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A Fuzzy Model for Evaluating the Mining Condition of Underground Coal Mines

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Abstract: In mining industries no mines are identical and each mine has its own unique set of mining conditions. In order to study the condition of mines for efficiency, safety and economy reasons, a fuzzy model is presented based on fuzzy evaluation. Relevant data from five mines were collected and the model was used to evaluate the mining condition of these mines. The evaluation results are in conformity with the real situation.

Key words: fuzzy model, mining condition, coal mine

In the mining industries no mines are identical and each mine has its own unique set of mining conditions, including geological factors,deposit characteristics and risk of hazards. Those elements and their interaction affect the profitability of mining operations and the value of the mine assets. In order to categorize the mines into different types for the purpose of asset assessment, mine acquisition, income taxation or safety regulation, this paper presents a fuzzy model for the evaluation of underground coal mining condition. The influencing factors are adopted from the evaluation system developed by the Consulting Committee on Technology for the Coal Industry in China (CCTCI), and are divided into three groups, namely geological, deposit and hazardous conditions. The weights for each group and the individual factors are determined using the Analytic Hierarchy Process (AHP) with experts opinions considered. The fuzzy method is used to evaluate the group indices and the overall mining condition index. Relevant data for five mines were collected and the model was used to evaluate the mining condition of these mines.

1 Influencing Factors and Weighting

1.1 Influencing factors

There are many factors that influence the mining condition of underground coal mines. One set of influencing factors for consideration in evaluating the mining condition of mines is that proposed by the Consulting Committee on Technology for the Coal Industry in China (CCTCI) [1]. According to this CCTCI system, twelve factors are selected to construct the influencing factor set and divided into three groups, namely geological, deposit and hazardous conditions, *i.e.*,

$U=\{u_1,u_2,u_3,u_4,u_5,u_6,u_7,u_8,u_9,u_{10},u_{11},u_{12}\}$,

where u_1 is the faults; u_2, the anticlines or synclines; u_3, the rock intrusions; u_4, the roof and floor rock properties; u_5, the coal seam stability; u_6, the coal seam inclination; u_7, the coal seam thickness; u_8, the coal seam depth; u_9, the surface topology; u_{10}, the risk of gases; u_{11}, the risk of underground water bodies; and u_{12}, the risk of spontaneous combustion.

1.2 Factor weight

There are many methods for determining weights, such as multivariate statistical analysis method [2], fuzzy equation method, Analytic Hierarchy Process (AHP) method [3] and expert consultation method. In this paper the AHP method was used to determine the weight of an influencing factor and the results are shown in **Table 1** [4].

Table 1 Influencing factors and their weight.

Geological factor (0.44)	Faults (0.35)
	Anticlines or synclines (0.05)
	Rock intrusions (0.05)
	Roof and floor rock properties (0.18)
	Coal seam stability (0.20)
	Coal seam inclination (0.17)
Deposit factor(0.31)	Coal seam thickness (0.44)
	Coal seam depth (0.31)
	Surface topology (0.25)
Hazardous factor (0.25)	Risk of gases (0.53)
	Risk of underground water bodies (0.35)
	Risk of spontaneous combustion (0.12)

2 Fuzzy Model for Evaluating Mining Condition

2.1 Set of evaluation indices

The mining condition of mines is described by four linguistic terms, and correspondingly the set of evaluation indices is defined as

V = {excellent, good, fair, bad}.

2.2 Membership degree of geological condition

According to a specification by the former Coal Bureau of China in 1991, each of the six geological factors (namely, faults, anticlines and synclines, rock intrusions, roof and floor properties, seam stability, and seam inclination) is categorized into four types with type I the best. By fuzzification, the degree of membership to the evaluation index for each type of the geological factors is defined as shown in **table 2**.

Table 2 Types of the geological factors and their membership degrees.

Type of geological factors	Membership degree
I	(0.8, 0.2, 0.0, 0.0)
II	(0.2, 0.6, 0.2, 0.0)
III	(0.0, 0.2, 0.6, 0.2)
IV	(0.0, 0.0, 0.2, 0.8)

2.3 Membership degree of deposit condition

There are three influencing factors that constitute the deposit condition, namely, seam thickness, seam depth, and surface topology. The surface topology, such as water bodies, buildings and railways, will reduce the amount of recoverable reserve. This effect is taken into account by the percentage of recoverable reserve (Q) to be left underground for protecting the surface from damage or subsidence. By fuzzification, the degree of membership to the evaluation index for the three deposit factors is defined as shown in **table 3–5**.

