Risk Assessment of Coal Mining under Sand Aquifers

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Abstract

This paper presents a method for risk assessment of coal mining under sand aquifers. A case study in a panel of the Quandian Coalmine, Chinese Henan province is proposed to illustrate the application of this risk assessment method. Hydrogeological characteristics of overburden stratums and fractures due to coal mining are considered in the risk assessment as it is essential for preventing groundwater and sand inrush. A risk assessment model is proposed by using a large number of measured data and tests results. Then a mathematical model based on three-dimensional spatial entropy of safety mining area is proposed. The safety mining of coal layer in the study area is assessed by means of three-dimensional spatial multivariate quantitative. Finally, the zoning map of different factors in a superposition way of three-dimensional space of mining suitability is provided for mining reference.

Key words: underground coalmining, sand aquifer, entropy, risk assessment, caving zone, water flow fractured zone

Introduction

Groundwater and/or sand inrush is one of the major safety problems in underground coal mining especially under sand aquifers. This kind of accident is affected by several factors, such as engineering geological and hydrogeological conditions, mining method and mine environment (Sui et al. 2008, Sun et al.2012; Wu et al. 2009). There are various studies that focused on the relationship between the water inrush and geological conditions, overburden failure and the overlying strata thickness (Xu 2012). According to a preliminary statistics, about half of the underground coal mines in China are threatened by groundwater, which means over 250×10^8 tons coal reserves are dangerous to mining.

Sand aquifers is considered as one of the main source for groundwater inrush. Evaluation of mining safety under sand aquifers is usually based on laboratory experiment, numerical simulation and mathematical method (Wang et al. 2008). Since the geological conditions are not predictable, application of these constitutions are not reliable in different coalmines.

A quantitative assessment method which consists of three maps and two interrelated predictions has been proposed by La Moreaux et al. (2014) and Wu et al. (2015). GIS technology enables more automated approaches and accurate methods to evaluate the hazard of coal mining (Malinowska and Hejmanowski, 2010).

Among the factors influencing the water and sand inrush in coalmines, mine layout and cutting height can be controllable by optimizing underground mine design. However, it is more difficult to control the effect of hydrogeological and engineering geological conditions on mining under sand aquifers, since the uncertainty of hydrogeological and geological conditions. Therefore, groundwater inrush is considered as one of the most complicated problems in underground coal mining. In order to overcome the uncertainties and ensure the safety of mining under sand aquifers, a risk assessment method is introduced in this paper.

Three-dimensional spatial entropy is proposed as a risk assessment method for the safety mining under unconsolidated aquifers. Groundwater and sand inrush risks in the Quandian Coalmine are assessed based on the different mining design.

Methods

A risk index method is developed to effectively predict and comprehensively evaluate the safety of mining under sand aquifers. The detailed description of this approach is given in the works of Sui and Yang (2015).

Tab. 1 lists the main indices which consists essential factors for the risk assessment of coal mining under sand aquifers. Five main factors are listed as the first-grade indices; geological structure, sand aquifers, hydrogeological barriers, mining activity and overburden. The second-grade indices contain 12 factors. Among them, the sand aquifers index reflects hydrogeology conditions of the Neogene system especially the specific capacity of its bottom aquifer. Geological structures, including fault and fold, can be considered as the pathway of groundwater inrush. Faults and fractures will be developed in mining procedure. Once the faults or fractures developed to the bottom of aquifer, groundwater and sand would inrush into the panel as an unpredictable accident. Thickness of hydrological barrier in soils and overlying stratum in rock is used to evaluate the possibility of preventing groundwater inrush. It is possible to prevent groundwater inrush if the thickness of the barrier is larger than the fractures. The mining activity can be considered as the trigger of groundwater inrush because of its direct cause of overburden failure.

***Table** 1 Controlling index system of mining safety under unconsolidated aquifers*

The first-grade index	The second-grade index
Geological structure	Faults in fractured zone Fold
Sand aquifers	Specific capacity of groundwater of the Neogene Hydraulic conductivity Thickness of the bottom aquifer
Hydrogeological barriers	Thickness of the bottom clay of the Neogene Thickness of the key aquifuge
Mining activity	Cutting height Mining depth Caving and fractured zone
Overburden	Thickness Elevation of bedrock

Information-entropy model is a quantitative method for data analysis and decision making. It is an effective way to determine the different weights of a large number of data obtained from measuring in the field and tests in the laboratory. The concept of information entropy was created by a mathematician named Claude Shannon. It is an effective way to determine the weight. The weight of vector is calculated by a simple spatial entropy method (Sui and Yang 2015), which means how much information there is in an event. In general, any event contains different information. More complicated event contains more information. The comprehensive value is defined in equation (1):

$$CE = \sum_{j=1}^{n} w_j \cdot F_j(x, y) \quad (1)$$

where CE is comprehensive value; w_j is the weight value of the j^{th} evaluation index; F_j is the function of evaluation index factor which attribute to the j^{th} thematic map.

