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and
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Risk assessment of floor water inrush in coal mines based on rock engineering systems

This paper presents an application of rock engineering systems (RES) method for risk evaluation of floor water inrush (FWI) in coal mines. The newly proposed approach involves 13 effective parameters relevant to the FWI. The interaction matrix based on the RES is introduced to study the interrelations between the parameters and their effects on the whole systems. And the relative interactive intensity and dominance of each parameter were calculated. As a result, an index is presented to assess and predict the risk grade of the FWI. Comparisons to evaluate results from present method and the actual behaviour corresponding to 20 cases are made. The results of the comparisons indicate a good agreement between assessment and observation. This risk assessment methodology provides a simple but efficient tool for systematically assessing the risk of FWI in coal mine.

Keywords: Floor water inrush; rock engineering systems; interaction matrix; risk assessment

Introduction

Water inrush hazard is an invasion of water with the potential to create an emergency situation and create a risk to health and safety of mine workers. China is the country with abundant coal resources in the world [1, 2], meanwhile, the coal mine accidents in the country happened very frequently, especially the mine water hazards. Floor water inrush can be extremely hazardous and results in significant negative consequences, including huge casualties and economic loss. For the coal field in North China, the exploitation of main coal seam easily causes water inrush due to the increasing threat of confined karst aquifer from coal seam floor. Therefore, it is necessary to assess the risk of water inrush through a coal mine floor and take effective measures to ensure coal mining safety on the confined aquifer with high water pressure.

Many researchers have tried to evaluate the risk of floor water inrush with various methods. Wang et al. constructed a secondary fuzzy comprehensive evaluation system to assess the risk of floor water inrush in coal mines [3]. Liu et al. evaluated the water inrush dangerousness of 9# coal floor of Zhangcun coal mine with the spatial data mining (SDM) [4]. Wu et al. used the analytic hierarchy process (AHP) to study the factors that affect floor water inrush from the underlying Ordovician limestone, and divided the mining area into different zones according to the risk level for water inrush during mining [5]. Li et al. combined grey relational analysis (GRA) and analytic hierarchy process (APH) to establish a risk assessment model of floor water inrush[6]. Qiu et al. applied the improved support vector machine (SVM) to predict the water inrush from coal floor [7]. Liu et al. combined the analytic hierarchy process and grey system theory to assess the risk of floor water inrush in deep mine [8]. Li et al. proposed an attribute synthetic evaluation system was combined with attribute mathematical theory and analytic hierarchy process to evaluate the risk of floor water inrush in coal mines [9]. Li et al. used the fuzzy clustering method to evaluate the water inrush risk from coal floor based on hydrogeological data [10].

The floor water inrush is a very complicated process which is subjected to the influences of various factors. These factors may have a certain effect on other factors, and may be affected by other factors to a certain extent, inversely. But previous models failed to describe and present the interactions between the individual contributory factors. In this study, in order to overcome such deficiency, a new RES based model is applied to evaluate the risk of FWI, considering 13 important parameters as the main factors. And the interrelations between the factors is determined by the expert semi-qualitative (ESQ). Then, the interactive intensity and the weights of each factor are identified by interaction matrix. According to the RES approach, the risk degree of FWI is classified by a new index, andthe field databases obtained from 20 mining faces in China is employed to validate it.

2. Rock engineering systems

The rock engineering systems (RES), initially proposed by J. A. Hudson [11], is a powerful approach to analyze the coupled mechanisms in rock engineering problems.The RES approach isused to establish and quantify the

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interrelationship among the parameters which have different effects on the outcome of the complex rock engineering system.

The RES approach has been widely applied to various engineering problems, for example, evaluation of the stability of underground excavations [12], blastability assessment of rock masses [13], geotechnical hazard assessing for TBM tunnelling [14], and rockfall hazard assessment [15], ranking the instability potential of natural slopes [16], assessment of the cavability of rock mess [17-19], and the assessment drillability of rock masses [20], etc.