Table 3 Membership degree of coal seam thickness h / m.

Range of seam thickness	Membership degree
$0.6 \le h \le 1.1$	$(0, 0, (10h-6)/5, 1-(10h-6)/5)$
$1.2 \le h \le 1.7$	$(0, (10h-12)/5, 1-(10h-12)/5, 0)$
$1.8 \le h \le 2.5$	$((5h-5.5)/7, 1-(5h-5.5)/7, 0, 0)$
$2.5 < h \le 4.0$	(1.0, 0, 0, 0)
$4.0 < h$	(0.7, 0.3, 0, 0)

2.3 Membership degree of hazardous condition

There are three major factors influencing the hazardous condition of underground coal mines, namely risk of gases, risk of underground water bodies, and risk of spontaneous combustion. According to the Rules on Underground Coal Mine Safety by the former Coal Bureau of China, a mine will be considered as high gas mine when the amount of gas emission is over 10 m^3/t. If the amount of gas emission is over 15 m^3/t, the mine operations will be disturbed seriously. By fuzzification, the degree of membership to the evaluation index for gas emission is defined as shown in **table 6.**

Table 4 Membership degree of coal seam depth H / m.

Range of seam depth	Membership degree
$H \le 50$	(1.0, 0, 0, 0)
$50 < H \le 200$	$(1-(H-50)/150, (H-50)/150, 0, 0)$
$200 < H \le 500$	$(0, 1-(H-200)/300, (H-200)/300, 0)$
$500 < H \le 800$	$(0, 0, 1-(H-500)/300, (H-500)/300)$
$800 < H$	(0, 0, 0, 1.0)

Table 5 Membership degree of surface topology Q / %.

Range of left-out reserve	Membership degree
$Q \le 10$	(1.0, 0, 0, 0)
$10 < Q \le 30$	$(1-(Q-10)/20, (Q-10)/20, 0, 0)$
$30 < Q \le 50$	$(0, 1-(Q-30)/20, (Q-30)/20, 0)$
$50 < Q \le 70$	$(0, 0, 1-(Q-50)/20, (Q-50)/20)$
$70 < Q$	(0, 0, 0, 1.0)

Table 6 Membership degree of gas emission q / m^3t^{-1}.

Range of left-out reserve	Membership degree
$q \le 1$	(1.0, 0, 0, 0)
$1 < q \le 6$	$(1-(q-1)/5, (q-1)/5, 0, 0)$
$6 < q \le 10$	$(0, 1-(q-6)/4, (q-6)/4, 0)$
$10 < q \le 15$	$(0, 0, 1-(q-10)/5, (q-10)/5)$
$15 < q$	(0, 0, 0, 1.0)

According to the regulation set up by former Coal Bureau of China, the hydro-geological condition and the spontaneous combustion susceptibility in underground coal mines are categorized into four types with type I the best, respectively. Based on this classification and by fuzzification, the degree of membership to the evaluation index for the hydro-geology and that for the spontaneous combustion susceptibility are defined as shown in **table 7 and 8**.

Table 7 Types of hydro-geology and their membership degrees.

Type of hydro-geology	Membership degree
I	(0.8, 0.2, 0.0, 0.0)
II	(0.2, 0.6, 0.2, 0.0)
III	(0.0, 0.2, 0.6, 0.2)
IV	(0.0, 0.0, 0.2, 0.8)

2.5 Two-stage fuzzy model for evaluation

The fuzzy evaluation model of underground coal mining condition is two-staged. The first stage is for evaluating each of the three groups of factors, *i.e.* geological factors, deposit characteristics, and risk of hazards, and the second stage is for evaluating the mining condition of a mine.

Table 8 Types of spontaneous combustion susceptibility and their membership degrees.

Type of susceptibility	Membership degree
I	(0.8, 0.2, 0.0, 0.0)
II	(0.2, 0.6, 0.2, 0.0)
III	(0.0, 0.2, 0.6, 0.2)
IV	(0.0, 0.0, 0.2, 0.8)

The geological condition index is

$$B_g=(a_{g1},a_{g2},a_{g3},a_{g4},a_{g5},a_{g6})\circ(R_{g1},R_{g2},R_{g3},R_{g4},R_{g5},R_{g6})^T=(b_{g1},b_{g2},b_{g3},b_{g4}).$$

The deposit characteristic index is

$$B_d=(a_{d1},a_{d2},a_{d3},a_{d4})\circ(R_{d1},R_{d2},R_{d3})^T=(b_{d1},b_{d2},b_{d3},b_{d4}).$$

