaluation indicators, which made the evaluation results more accurate. Ding et al. [16] made great contributions to the strength criterion, which has guiding significance for the stability evaluation of goafs.

The above methods have evaluated and graded the stability of goafs using different approaches, and some results were achieved. However, these methods cannot overcome the problem that the influencing factors are very complex and uncertain. However, a cloud model can be used to comprehensively solve the two uncertainty problems of randomness and fuzziness in an evaluation. Therefore, it is very important to introduce a cloud model to evaluate the stability of a goaf. In this paper, combined with the entropy weight method to determine the weight of each evaluation index, the cloud model is used to evaluate goaf stability, and the entropy weight-normal cloud model of goaf stability is established, which provides a new idea for goaf stability evaluation.

2. Entropy Weight-Normal Cloud Goaf Stability Evaluation Model

2.1. Cloud Model Theory. A cloud model, which is a mathematical model proposed by Professor Li [17], is used to realize the qualitative and quantitative transformation of uncertainty concepts. It has been successfully used in data mining, simulation prediction, decision analysis, intelligent control, and other fields.

2.1.1. Definition of a Cloud. Let M be a set represented by exact numerical values, $M=\{x\}$, which is referred to as the universe. C is a qualitative concept in universe M. If the quantitative value $x\in M$ is a random realization of qualitative concept C, the uncertainty of any element x in qualitative concept $C\,\mu(x)\in[0,1]$ is a random number with stable tendency; then, the distribution of x in universe M is called a cloud, and each x is called a cloud drop:

$$\mu : \mathrm{M} \longrightarrow [0,1]\,\forall x \in \mathrm{M}\, x \longrightarrow \mu(x). \tag{1}$$

If $x\sim N(E_x, E'^2_n)$, is satisfied, where $E'_n\sim N(E_n, H_e^2)$, the uncertainty of C meets the following requirements:

$$\mu(x) = e^{-\left(x-E_x\right)^2/2E'^2_n}, \tag{2}$$

where $\mu(x)$ is the degree of certainty; x is the variable value; E_x is the expectation; and E'_n is the entropy. Then, the distribution of x in universe M is called a normal cloud distribution. A normal cloud model is the most commonly used and universal cloud model. Many relevant studies have shown that the expectation curves of cloud models with qualitative knowledge in a large part of natural science approximately obey a normal or seminormal distribution [18]. Therefore, this paper uses a normal cloud to evaluate the stability of a goaf.

2.1.2. Digital Characteristics of a Cloud. The digital characteristics of a normal cloud are determined by the expectation E_x. Entropy E_n and hyperentropy H_e as a whole reflect the quantitative characteristics and qualitative concepts of the research object, and expectation E_x is the central value of the qualitative concept in the domain of discourse, that is, the most typical sample of the quantitative concept. Entropy E_n is the measure of the fuzziness of the qualitative concept, which reflects the value range acceptable to the qualitative concept in the domain. Hyperentropy H_e is the measure of uncertainty of entropy, which reflects the dispersion degree of cloud droplets. According to the above cloud model concept, the cloud digital characteristics of the goaf stability evaluation index S for a certain level standard can be calculated according to the following formula [19]:

$$\left.\begin{aligned} E_x &= \frac{C_{\max}+C_{\min}}{2} \\ H_e &= K \\ E_n &= \frac{C_{\max}-C_{\min}}{6} \end{aligned}\right\}, \tag{3}$$

where $C_{\min}$ and $C_{\max}$ are the minimum and maximum boundary values of the corresponding grade standards, respectively, and k is a constant that can be adjusted according to the fuzzy threshold of different variables, which is taken as 0.01 in this paper. For variables with unilateral boundaries, such as $(-\infty, C_{\max}]$ or $[C_{\min}, +\infty)$, the default boundary parameters can be determined according to the lower or upper limit of the variable, and then the parameters of the cloud model can be calculated according to equation (3).

