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Water-conserving mining influencing factors identification and weight determination in northwest China

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Abstract Water-conserving mining is an effective way to alleviate the contradiction between fragile ecological environment and high-intensity coal mining in the arid and semi-arid region of northwest China. It needs to consider the engineering and geological conditions, hydrogeological conditions and mining methods of coal seams. From the three aspects, this paper systematically analyzes the influencing factors and establishes an identification model with multi-level structures. The model includes three primary factors (including the engineering and geological conditions, hydrogeological conditions and mining methods), nine secondary factors (including overlying strata thickness, aquiclude, mining parameters and etc.), sixteen third-tier factors (including the faults, aquiclude thickness and effective mining height and etc.) and twelve fourth-tier factors (including the fault throw exponent, aquiclude permeability and coal pillar sizes and etc.). On the basis, the analytic hierarchy process is used to build the judgment matrix and obtain the weight of each influencing factor. The results indicate that the overlying strata thickness, aquiclude and effective mining height are the most important factors among the primary factors of engineering and geological conditions, hydrogeological conditions and mining methods, respectively. The research results could provide theoretical references for the water-conserving mining of coal resources in northwest China.

1 Introduction

The northwest region is China's major coal-production region (Gu 2015). During the 'Eleventh Five-Year Plan' period, 13 national key constructed large coal bases are mainly in Shanxi, Shaanxi, Inner Mongolia and Ningxia areas with fragile ecological environment and serious soil and water loss (Miao et al. 2009). Most coal seams in these areas have large thickness and shallow burial depth. Therefore, large-scale and high-intensity coal mining could easily lead to water inflow and leakage in shallow strata, aggravate the fragile ecological environment and even bring catastrophic destruction (Zhang et al. 2017). To solve the contradiction between fragile ecological environment and high-intensity coal mining in northwest China, the concept of water-conserving mining has been put forward in academic circles (Fan 2005).

As an important part of green mining (Qian et al. 2007), the water-conserving mining was originally to solve the underground seepage during the mining process of Jurassic coal seams in northern Shaanxi. As the concept of green mining gradually enjoys popular support, it has been promoted and applied in northern China and Xinjiang areas and has achieved remarkable results (Wu 2014; Zhang et al. 2015). Through many years' theoretical researches and engineering practice, the water-conserving mining

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theory and technology system has initially formed in order to protect ecological water level (Wang et al. 2010; Fan 2017).

The above-mentioned researches have made important contributions in water-conserving mining in areas with fragile ecological environment. They have improved the theoretical basis of water-conserving mining, supplemented the technology system and broadened the concept of water-conserving mining. These researches also have pointed out the factors that must be considered during the water-conserving mining. Fan et al. (2016) has analyzed the relationship between groundwater level decline and high-intensity mining of coal seams. It has pointed out that the mining intensity is determined by the dimensions of working face, mining height and advance velocity and etc. Huang (2017) holds that mining depth, mining height, overlying strata thickness and properties determine the development of upward and downward cracks of water-resisting rocks. Miao et al. (2007) has studied the water-resisting capability of composite water-resisting key layer from the aspect of strata combination. Wang et al. (2010) has divided the spatial relations between the coal and the aquifer (aquifuge) based on overlying strata thickness, mining height, aquifer thickness, aquifuge thickness, water-physical properties and etc. Ma et al. (2013) has divided the aquifers based on loose aquifer thickness, permeability coefficients and supply patterns. In addition, the empirical calculation formula of height of water flowing fractured zone has been given based on the mining height.

The above-mentioned researches have analyzed the influencing factors of water-conserving mining from different perspectives. Due to various research starting points, they have different emphases. This paper divides the influencing factors into engineering and geological conditions, hydrogeological conditions and mining methods. Taking Yulin-Shenmu mining area as the research background, this paper analyzes the influencing factors from the above three aspects. Then the analytic hierarchy process is used to calculate the weight of each factor. The results could provide references for the water-conserving mining of coal mines in northwest China.

2 Multilevel structural model

The influencing factors of water-conserving mining are analyzed from the aspects of engineering and geological conditions, hydrogeological conditions and mining methods. A four-level structure model has been established.

2.1 Engineering and geological conditions

2.1.1 Overlying strata thickness

The relative relation between the overlying strata thickness and the development height of water flowing fractured zone directly determines whether water resource losses will occur due to mining (Zhang and Peng 2005).

2.1.2 Lithology of overlying strata

The soft rock strata have better water-resisting effects, such as clay, the flexible rock with high shale content, strata with good consolidation and undeveloped cracks and karst (Chai and Li 2014).

2.1.3 Physical and mechanical properties

The physical and mechanical properties mainly refer to the rock's bulk density and strength. When the coal seam roof has certain intensity, the fractured blocks after caving could more easily interact and form the structure with certain bearing capacity, thus reducing the deformation and failure degree of the overlying strata and the final development height of the water flowing fractured zone.

2.1.4 Strata combination

The water-resisting strata composed of hard and soft strata are helpful to resist the integrative action of mine pressure and water pressure and could be key water-resisting strata (Miao et al. 2007).

2.1.5 Geological structure

(1)   The fault

The faults could damage the integrity of the rock and influence the mechanical properties. The faults in overburden make the development height of the water flowing fractured zone larger than that in normal areas, which is not good for safety underwater mining (Huang et al. 2009). Generally, the fault density, length and throw index are needed to comprehensively describe the fault (Meng et al. 2000).

The fault density q_1 refers to the number of faults in the unit area.

$$q_1 = n_1/s, \text{ number/km}^2$$

where n_1 refers to the number of faults in the block, and s refers to the area of the block, m^2.