In the RES approach, the basic analytical tool is the interaction matrix which is composed of various parameters and the interaction mechanisms between them. In the interaction matrix, the main parameters or factors affecting the system are identified and arranged along the leading diagonal of the matrix. And the interactions between the diagonal elements are placed on the corresponding off-diagonal positions. As a specific example, Fig.1 shows a simplest 2×2 interaction matrix with only 2 parameters. The (i,j)-th element in the matrix represents the influence of parameter i on parameter j. As a note, the influence of parameter i on parameter j is not the same as the influence of parameter j on parameter i, so the matrix is usually asymmetric, andnumber of parameters in the interaction matrix is limitless in principle.

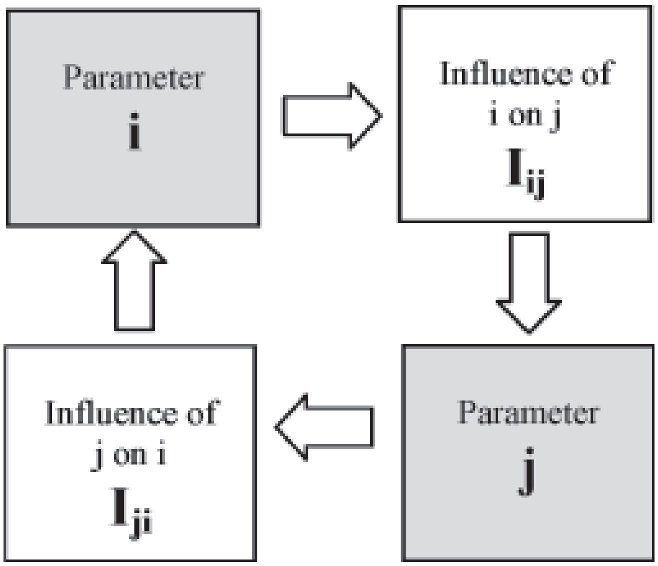

Fig.1 The principle of interaction matrix [11]

After having determined the leading diagonal elements of the matrix, the appropriate numerical values of the interaction boxes (i, j) and (j,i) must be confirmed, which is based on the influence degree of one factor or the other factors.The assignment of values to the off-diagonal boxes is referred to as coding the matrix. There are a wide number of coding methods have been developed for the numerical coding the interaction matrix, such as the binary approach; expert semi-quantitative (ESQ) coding method; continuous quantitative coding (CQC) approach and probabilistic expert semi-quantitative (PESQ) methodology etc. Among these methods, the ESQ is the most common coding method. According to this method, only one unique code is assigned to each interaction between the parameters based on expert opinion. The coding values are ranked on a scale of 0 to 4, with 0 representing no interaction; 1 representing weak interaction; 2 representing medium interaction; 3 representing strong interaction; and 4 representing critical interaction.

After coding of the interaction matrix, the relative importance of each parameter can be quantified. The summation of each row in the interaction matrix represents the way in which a parameter (P_i) affects the rest of the system, and is termed as "Cause" value (C_i). And the summation of each column in the interaction matrixis name as "Effect'" value (E_i). It shows the effect whichthe rest of the system has on that parameter. Thus, the coordinate (C_i, E_i) values for each parameter can be plotted in cause and effect coordinate system, forming the so called C-E plot (Fig.2).The position of each parameter in C-E plot specifies the parameter interaction situation. The specific values of the interaction intensity and the parameter dominance of each parameter are $\left(C_i + E_i\right)/\sqrt{2}$ and $\left(C_i - E_i\right)/\sqrt{2}$ respectively. The parameters located in the low right corner are called dominant, and the subordinate parameters are located in the top left portion of the plot.