2.1.3. Cloud Generator. A cloud generator mainly includes a forward cloud generator and reverse cloud generator. A forward cloud generator can realize the transformation from a qualitative concept to a quantitative value. In other words, a certain number of cloud droplets are generated according to the three digital characteristics of the cloud model. In contrast, a reverse cloud generator is used to realize the transformation from a quantitative value to a qualitative concept. Since the stability evaluation of a goaf is from qualitative to quantitative, a positive cloud generator is adopted in this paper. The specific algorithm steps are as follows:

(1) Calculation of entropy E_n and hyperentropy H_e based on specific grading metrics

(2) According to the calculated entropy E_n and hyperentropy H_e, a random number e of normal distribution $E_n' \sim N(E_n, H_e^2)$ are generated

(3) Based on specific input value x and expected value E_x, the uncertainty is calculated according to equation (1)

2.2. Goaf Stability Evaluation Index System. There are many factors affecting goaf stability, and the correlation is complex. Based on the perspective of influence significance, relative independence, ease of obtaining, and ease of quantifying, 14 factors affecting goaf stability are selected as evaluation index factors in this paper [20]. These factors are the influence of the rock mass structure, geological structure, rock quality index, influence of underground visible water and underground water on the surrounding rock, influence of surrounding mining, situation of adjacent goaf, engineering layout, span, area, height, size and layout of the ore pillar, burial depth, and goaf specification, which are expressed as S_1, S_2, S_3, S_4, S_5, S_6, S_7, S_8, S_9, S_{10}, S_{11}, S_{12}, S_{13}, and S_{14}, respectively. The rock quality index, span, area, height, and buried depth are divided into grades I, II, III, and IV, which represent extremely stable, stable, unstable, and extremely unstable classifications, respectively, according to the actual measured data. The classification standards are shown in Table 1. The rock mass structure, geological structure, underground visible water, influence of an underground water body on the surrounding rock, influence of surrounding mining, situation of an adjacent goaf, engineering layout, size and layout of the ore pillar, and specifications of the goaf are determined using a semiquantitative method. The values 1, 2, 3, and 4 correspond to grades I, II, III, and IV, respectively. The classification standards are shown in Table 2. Classification criteria refer to relevant research results [21].

2.3. Determination of the Weight of the Evaluation Index Based on the Entropy Weight Method. The weight reflects the role of an evaluation index affecting the stability of the goaf in the overall evaluation. In this paper, the entropy weight method is used to determine the weight. Generally, the smaller the information entropy of an index is, the greater the degree of variation, the greater the amount of information it provides, and the more significant its role in the comprehensive evaluation. The weight of the corresponding index is also larger [22], so the weight of each index can be calculated through the variation degree of the index. The specific calculation steps are as follows:

Table 1: Classification and assignment of quantitative indexes for goaf stability evaluation.

Indicator	Stability level			
	Level I	Level II	Level III	Level IV
Rock quality (S_3), %	>60	50~60	40~50	<40
Span (S_9), m	<40	80~40	80~120	>120
Area (S_{10}), m^2	<800	800~1200	800~1200	>2700
Height (S_{11}), m	<8	8~20	20~30	>30
Depth (S_{13}), m	<100	100~200	200~400	>400

(1) Build a judgement matrix. If there are m evaluation objects and n evaluation indexes, the value of the j-th index corresponding to the i-th object is x_{ij}, and the original information evaluation matrix X can be constructed:

$$X = \begin{bmatrix} \overset{11}{x} & \overset{12}{x} & \cdots & \overset{1j}{x} \\ \overset{21}{x} & \overset{22}{x} & \cdots & \overset{2j}{x} \\ \vdots & \vdots & \vdots & \vdots \\ \overset{i1}{x} & \overset{i2}{x} & \cdots & \overset{ij}{x} \end{bmatrix}. \quad (4)$$

(2) Normalize the matrix X when the indicator is as large as possible:

$$y_{ij} = \frac{x_{ij-}\min_j(x_{ij})}{\max_j(x_{ij}) - \min_j(x_{ij})}. \quad (5)$$

When the index is as small as possible,

$$y_{ij} = \frac{\max_j(x_{ij}) - x_{ij}}{\max_j(x_{ij}) - \min_j(x_{ij})}. \quad (6)$$

(3) Calculate the contribution of the j-th index and the i-th object:

$$P_{ij} = \frac{y_{ij}}{\sum_{i=1}^{m} y_{ij}}. \quad (7)$$

If $P_{ij} = 0$, define $\ln P_{ij} = 0$.

