Qualitative and Quantitative Decision-Making Model to Determine the Size of Safety Pillars for Mining Under Sand Aquifers

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Abstract

A qualitative and quantitative decision-making model is proposed for determining the size of safety pillars under sand aquifers. The qualitative model is based on a fishbone chart, which includes hydrogeological and engineering geological conditions and their changes due to mining activities. The quantitative model is a decision-making model based on geographic information system and entropy values. The decision models are demonstrated using data from different coalmines in China. The qualitative model is simple and can be widely applied in determining the size of safety pillars under sand aquifers.

Keywords: Underground mining, Decision-making model, Geographic information system (GIS), Sand aquifers

Introduction

Sand and water inrush are major issues when mining under sand aquifers, greatly affecting the normal production of a coal mine (Sui and Dong 2008). The panel and the roadway may be clogged with silt, and the machinery equipment can be buried. Cleaning and recovery of the mine's production is difficult, and such incidents, therefore, cause serious economic losses. The conditions and mechanism of coal mine sand and water inrush are complicated, mostly related to the scale and characteristics of the overburden aquifers, the coal seam, the mining method, the thickness and strength of the overburden rock, and the failure form of the overburden rock (Sui et al. 2011). Sand and water inrush can occur under various conditions, such as fault conduction, direct mining and conduction (general thickness of bedrock is thinner), and borehole conduction (Figures 1(a), (b), and (c), respectively).

Therefore, the size of pillars left under aquifers is a key parameter for decision-making regarding the safety of mining under sand aquifers. This study proposes a qualitative and quantitative decision-making model for determining the size of safety pillars under sand aquifers which is proposed by Yang et al. (2017). The quantitative model is a decision-making model based on geographic information system (GIS) and entropy values. The decision models are demonstrated using data from different coalmines in China. The qualitative model is simple and shows great promise for applications in determining the size of safety pillars under sand aquifers. The quantitative method is effective and advantageous, as the influence of multiple factors has been quantitatively considered in accordance with the geological and mining conditions. The model provides more optimal direction on mining under sand aquifers. For further study in mines where the geological structure is more complicated, a three-dimensional (3D) quantitative model should be developed.

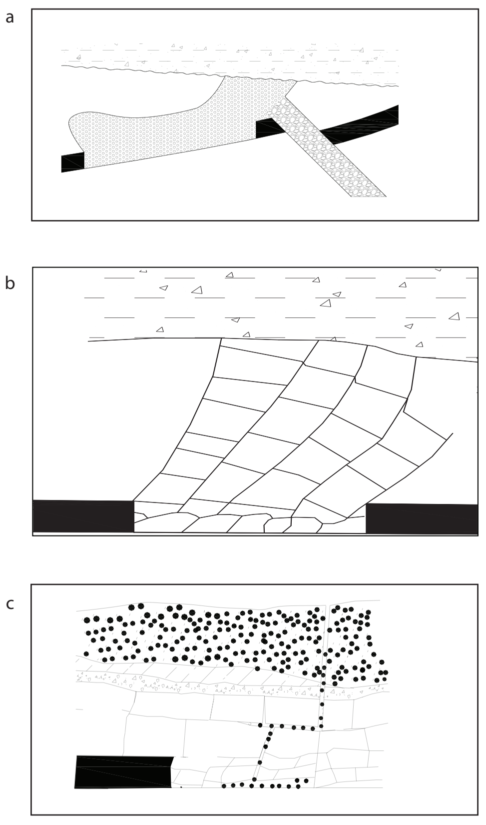
Methods

In accordance with China's regulations for coal pillar designs for main roadways and coal mining under buildings, water bodies, and railways (State Administrator of Work Safety, 2017) and the regulations for preventing water hazards for coalmines (State Administrator of Work Safety, 2018), there exist three types of safety pillars under aquifers as listed in Table 1.

Table 1 *Types of safety pillars under aquifers*

Types	I	II	III
Safety pillars	Water-proof	Sand prevention	Anti-collapse

The present qualitative model is based on a fishbone chart, which includes hydrogeological and engineering geological conditions and their changes due to mining activities. Four basic maps, including a specific capacity distribution map, an isopach map of overburden, a contour map of the elevation of the bedrock surface, and an isopach map of the bottom clay, are superimposed and analyzed. The bottom clay and the overburden thickness are beneficial factors for the safety of mining under sand aquifers. Next, the height of overburden failure, the flow rate through the fractured zone into the panel, and the quicksand risk assessment are predicted. A qualitative comprehensive model is finally proposed to determine the size of the required safety pillars under aquifers (Figure 2).