The interactive intensity value of each parameter can be used as an indicator of parameter's significance in the system. The percentage value of (C_i + E_i) can be used as the parameter's weighting factor (α_i) as follows in Eq.(1):

$$\alpha_i = \frac{C_i + E_i}{\sum_{i=1}^{n}\left(C_i + E_i\right)} \times 100 \quad \ldots \quad (1)$$

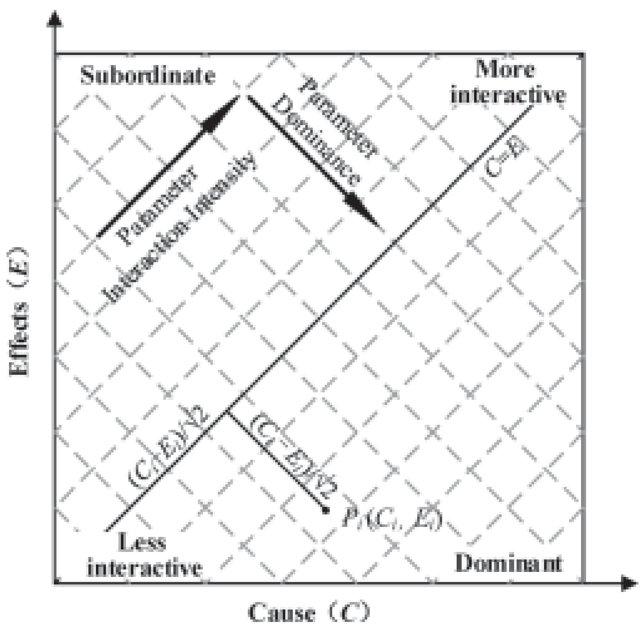

Fig.2 The view of cause-effect (C-E) plot [11]

TABLE 1: THE CONTRIBUTING FACTORSOF FWI ARE USED TO DEFINE THE RES BASED MODEL

Categories	No.	Parameters
Hydrogeology conditions	P1	Confined water pressure
	P2	Aquifer water yield property
	P3	water source supplement
	P4	Karst development degree
Floor rock properties	P5	Aquifugethickness
	P6	AquifugeStrength
	P7	Aquifugeintegrity index
Geological structure	P8	Fissure percentage
	P9	Fault density
	P10	Fault water transmitting ability
Coal working face parameters	P11	Mining thickness
	P12	Inclined length of mining face
	P13	Mining depth

TABLE 2: THE INTERACTION MATRIX FOR THE PARAMETERS AFFECTING ON THE FWI

P1	2	2	3	3	3	3	1	0	3	3	3	0
3	P2	4	3	2	2	1	2	0	2	2	2	0
2	4	P3	2	1	0	0	0	0	1	0	0	0
1	3	2	P4	1	1	1	0	0	0	0	0	0
2	1	2	1	P5	4	4	0	2	0	2	2	0
2	2	2	2	0	P6	4	2	2	3	2	2	0
2	2	2	3	2	3	P7	1	0	0	2	2	0
2	2	3	3	3	2	1	P8	3	1	0	0	0
1	2	2	1	3	3	4	2	P9	1	0	0	0
1	3	4	2	2	2	2	1	2	P10	1	1	0
0	0	0	0	3	3	1	2	0	0	P11	1	2
0	0	0	0	3	3	1	2	0	0	1	P12	0
3	1	2	2	1	1	0	1	1	0	2	2	P13

where C_i – cause of the i-th parameter, E_i – effect of the i-th parameter, i – number of parameter, and n – total number of parameters.

3. An RES based model for risk assessment of the FWI

3.1 SELECTION OF PRINCIPAL FACTORS INFLUENCING THE FWI

In reviewing the literatures published [3-8, 21-23], many factors affect FWI. As show in the Table 1, 13 factors have been selected to represent the risk degree of FWI by site investigation, theoretical analyses and historical research. And these factors could be divided in 4 categories: geological structure, hydrogeology conditions, floor rock properties, coal working face parameters. As a result, these 13 principal factors have been selected to define the RES based model.

3.2 INTERACTION MATRIX AND RATING OF PARAMETERS

3.2.1 Interaction matrix

The 13 principal factors affecting on the risk of FWI were located along the leading diagonal of the interaction matrix and the interaction among the selected parameters were placed on off-diagonal cells. In order to rate the interaction between the selected parameters, the ESQ coding methodhas been usedin this paper. Based on the views of many experts from university and coal mine enterprises, having the research experience in mine water hazard for many years, the interaction matrix for parameters affecting the FWI was obtained as shown in Table 2.