(4) Calculate the information entropy of each index. The information entropy of the j-th index is calculated as follows:

$$E_j = -\ln(m)^{-1} \sum_{i=1}^{m} P_{ij} \ln P_{ij}. \quad (8)$$

(5) Calculate the weight of each indicator. The weight of the j-th indicator is calculated as follows:

$$\omega_{ij} = \frac{1 - E_j}{n - \sum E_j}. \quad (9)$$

2.4. Comprehensive Uncertainty. The cloud droplets of each evaluation index are generated using a forward cloud generator, and specific data x are input to obtain the membership degree $\mu(x)$ of each evaluation index. Then, combined with the weight of each evaluation index calculated using the entropy weight method, the comprehensive

Table 2: Classification and assignment of qualitative indexes for goaf stability evaluation.

Stability level	Assignment	Influence factor								
		Rock mass structure (S_1)	Geological structure (S_2)	Underground visible water (S_4)	Influence of groundwater on surrounding rock (S_5)	Impact of surrounding mining (S_6)	Adjacent empty space (S_7)	Project layout (S_8)	Pillar size layout (S_{12})	Specification and shape of goaf (S_{14})
Level I	1	Complete block structure	No fault and fold	No drenching trace	No water impact	The mining area is not affected by blasting operation	There is no adjacent empty area within the affected area	Reasonable	Code for pillar layout	$\theta < 1$
Level II	2	Layered structure	Small fold influence	Visible water trace of rainfall	Less impact on water body	The impact of blasting operation in the mining area is small	There is no adjacent empty area within the affected area	More reasonable	There are pillars but they are not standard	$1 \le \theta < 2$
Level III	3	Structural fragmentation	Partial cutting or folding of fault has great influence	Heavy rainfall and drenching	General impact on water body	Large impact of blasting operation in mining area	The area and quantity of empty areas within the scope of influence are large, but they are scattered	Partially reasonable	There is no pillar or the layout is not standard and starts to be damaged	$2 \le \theta < 3$
Level IV	4	Loose structure	Fault penetrates rock mass	Rain in rainy season	Great impact on water body	The mining area has a great impact on blasting operation	The area of empty areas within the influence range is large, the number is large, and the adjacent areas are close	Less reasonable	There is no pillar or the layout is very irregular and seriously damaged	$2 \le \theta < 3$

uncertainty is calculated according to equations (1) and (6). fd6

$$U = \sum_{j=1}^{m} \mu(x)\omega_j, \quad (10)$$

where $\mu(x)$ is the uncertainty of each index and ω_j is the weight of the evaluation index.

2.5. Specific Implementation Process. The basic idea of establishing a goaf stability evaluation model based on an entropy weight cloud model is to select evaluation indexes and corresponding classification standards according to the actual goaf situation and relevant data, determine the corresponding weight of each index with the entropy weight method for specific goaf data, and determine the cloud digital characteristics according to the classification standards of each index. A cloud model of each index and each grade is generated based on a forward cloud generator, and the membership degree of each index corresponding to each grade is calculated according to the measured data. Finally, the stability evaluation results of the goaf are obtained according to the maximum membership degree principle. The specific process is shown in Figure 1.

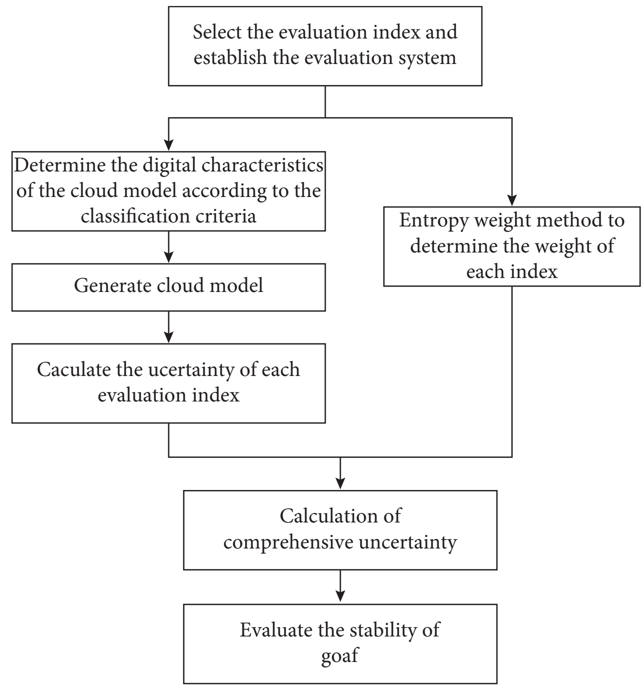


Figure 1: Stability evaluation process of goaf.