In order to compare the different comprehensive evaluation values, it is necessary to normalize the risk index. The method was given in equation (2).

$$RI = \frac{CE_x - CE_{min}}{CE_{max} - CE_{min}} \quad (1 \le x \le N) \quad (2)$$

where RI is risk index, CE is comprehensive value, CE_{max} and CE_{min} are the maximum and minimum of the grid domain, respectively, x means the x^{th} grid, N is the total number of grid. The risk index will be a value between 0 and 1.

A case study

Site description

The Quandian Coalmine is located in the southeastern part of the Yuzhou Coalfield, 16 km southeast of Zhengzhou. Coal seams are covered by the Cenozoic System with an average thickness of 220m. Panel 11050 is located in the east wing of the 11th District, with a design length of 820m, and a width of 158m as shown in Figure 1. Strikes of this panel is in NEE and SWW. There are two recoverable seams, the seam Ⅱ$_1$ and seam Ⅱ$_3$. The thickness of the former is from 0 to 10.38m, averaging 4.52m, and the thickness of the latter from 0 to 2.51m, averaging 1.66m. The overlying strata of the coal seam has a thickness ranging from 0 to 150m. The Cenozoic System is classified into seven engineering geological types according to borehole data. Figure 2 shows a cross section of Panel 11050. Tab. 2 lists 10 faults that found in the area according to 3D seismic exploration.

***Table** 2 Occurrence and statistics of the fauts area outcrop belt throw in the 11th mining area*

Fault No.	Throw (m)	Dip angle (°)
DF_{226}	0-15	67
FB_1	0-50	65
DF_{221}	0-6	70
DF_{220}	0-3	70
DF_{222}	0-5	59
DF_{225}	0-13	70
DF_{22}	3	58
DF_{219}	0-13	70
DF_{21}	3	62
DF_{20}	2	43

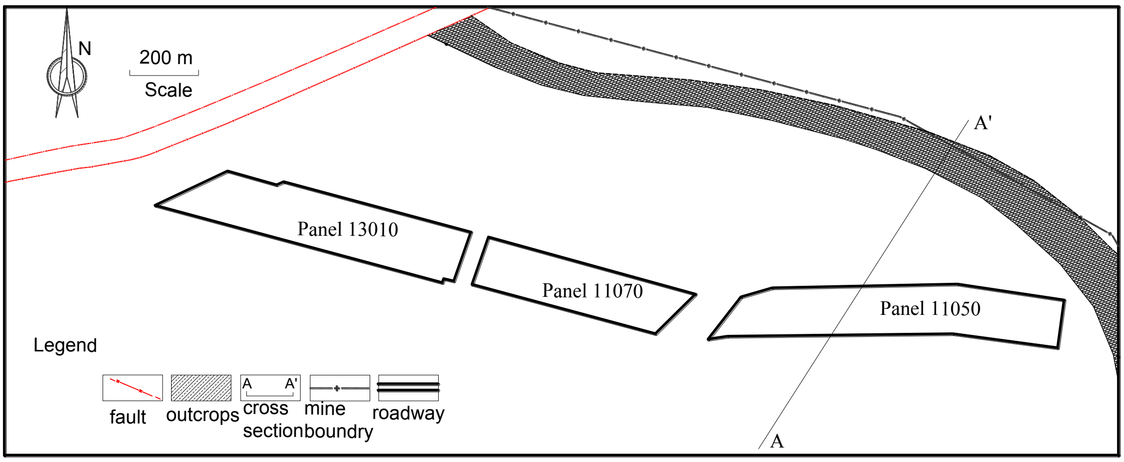
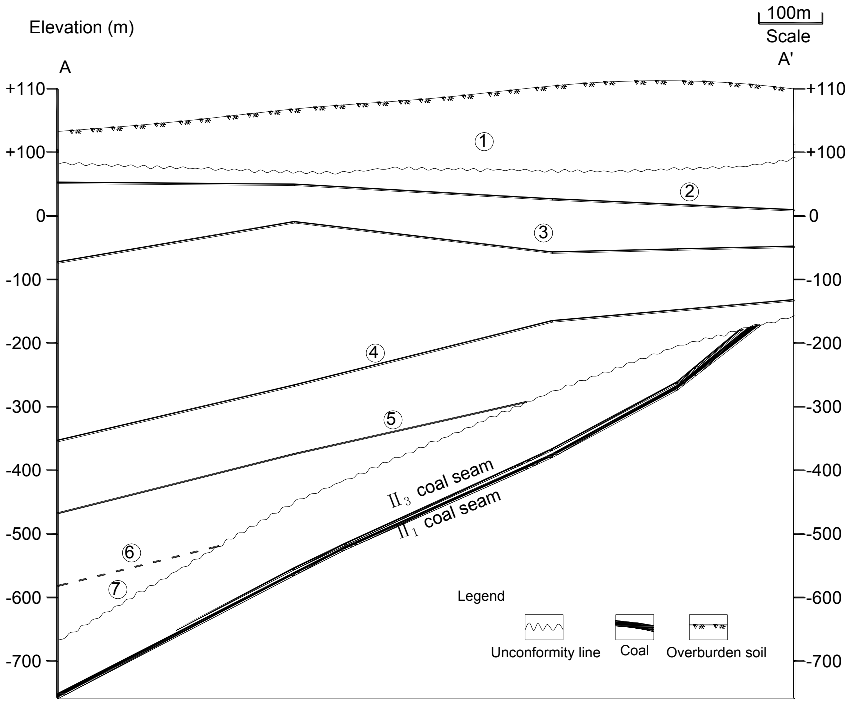