(a) ***fault*** *conduction;*

(b) ***direct*** *mining and conduction;*

(c) ***borehole*** *conduction*

Figure 1 *The conduction form of water and sand inrush*

With the rapid development of computer technology, space decision-making technology has also progressed significantly. The quantitative model is a decision-making model based on GIS and entropy values. An evaluation index system for controlling the mining safety under sand aquifers has been defined with reference to engineering geological and hydrogeological conditions. The factors included in the qualitative model are extensively and quantitatively defined and analyzed using GIS. Thematic map layers of the main factors that determine the safety of mining are generated based on geological data and other information. The risk index of mining under aquifers has been defined by Sui and Yang (2016) based on the weighted linear combination and information entropy. Figure 3 shows the flowchart of the quantitative model. First, the factor values are normalized according to the methodology proposed by Yang et al. (2017, 2018)

The entropy values of the thematic map layers are defined as follows.

$$e_j = \frac{1}{\ln(m)} \sum_{i=1}^{m} p_{ij} \ln(p_{ij}) \quad (k > 0, e_j \geq 0) \qquad (1)$$

The weights of the thematic map layers are calculated using formula (2).

$$\begin{cases} g_j = \dfrac{1 - e_j}{j - \sum_{j=1}^{n} e_j} (0 \leq g_j \leq 1, \sum_{j=1}^{n} g_j = 1) \\ w_j = \dfrac{1 - g_j}{\sum_{j=1}^{n} g_j} (1 \leq j \leq n) \end{cases} \qquad (2)$$

Case Study

The Taiping Coalmine is located in the city of Jining, China. The study area falls within Panels S02 and S03, which are located in the southern region of the sixth mining area. The hydrogeological structure, which affects the mining of coal seam No. 3, comprises sandstone aquifers developed in Jurassic bedrock,