Table 3 gives the cause (C), effect (E), interactive intensity (C+E), dominance (C-E) and weight of each parameter (α_i) affecting the FWI based on Eq.(1). Also, the C-E plot and C+E histogram for each parameter are illustrated in Fig.3 and Fig.4, respectively. From Figs.3 and 4, it can be seen that confined water pressures (P_1), aquifer water yield property (P_2), aquifuge thickness (P_5), aquifuge strength (P_6) and aquifuge integrity index (P_7) have the most interaction in the system.

TABLE 3: WEIGHTING OF THE SELECTED PRINCIPLE PARAMETERS

No.	C	E	C+E	C-E	a_i (%)
P1	26	19	45	7	9.87
P2	23	22	45	1	9.87
P3	10	25	35	-15	7.68
P4	9	22	31	-13	6.80
P5	20	24	44	-4	9.65
P6	23	27	50	-4	10.96
P7	19	22	41	-3	8.99
P8	20	14	34	6	7.46
P9	19	10	29	9	6.36
P10	21	11	32	10	7.02
P11	12	15	27	-3	5.92
P12	10	15	25	-5	5.48
P13	16	2	18	14	3.95
Sum	228	228	456	0	100

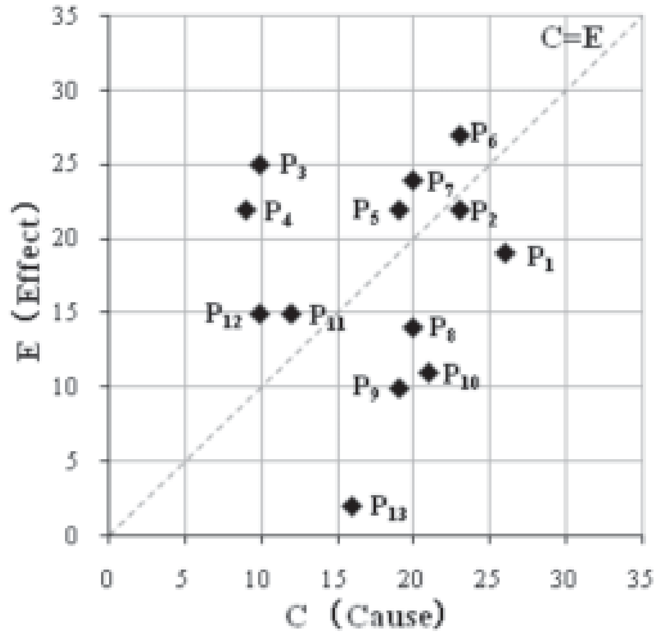

Fig.3 C-E plot for principal parameters of floor water inrush

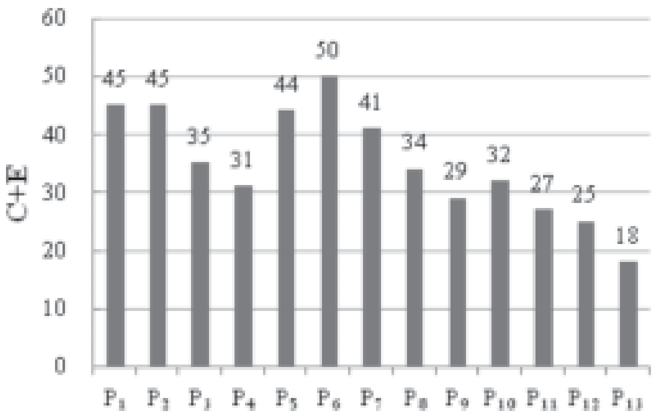

Fig.4 Histogram of interactive intensity corresponding to principal parameters involved in FWI study

This factors need to be controlled to prevent FWI accident, because small changes in these parameters could possibly induce effective changes in the system. It also shows that mining depth (P_{13}) has the most impact on the system, whereas, water source supplement (P_3) has the less impacton the system. The analysis results are basically consistent with other previous evaluation methods.

3.2.2 Rating of parameters

The rating of the parameter's values was carried out based upon their effect on the FWI. Totally five classes of rating from 0 to 4 were taken into consideration, where 0 denotesthe best case (very low condition) and 4 the worst (most favourable condition). In the case of FWI, the rating of each factor ispresented in Table 4. The ranges of factors were proposed based on the information obtained from previous studies by other researchers [3, 4, 6-10, 22-26].