***Figure** 1 Layout of panels in the 11th District of the Quandian Coalmine that shows.*



①The Quaternary clay, sand and gravely sand; ②Clay, sandy clay; ③ Clayey and gravely sand, medium and fine sand; ④Clay, sandy clay with a thin layer of fine sand, interbedded silty clay with fine sand; ⑤Gravel sand, medium sand clay; ⑥Clay, sandy clay and clayey sand and gravel; ⑦Gravel sand, silty clay.

***Figure** 2 A-A' cross section of Panel 11050*

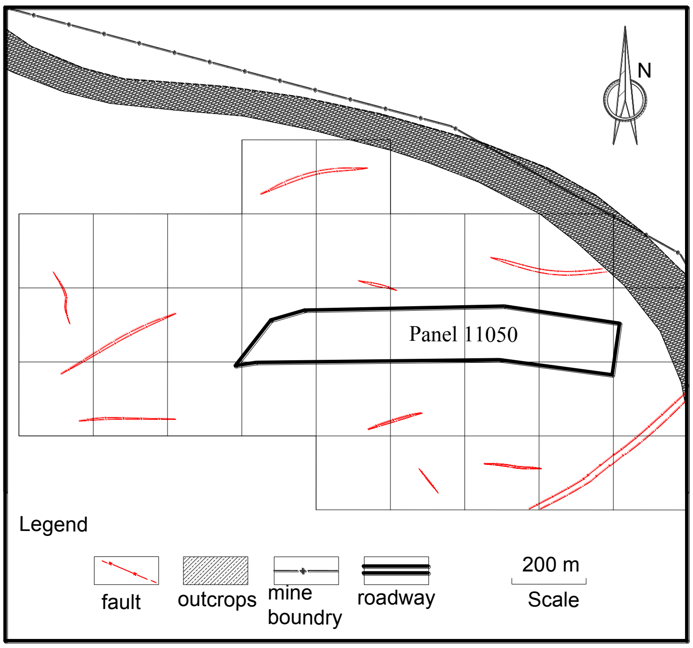


***Figure 3** Faults in the study area*

Nonlinear three-dimensional quantitative analysis of faults

Fault structure in the study area is evaluated by using three-dimensional quantitative method of nonlinearity, an evaluation method which is more reasonable and accurate than the density evaluation method. The fractal dimensions of the fault contains the number of faults, intersect relations and scale, etc.