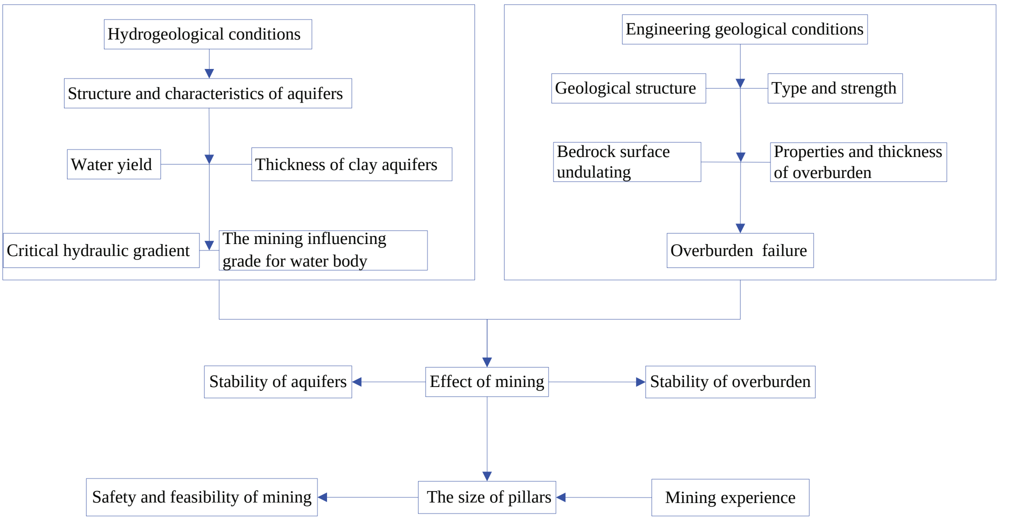


Figure 2 *Flowchart of qualitative decision-making for sand and water inrush*

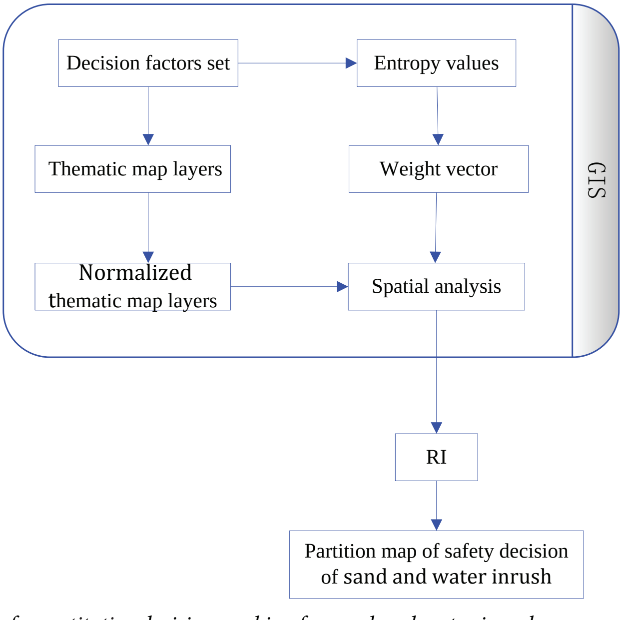


Figure 3 *Flowchart of quantitative decision-making for sand and water inrush*

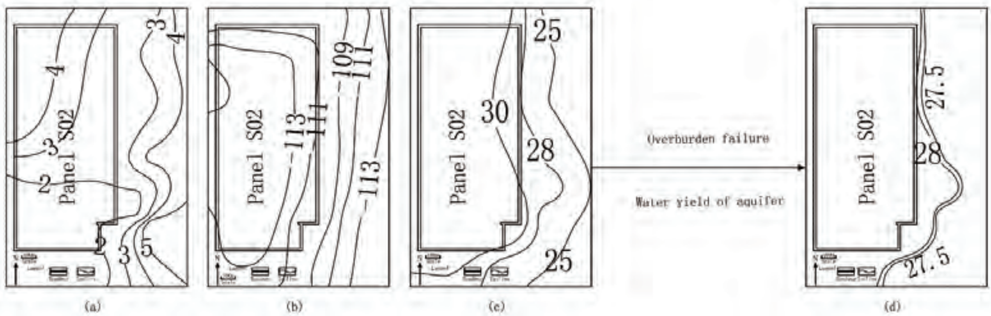
clay aquifuge, and sand aquifer in unconsolidated Neogene sediments. Based on the data shown on the basic maps, the overburden isopach map, the contour map of the elevation of the bedrock surface, and the isopach map of the bottom clay are analyzed via superposition. Next, the height of overburden failure, the flow rate through the fractured zone into the panel, and the quicksand risk assessment are predicted. Figure 4 shows the size of the safety pillars under the aquifers determined by the qualitative comprehensive model.

Based on the GIS and entropy values, an evaluation index system including the water-yield property of the bottom aquifers, the height of overburden failure, the overlying strata thickness, the thickness of the bottom clay layer of the Neogene system, and the bedrock surface elevation are defined. The factors included in the qualitative model are extensively and quantitatively defined and analyzed using GIS. Figure 5 shows the risk assessment based on the thematic map layers of the main factors that determine mining safety.

Results and Discussions

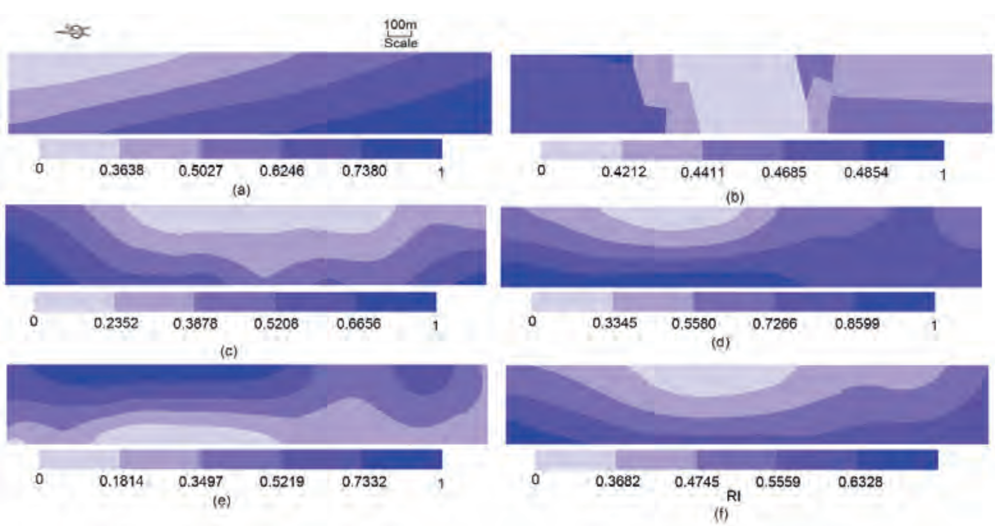
Based on the results derived for different panels of the study area, the qualitative approach is simpler and presents great application potential for determining the size of safety pillars required under sand aquifers. The quantitative method is effective and advantageous, as the influence of multiple factors has been quantitatively considered in accordance with the geological and mining conditions. In accordance with the results of the qualitative model, the decision factors are classified and listed in Table 2.