The hazardous risk index is

$$B_h=(a_{h1},a_{h2},a_{h3})\circ(R_{h1},R_{h2},R_{h3})^T=(b_{h1},b_{h2},b_{h3},b_{h4}).$$

The overall mining condition index is

$$B=(a_1,a_2,a_3)\circ(R_g,R_d,R_h)^T=(b_1,b_2,b_3,b_4),$$

where

$$(R_g,R_d,R_h)^T=\begin{bmatrix} b_{g1} & b_{g2} & b_{g3} & b_{g4}\\ b_{d1} & b_{d2} & b_{d3} & b_{d4}\\ b_{h1} & b_{h2} & b_{h3} & b_{h4}\end{bmatrix}.$$

According to the rule of maximizing membership degree, the final evaluation result can be obtained from the set of overall mining condition index, *i.e.*,

$$b_{max}=\max(b_1,b_2,b_3,b_4).$$

The linguistic term corresponding to b_{max} is the final evaluation result of the mining condition of a mine.

3 Illustrating Example

There are five mines, and the relevant data collected from the mines are shown in **table 9**.

Using the above mentioned models and the data in table 9, the evaluation index for the geological condition of Mine 1 is

$$B_g=(0.35, 0.05, 0.05, 0.18, 0.20, 0.17)\circ\begin{vmatrix} 0.8 & 0.2 & 0.0 & 0\\ 0.8 & 0.2 & 0.0 & 0\\ 0.8 & 0.2 & 0.0 & 0\\ 0.2 & 0.6 & 0.2 & 0\\ 0.2 & 0.6 & 0.2 & 0\\ 0.8 & 0.2 & 0.0 & 0\end{vmatrix}=(0.35, 0.2, 0.2, 0).$$

After normalization, the evaluation index for geological condition becomes (0.46, 0.27, 0.27, 0). By the same procedure, the evaluation index for the deposit characteristics and hazardous risk factors can be determined as (0.64, 0.36, 0, 0) and (0.55, 0.21, 0.12, 0.12), respectively.

The overall evaluation index for the mining condition of Mine 1 can be calculated as

$$B=(0.44,0.31,0.25)\circ\begin{vmatrix} 0.46 & 0.27 & 0.27 & 0.00\\ 0.64 & 0.36 & 0.00 & 0.00\\ 0.55 & 0.21 & 0.12 & 0.12\end{vmatrix}=$$

(0.44, 0.31, 0.27, 0.12).

After normalization, the overall evaluation index for the first mine becomes

$$B_1=(0.39, 0.27, 0.24, 0.10).$$

This means that the membership degrees of mining condition for the first mine to the linguistic terms {excellent, good, fair, bad} are 39%, 27%, 24%, and 10%, respectively. According to the rule of maximizing

Table 9 Data from the sample mines.

Influencing factors	Mine 1	Mine 2	Mine 3	Mine 4	Mine 5
Faults	I	II	I	III	I
Anticlines or synclines	I	II	II	III	I
Rock intrusions	I	II	I	I	I
Seam stability	II	II	II	III	I
Roof and floor rocks	II	II	III	II	I
Seam inclination	I	I	II	III	I
Seam thickness / m	3.3	1.4	6	1.5	4.6
Seam depth / m	78	183	296	477	92
Left-out reserves / %	24	33	40	48	21
Gas emission / m^3t^{-1}	0.3	3	10	16	0.3
Hydro-geology	I	I	II	III	I
Spontaneous susceptibility	II	II	II	III	I

membership degree, the mining condition for the first mine can be considered as excellent.

Similarly, the overall evaluation index for the other four mines can be obtained as follows,

$B_2 = (0.32, 0.36, 0.32, 0.00)$,

$B_3 = (0.31, 0.31, 0.35, 0.03)$,

$B_4 = (0.19, 0.29, 0.33, 0.19)$,

$B_5 = (0.54, 0.46, 0.00, 0.00)$.

The evaluation results for all the five mine are listed in **table 10**.

Table 10 Linguistic description of the mining condition for the sample mines.

Mine number	Linguistic description
Mine 1	Excellent
Mine 2	Good
Mine 3	Fair
Mine 4	Fair
Mine 5	Excellent

4 Conclusions

A fuzzy model for evaluating the mining condition of mines was presented. Relevant data from five mines were collected and the model was used to evaluate the mining condition of these mines. The evaluation results are in conformity with the real situation.

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