The study area is divided into 33 square grid with a side length of 100 m as shown in Figure 3. Then, the similar ratio is showed as: r = 1, 1/2, 1/4 and 1/8, respectively. The similarity of dimensions is showed as D_s (Li et al. 2014). The 3D thematic maps of the geologic structures have been analyzed by the 3D Analyst Tools of the ArcGIS as shown in Figure 4a.

$$D_s = -\frac{\log N(r)}{\log(r)} \quad (3)$$

where the $N(r)$ is the number of the grid crossing by fault trace, r is the similarity ratio of square grid.

Overburden failure height due to mining

Two scale models with a scale of 1:200 were constructed to simulate mining process.

The heights of mining overburden failure zone was calculated by using different methods which are summarized in Tab. 3. Also, the results was compared with the measured data from Xin'an Coalmine where shares the similar geological conditions. Moreover, results from scale models were listed in Tab. 3 for comparison. Recommended results were used to evaluate mining upper limit of coal seams under the sand aquifers.

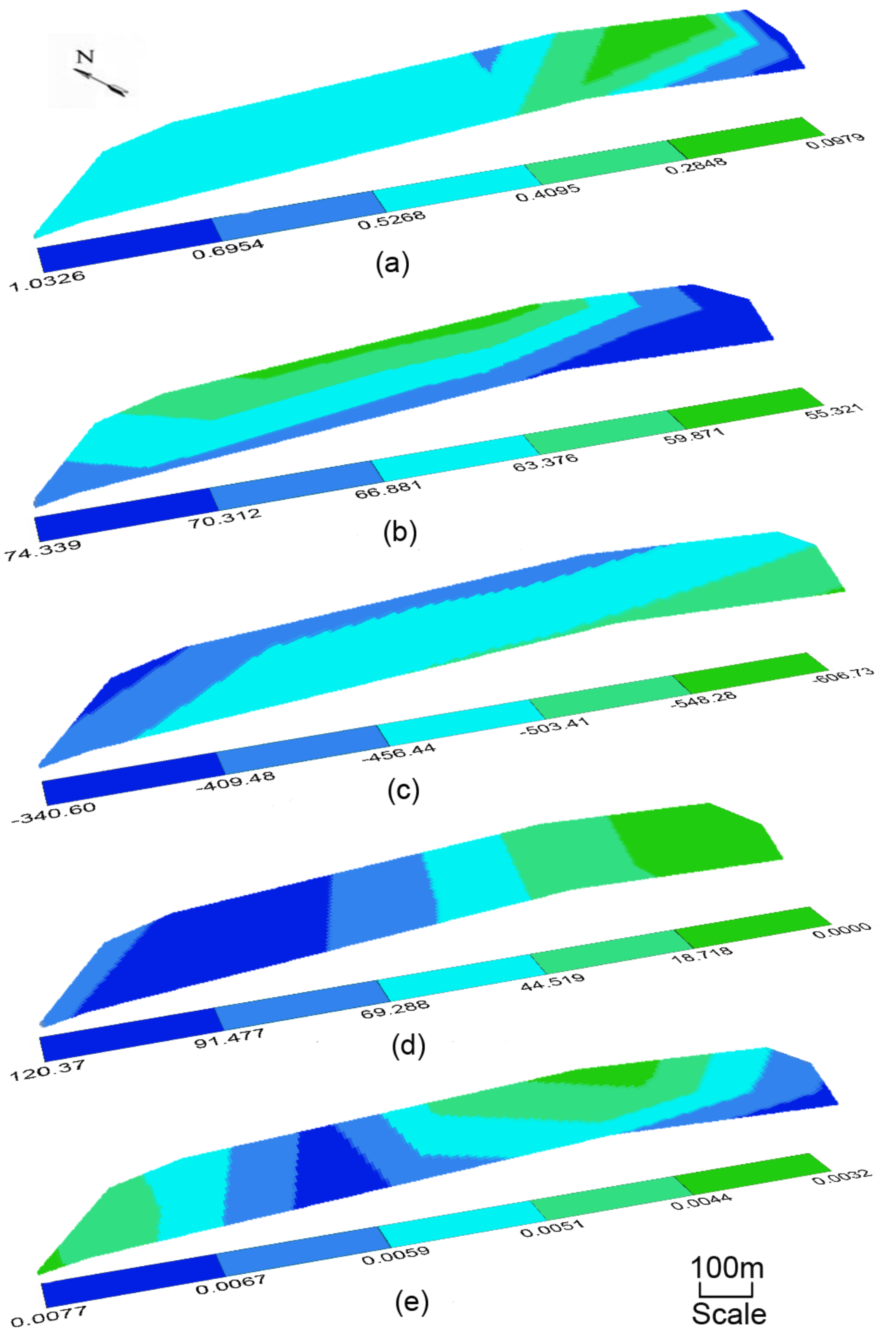
Table *3 Prediction of overburden caving zone and water flowing fractured zone*