Based on the results of the quantitative model, the relationship between risk index (*RI*) and decision factors is shown in Figure 6. When the water-yield property or the unit



*(**a) isopach** map of the bottom clay; (b) contour map of the elevation of bed rock surface; (c) isopach map of overburden; (d) the size of safety pillars under aquifers*

***Figure 4** The flow chart of the qualitative comprehensive model of Panel S02*



***(a) water-yield** property of the lower aquifers; (b) height of overburden failure; (c) overlying strata thickness; (d) thickness of the bottom clay layer of the Neogene system; (e) contour map of the elevation of bedrock surface; (f) risk index of the quicksand*

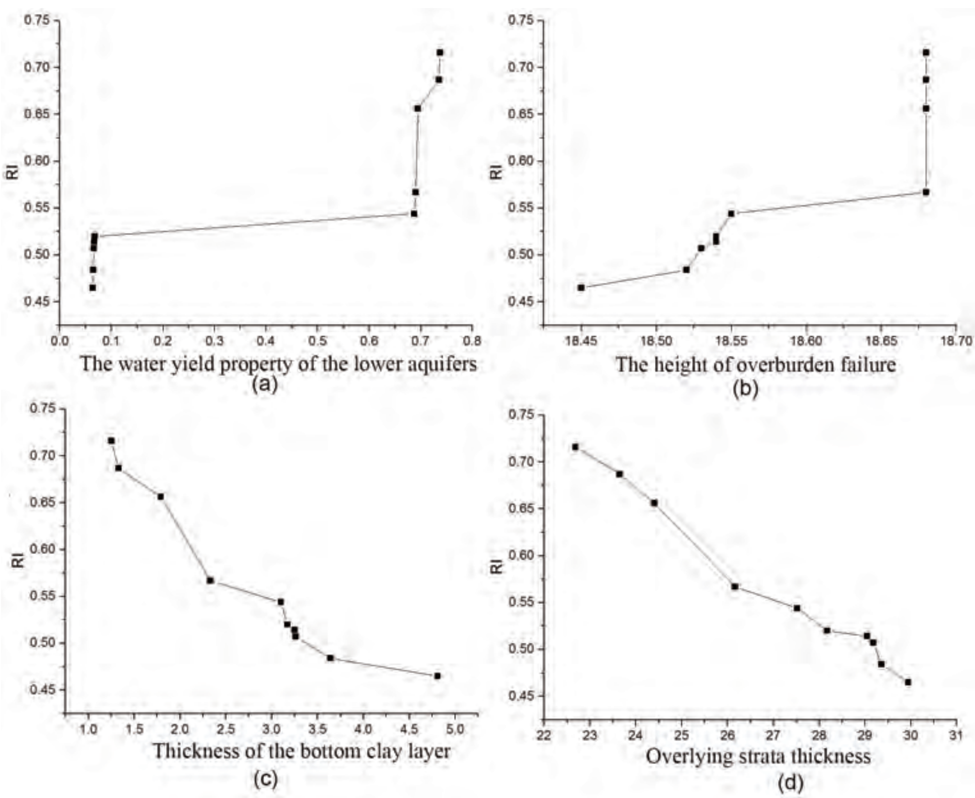
***Figure 5** Flowchart of the quantitative model of Panel S03* water inflow (q) is greater than 0.1 L/s·m, RI increases rapidly.

Conclusions

The decision models are demonstrated using data from different panels (S02 and S03) of the Taiping Coalmine in China. The proposed qualitative approach is simple and has great potential for application in determining the size of safety pillars under sand aquifers. In this study, the influence of multiple factors has been quantitatively considered in accordance with the geological and mining conditions thereby making the proposed

***Table 2** Decision factors based on the qualitative model*

Decision factors	Classification	Remarks
Water-yield property of lower aquifers	Weak: $q \le 0.1$ L/(s·m)	q: Unit water inflow;
	Medium: 0.1 L/(s·m) $<$ $q \le 1.0$ L/(s·m)	A: Mining thickness;
	Strong: 1.0 L/(s·m) $<$ $q \le 5.0$ L/(s·m)	H_l: Thickness of overburden
	Extremely strong: $q >$ 5.0 L/(s·m)	
Thickness of the bottom clay layer	Very good: $>7A$; Good: 5 $A \approx 7$A	
	Medium: 2 $A \approx 4A$; Poor: $<2A$	
Height of overburden failure(H_l)	Very good: $<4A$; Good: 4 $A \approx 8A$	
	Medium: 8 $A \approx 16A$; Poor: $>16A$	
Thickness of overburden (H/H_l)	Very good: >1.4; Good: 1.4-1.2	
	Medium: 1.2-1.0; Poor: <1	



*(**a) Water-yield** property of the lower aquifers of the Neogene; (b) height of overburden failure; (c) thickness of the bottom clay layer of the Neogene system; (d) overlying strata thickness*

***Figure 6** The relationship between RI and decision factors* quantitative approach highly effective and advantageous. The proposed model provides optimal directions for mining under sand aquifers. For further study in mines where the geological structure is more complicated, a 3D quantitative model should be developed.

Acknowledgments

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