3. Engineering Application Examples

The Xishan mine of Shandong Gold Mining and the Dabaoshan mine are taken as examples. Based on the actual situation, a total of 25 goafs, 12 goafs [12] in the Xishan mine, and 13 goafs [10] in the Dabaoshan mine are selected. The value of each evaluation index is taken. The specific situation of each goaf is shown in Table 3.

3.1. Determination of the Weight of Each Index. According to the above steps, the entropy weight method is used to determine the weight of each index. When normalizing the data, the larger the rock quality (S_3) index is, the better, which is calculated using equation (5), and the smaller the other 13 indexes are, the better, which is calculated using equation (6). The weight calculation results of each index are shown in Table 4.

3.2. Cloud Model Generation. Based on the theory of a normal cloud model, the numerical feature expectation E_x, entropy E_n and superentropy H_e of the cloud model are determined according to the grading criteria of the stability evaluation index of the mining area and equation (3), and a sufficient number of cloud drops are generated using MATLAB 2016a with a forward cloud generator to generate the cloud model corresponding to each index. The cloud models for five of the rock mass indicators, span, area, height, and depth of burial are shown in Figure 2.

3.3. Goaf Stability Evaluation Results. The goaf stability evaluation results are determined by the membership degree of each evaluation index and the weight of each index in the cloud model. Goaf No. 17 is taken as an example to demonstrate the calculation process. First, according to the cloud model and the 14 corresponding index data of the goaf, the uncertainty of each index value belonging to goaf stability level 4 is generated. The comprehensive uncertainty is calculated using the weight sum equation (10) of each index determined in Table 4. The results are $U_{\mathrm{I}} = 0.5808$, $U_{\mathrm{II}} = 0.2693$, $U_{\mathrm{III}} = 0.0378$, $U_{\mathrm{IV}} = 0.0005$, and $U_{\mathrm{I}} > U_{\mathrm{II}} > U_{\mathrm{III}} > U_{\mathrm{IV}}$; see Table 5 for the specific data. According to the maximum comprehensive certainty value, it can be concluded that the evaluation result of the goaf is grade I, which represents an extremely stable goaf, and is consistent with the actual situation.