Cutting height (m)	Caving zone				Water flow fractured zone	
	Code (CCIB)	Xin'an Coalmine	Scale model test	Recommended (m)	Code (CCIB)	Recommended (m)
	H_c/M	H_c/M	H_c/M		H_f/M	
2.0	4.62/6.24		4	12.48	17.58	35.16
2.8	3.90/5.27			14.76	14.38	40.26
3.0	3.75/5.61			16.83	13.77	41.31
4.0		5.46	6.80, 5.50	22.00		47.08
5.0		4.75	3.76-4.63	23.75		50.95
6.0		4.75	3.76-4.63	28.50		54.42
7.0		4.75	4.51	33.25		57.89
7.2		4.75		34.20		58.58
7.5		4.75		35.63		59.62
7.8		4.75		37.05		60.66
8.0		4.75		38.00		61.36
9.0		4.58		41.22		64.83

H_f: height of the fractured zone; H_c: ration of height of caving height; M : cutting height.

Evaluation of Mining feasibility based on 3DGIS

Eleven indices (excluding the index Fold in Tab. 1) as the second-grade evaluation indexes have been analyzed by using 3DGIS. The 3D thematic maps of five main factors as the first-grade indices have been obtained by the model of three-dimensional spatial entropy (Figure 4). An entropy mathematical model was established to quantify the relationship based on the calculation and analysis. Quantitative analysis and dimensionless normalization for the first-grade main factors and their importance degree are determined. Finally, a model of three-dimensional spatial entropy based on GIS is set up, the three-dimensional space superposition of mining suitability zoning map integrated many factors is provided for mining reference as shown in Figure 5.



(a) Geological structure; (b) Sand aquifers; (c) Hydrogeological barriers; (d) Mining activity; (e) Overburden

***Figure** 4 Perspective drawing of each factor's three-dimensional space*

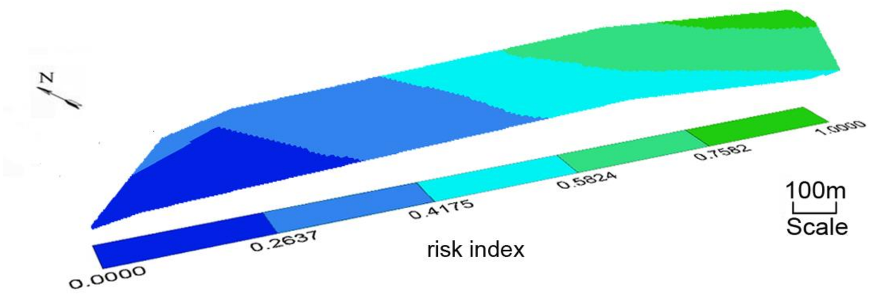


***Figure** 5 Three-dimensional zoning for mining feasibility*

Conclusions

In this paper, a risk assessment method has been proposed for effectively predicting and comprehensively evaluating the safety of mining under sand aquifers. Since analysis of risk assessment of coal mining under sand aquifers has the characteristics of complexity and variability, two or even multivariate mathematical model of three-dimensional spatial entropy is constructed based on GIS, various indices and their relationship have been considered simply and fast, accurate and practical. A panel of the Quandian Coalmine in the Henan province of China was evaluated by using risk assessment model. In the assessment, overburden hydrogeological conditions, engineering geological conditions and overburden failure due to mining were analyzed and several indexes were quantified for the model.

By using a large number of measured data and test results, a mathematical model of three-dimensional spatial entropy of safety mining area is established. And the safety mining of coal layer in the study area is assessed by using three-dimensional spatial multivariate quantitative method. Finally, the zoning map of many factors of three-dimensional space was proposed for determination of mining methods In the region with high risk where $RI \geq 0.7582$, the cutting height of II_1 seam was limited within 2.8m. There was no serious disturbances and accidents such as groundwater inrush and quicksand during mining from September 2013 to March 2015.

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