3.2.3 Risk analysis associated with the FWI

In order to establish the risk assessment model for floor water inrush of each coal working face, a risk index G is defined as an overall indicator of the risk degree classification, which can be calculated according to Eq.(2).

$$G = \sum_{i=1}^{13} a_i \frac{P_i}{P_{max}} \quad \text{...} \quad (2)$$

where: i refers to parameters (1 to 13); a_i is the weight of each parameter (%) obtained from Equation 1; P_i is the rating value of parameter i; P_{max} is the max rating value of parameter i (which is 4); which G is FWI risk index of each coal working face. And G is taking value in a percent scale (0-100). The maximum value of the index is 100 which refer to the most unfavourable conditions and the minimum index is 0 which refer to the most favourable conditions.

4. Model validation

In order to validate and assess the applicability of the RES model, the databases for all 13 selected parameters have been collected from 20 mining faces in China. The databases were collected by using publications and reports from the literature, or direct correspondence with the associated mines. And the 20 cases of the computation results regarding the risk indexes are given in Table 5. After computing their G values by the proposed RES model, their corresponding risk levels are received based on the index G. Table 5 shows the detail of the 20 validation cases.Compare the actual results of the collect cases with the assessment results by the RES model. Assume 0 for no occurrence of floor water inrush, and 1 for occurrence of floor water inrush.

Regarding the true situation of the selected 20 cases

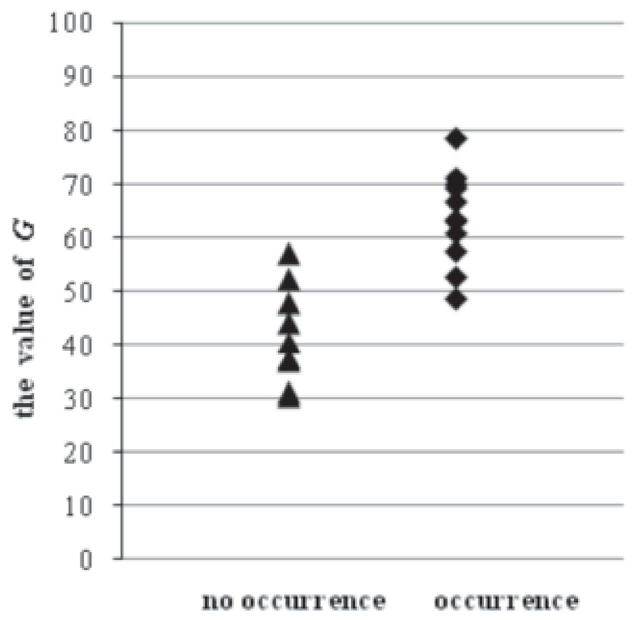

Fig.5 The calculated G values and real situation of 20 cases

TABLE 4: PROPOSED RANGE AND THEIR RATING FOR THE EFFECTIVE PARAMETERS IN FWI

Parameters		Values/description rating				
		0	1	2	3	4
Hydrogeology conditions						
P1	Confined water pressure (Mpa)	<1	1-2	2-3	3-4	>4
P2	Aquifer water yield property L/s·m		<0.1	0.1-1	1-5	>5
P3	Water source supplement	very low	low	medium	high	very high
P4	Karst development degree		weak	medium	strong	extremely strong
Floor rock properties						
P5	Aquifuge thickness (m)	>100	75-100	50-75	25-50	<25
P6	Aquifuge strength (Mpa)	>2.6	2.1-2.6	1.7-2.1	1.3-1.7	<1.3
P7	Aquifuge integrity index Kv	>0.75	0.55-0.75	0.35-0.55	0.15-0.35	<0.15
Geological structure						
P8	Fissure percentage KT (%)	<2	2-5	5-8	8-10	>10
P9	Fault density (lip/km^2)	<1.5	1.5-2.0	2.0-2.6	2.6-3.2	>3.2
P10	Fault water transmitting ability (%)	<10	10-30	30-50	50-70	>70
Coal working face parameters						
P11	Mining thickness (m)	<1.1	1.1-1.6	1.6-2.1	2.1-2.5	>2.5
P12	Inclined length of mining face (m)	<25	25-90	90-135	135-200	>200
P13	Mining depth (m)	<400	400-500	500-650	650-800	>800