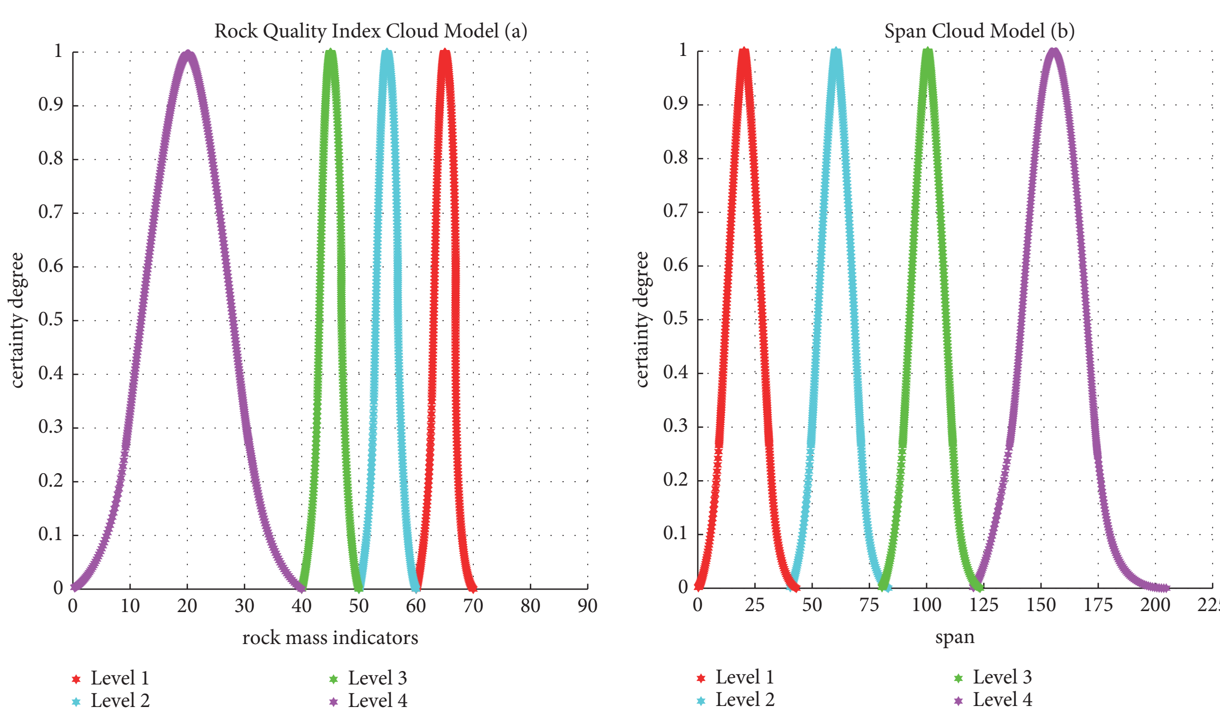
According to the above process, the stability evaluation results of the 25 goafs are calculated and compared with their actual situations, as shown in Table 6. The results show that the evaluation results are essentially consistent with the actual situation, which shows that the application of the entropy weight cloud model to evaluate goaf stability is effective and feasible. At the same time, there are many complex factors affecting goaf stability. Using the entropy weight method to determine the weight can reduce the influence of subjective factors and make the evaluation results more objective. Moreover, goaf stability is a qualitative concept. The use of a cloud model can realize the qualitative and quantitative transformation of the uncertainty concept and can convert the fuzziness and randomness of a goaf into a quantitative

Table 3: Measured data of influencing factors and indicators of goaf stability.

	Sample serial number	Goaf stability evaluation index													
		S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}	S_{11}	S_{12}	S_{13}	S_{14}
Xishan mine of Shandong gold mining	1	1	1	59	2	3	3	2	3	125	896	170	1	71	2
	2	4	4	39	3	3	4	4	2	75	703	30	1	160	2
	3	2	2	38	3	3	1	4	3	185	852	145	4	298	2
	4	4	4	39	2	3	1	2	4	115	734	100	4	396	4
	5	4	4	58	2	3	4	4	1	445	1705	140	1	82	1
	6	3	3	51	3	4	1	3	1	65	221	35	2	439	1
	7	4	4	46	3	3	2	4	2	30	34	30	3	66	1
	8	1	1	54	1	3	3	2	2	45	67	15	4	63	2
	9	1	1	57	3	1	2	3	4	60	87	40	4	225	3
	10	4	4	36	2	4	3	2	3	80	110	25	1	129	3
	11	3	3	38	2	2	3	3	2	65	82	30	2	152	4
	12	3	3	47	1	3	2	4	2	25	40	45	1	125	3
Dabaoshan mine	13	3	1	38	2	2	4	4	2	85	5190	15	4	260	2
	14	2	2	56	2	2	4	4	1	60	1230	8	3	260	2
	15	3	3	35	2	2	4	4	2	62	2560	14.5	4	290	3
	16	3	3	47	2	2	4	4	3	160	6890	26.3	4	305	4
	17	2	1	55	1	1	1	1	1	26	2870	15.8	2	305	1
	18	2	1	57	2	2	4	4	1	96	2260	21	3	335	2
	19	1	1	67	2	2	1	1	1	60	1200	10	1	335	1
	20	1	2	53	3	3	4	4	2	85	3970	60	4	240	2
	21	1	2	59	1	1	1	1	1	40	2260	15	1	305	2
	22	1	1	62	2	2	1	1	1	35	1450	13	1	290	1
	23	1	1	52	2	2	3	3	1	35	2590	6	1	201	1
	24	1	1	55	1	1	3	3	1	65	2430	12	1	208	1
	25	1	1	54	1	1	3	3	1	68	1800	10	1	208	2

Table 4: Entropy of evaluation indices.

Evaluating indicator	S_1	S_2	S_3	S_4	S_5	S_6	S_7
Entropy weight	0.1151	0.0953	0.0055	0.0302	0.0596	0.1249	0.2028
Evaluating indicator	S_8	S_9	S_{10}	S_{11}	S_{12}	S_{13}	S_{14}
Entropy weight	0.0609	0.0090	0.0241	0.0268	0.1363	0.0328	0.0834



(a) (b)

Figure 2: Continued.

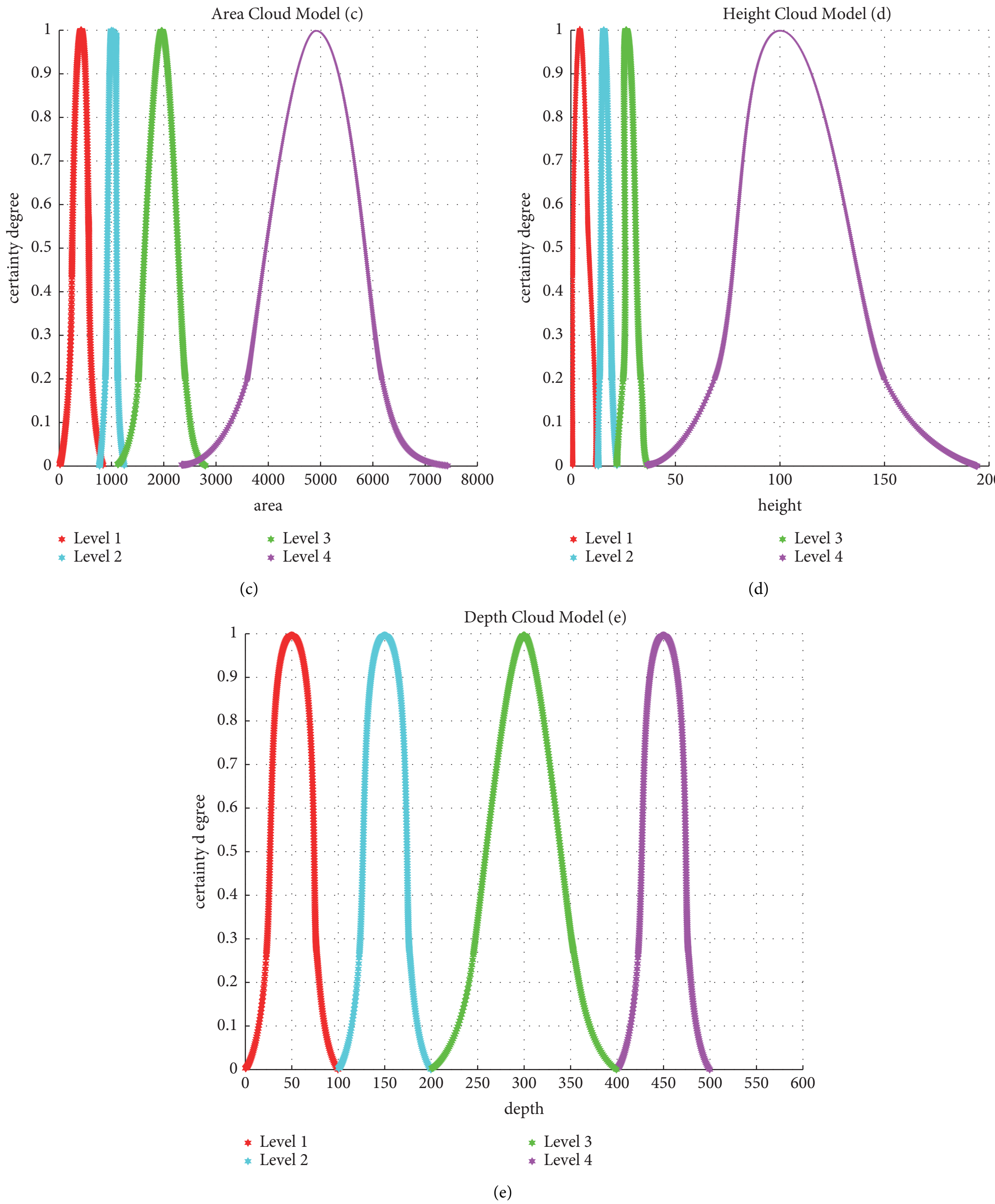


Figure 2: Each evaluation index belongs to the cloud model of the goaf stability level.