TABLE 5: ENGINEERING PRACTICE EVALUATION

No.	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	G	Actual value
1	4	4	4	3	3	3	3	2	4	2	4	1	3	78.56	1
2	0	2	4	1	4	4	3	4	2	3	4	2	3	69.19	1
3	0	1	3	2	4	1	1	0	1	1	2	3	1	37.66	0
4	4	3	2	1	4	1	1	4	2	1	1	0	1	52.3	0
5	1	1	1	4	4	4	4	2	2	0	2	0	4	57.07	0
6	3	3	3	2	3	3	4	4	0	1	2	0	3	63.54	1
7	3	4	4	2	3	0	2	4	1	2	4	3	4	66.61	1
8	3	3	4	4	2	2	3	2	2	4	2	3	4	71.27	1
9	2	4	3	3	3	4	4	3	3	2	1	0	2	70.18	1
10	1	2	2	2	1	3	4	2	2	2	1	1	1	48.52	1
11	4	3	2	2	1	2	3	2	2	3	4	2	3	62.94	1
12	2	4	4	1	4	1	2	0	4	2	2	3	3	60.96	1
13	2	4	2	4	2	0	1	2	1	3	2	4	1	52.52	1
14	1	2	3	2	3	2	0	0	1	1	2	1	0	36.95	0
15	1	1	0	2	1	0	0	3	2	3	2	1	2	31.09	0
16	2	1	4	1	3	3	2	4	1	0	4	2	3	57.4	1
17	4	3	3	2	1	0	3	0	2	1	1	2	3	47.7	0
18	0	1	2	2	2	3	2	1	0	2	1	4	1	40.57	0
19	0	2	3	1	1	0	1	2	2	2	2	0	0	30.43	0
20	1	2	2	4	0	2	3	2	4	0	0	2	1	44.08	0

(Fig.5), it appears to be a clear relationship between the G values with the occurrence of FWI. The occurrence of FWI cases almost had values of G over 50 (10 in 11), and no occurrence of FWI had values of G below 50 (7 in 9). The results obtained from the proposed method show a good agreement with the results of actual value. So the values of G can be employed to assess and predict the risk degree of FWI in coal mines.

5. Discussion and conclusions

Based on the rock engineering systems (RES) theory, a powerful method is presented to systematically evaluate the risk of floor water inrush in coal mining. The RES method is a simple but efficient tool of comprehensively considering all the effective factors and their interaction, and without numerous complicated computations.The analysis results obtained from the RES method helps understanding the interaction of parameters and their considerable effect on the FWI.

13 effective parameters considered as inputs tothe models and the risk level of the FMI as outputs. The interaction matrix corresponding to these parameters are constructed by expert semi-quantitative coding method. The C-E plot indicated that the hydrogeology conditions (confined water pressures, aquifer water yield property) and floor rock properties (aquifuge thickness, aquifuge strength and aquifuge integrity index) have the most remarkable influence on the FWI. And a new index has been used to assess the risk of FWI based the RES approach. The selected databases from 20 coal working faces are used for the risk analysis and to develop the FWI predictive models.The results of the risk analysis show that the level of risks determined is relatively in a good agreement with the actual situation. It means that the RES-based model defined for risk analysis may be used to predict the risk of FWI in a coalface.

The interaction matrix value coded by expert semi-quantitative method is manually determined by experts, making it difficult to be judged with objectivity. The validity of analysis results based on such interactions might be questioned. To minimize this subjectiveinfluence, the Artificial Neural Network coding method or the fuzzy system can be used in future study.

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RISK ASSESSMENT OF FLOOR WATER INRUSH IN COAL MINES BASED ON ROCK ENGINEERING SYSTEMS

(Continued from page 353)

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