Table 5: Calculation data of stability evaluation of sample 19 goaf.

Evaluating indicator	Weighting	Degree of certainty			
		I	II	III	IV
S_1	0.1151	0	1	0	0
S_2	0.0953	1	0	0	0
S_3	0.0055	0	0	1	0
S_4	0.0302	1	0	0	0
S_5	0.0596	1	0	0	0
S_6	0.1249	1	0	0	0
S_7	0.2028	1	0	0	0
S_8	0.0609	1	0	0	0
S_9	0.0090	0.6672	0	0	0
S_{10}	0.0241	0	0	0.005261	0.03494
S_{11}	0.0268	0	0.6682	0	0
S_{12}	0.1363	0	1	0	0
S_{13}	0.0328	0	0	0.9894	0
S_{14}	0.0834	1	0	0	0

Table 6: Evaluation results of goaf stability and comparison with the actual situation.

Sample	Comprehensive uncertainty				Discrimination results	Actual level
	U (I)	*U* (II)	*U* (III)	*U* (IV)		
1	0.2663	0.3237	0.2460	0.1224	II	II
2	0.1374	0.1725	0.1887	0.4429	III ~ IV	III
3	0.1251	0.1998	0.1868	0.4702	III ~ IV	III
4	0.1254	0.2361	0.1553	0.5175	IV	IV
5	0.2858	0.0333	0.0610	0.5826	IV	IV
6	0.2831	0.1431	0.3516	0.1820	III	III
7	0.1207	0.1905	0.2298	0.4133	III ~ IV	III
8	0.2816	0.3716	0.1894	0.1363	II	II
9	0.1888	0.1949	0.3252	0.2925	III	III
10	0.2457	0.2501	0.2963	0.1750	III	III
11	0.0139	0.3924	0.4433	0.0835	III	III
12	0.1901	0.1992	0.2585	0.2996	III ~ IV	III
13	0.0954	0.2613	0.1318	0.4779	IV	IV
14	0.0611	0.3965	0.1570	0.3278	II	II
15	0.0004	0.1884	0.3260	0.4642	IV	IV
16	0	0.0958	0.3240	0.5614	IV	IV
17	0.5808	0.2693	0.0379	0.0005	I	I
18	0.1562	0.3276	0.1732	0.3278	II ~ III	II
19	0.8189	0.1058	0.0190	0.0027	I	I
20	0.1152	0.1777	0.1029	0.4759	IV	IV
21	0.7335	0.2023	0.0390	0.0000	I	I
22	0.8197	0.1168	0.0328	0.0011	I	I
23	0.5008	0.0934	0.3299	0.0000	I	I
24	0.5843	0.0229	0.3362	0.0000	I	I
25	0.5008	0.0915	0.1426	0.0000	I	I

value of certainty. Therefore, the use of a cloud model has advantages in representing the uncertainty of goaf stability and makes the evaluation results more accurate.

4. Conclusion

In this paper, a cloud model is used to evaluate goaf stability. Taking 25 goafs as samples, 14 factors affecting their stability are selected. According to the actual data, the hierarchical model of each influencing factor is established and solved. Combined with the actual data from the Xishan and Dabaoshan mining area of the Shandong gold mining industry, the cloud model is used to evaluate 25 mined-out areas, and the classification results are compared with the actual situation.

The accuracy of model forecast is 96% with high accuracy. In addition, the predicted results of No. 2, 3, 7, 12, and 18 samples are of high risk level, which indicates that the predicted results are conservative and are beneficial to prevent goaf collapse. This method provides a new idea for mine safety production and goaf treatment and has important theoretical and practical significance.

Data Availability

The data of this paper are available, and the data come from other papers.

Disclosure

This paper was completed under the guidance of Professor Yun Lin.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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