The fault length q_2 refers to the total length of the faults in the unit area of the block.

$$q_2 = \sum_{i=1}^{n} l_i/s$$

where l_i refers to the length of the ith fault, m. The fault throw index q_3 refers to the ratio of fault throw h to the mining height of the coal seam. To better discriminate the index, the logarithmic function of coal seam mining height could be used to amend the q_3.

$$q_3 = \frac{1}{n_1} \sum_{i=1}^{n} \frac{h_i}{m} \times \frac{1}{\ln(m+1)}$$

where h_i refers to the fault throw, m, and m refers to the mining height of the coal seam, m.

(2)　The folds

The folds could affect strata movement to certain extent (Sun et al. 2007). The quantitative index of fold development degree could be described by deformation coefficient, that is the fold section coefficient and fold plane coefficient (Yuan et al. 1992).

2.2 Hydrogeological conditions

2.2.1 The aquifers

(1)　Recharge

If the recharge source is meteoric water or surface runoff, the recharge rate will change with the season and climate.

(2)　Thickness

The aquifer thickness is directly related to storage capacity and thus influence the classification of water abundance (Ma et al. 2013).

(3)　Permeability coefficient

As the permeability coefficient increases, the storage capacity and receiving capacity will enhance (Ma et al. 2013). The permeability coefficient k is also called hydraulic conductivity. It is defined as the unit flow under a unit hydraulic gradient.

$$K = k\frac{\gamma}{\mu}$$

where k refers to the permeability of rocks, md; γ refers to the bulk density of water, kN/m^3; μ refers to the dynamic viscosity of the water, N s/m^2.

(4)　Groundwater depth

The shallow groundwater has a significant impact on ground ecosystem (Ma et al. 2017; Wang et al. 2013) and is the primary objects of protection during the water-conserving mining.

(5)　Water-level difference of vertically adjacent aquifers

The vertically adjacent multilevel aquifers have some hydraulic connections and the water level is close. The water-level changes during the mining could lead to cross flow between adjacent aquifers (Li et al. 2017a, b).

2.2.2 The aquifuge

(1)　Thickness

The effective thickness of the aquifuge could directly affect the water-resisting capacity (Ma et al. 2015).

(2)　Horizon

The greater the distance between the aquifuge and the coal seam, the smaller the influence of mining will be, and the water-resisting capacity could be kept maximum.

(3)　Water-physical properties

The water-physical properties of the aquifuge mainly include the permeability coefficient, expansibility and water sensitivity. The rock strata with smaller permeability coefficient tend to have better water-resisting capacity. The strata with bigger expansibility are prone to swelling after absorbing water, which is helpful for reclosing of rock fractures and recovery of water-resisting capacity (Li et al. 2017a, b). When the rock has strong water sensitivity, its strength will be reduced and tend to be muddy after being soaked with water. The fractures in rock strata could easily close and the water-resisting capacity increases greatly.

2.3 Mining methods

2.3.1 Mining methods

The selection of mining methods could affect the final development height of the water flowing fractured zone (Kang 1998). Under the same conditions as others, the slice mining could effectively reduce the development height compared with the method of mining all height at one time (Fan et al. 2015).

2.3.2 Mining parameters

(1)　The effective mining height

The mining height is the most direct and important influencing factor of the development height of the water flowing fractured zone. At present, the widely used empirical formula is fixed by taking the height of the water flowing fractured zone as the parameter (Shi et al. 2012).

Table 1 Evaluation table of the relative weight

Engineering-geological conditions $B1$	Thickness $C1$	Lithology $C2$	Physical and mechanical properties $C3$	Strata combination $C4$	Geological structure $C5$
Thickness $C1$	1	1	1	3	5
Lithology $C2$	1	1	1	3	5
Physical and mechanical properties $C3$	1	1	1	3	5
Strata combination $C4$	1/3	1/3	1/3	1	5
Geological structure $C5$	1/5	1/5	1/5	1/5	1

(2) Mining depth

As the mining depth increases, the ground pressure also increases, thus making the overburden movement scale increase and promoting the development of water flowing fractured zone (Shi et al. 2012).

(3) Advance velocity

The integral subsidence of the overburden is nearly proportional to the advance velocity of the working face. The faster the advance velocity, the more gently the subsidence basin will be. The maximum dynamic deformation of overburden movement will decrease as the working face advances (Ma et al. 2014).

(4) Inclination of the working face

During the inclined mining, the roof will slip along the inclination after caving, thus making the height of the water flowing fractured zone increase significantly (Li et al. 2015).

(5) Working face dimensions

The height of the overburden water flowing fractured zone will increase as the working face advances. After reaching the full mining, the water flowing fractured zone will stop upward developing (Ma et al. 2011).

(6) The stability of coal pillars

The stability of coal pillars could directly affect the movement and deformation of overburden supported and controlled by coal pillars. The coal pillar stability is determined by its sizes and mechanical properties of the coal.

3 Weight of influencing factors

3.1 Analytic hierarchy process

The analytic hierarchy process (AHP) is a multi-criteria decision method involving both quantitative and qualitative

analysis (Wu et al. 2011). It could be used to calculate the weight of influencing factors of water-conserving mining. The specific steps are as follows:

(1) The determination of influencing factors
$U = \{u_1, u_2, \ldots, u_n\}$

(2) Judgement matrix construction

With the 1–9 and their reciprocals scale method, the relative importance of each element could be reflected by fixing the values of the judgement matrix elements. The specific values in line with the actual mining conditions could be used to show the importance of factor comparison. The specific values should be fixed by the corresponding factors of the judgment matrix, that is $S = (u_{ij})_{n \times n}$. Table 1 shows the relative weight evaluation of sub-factors of primary factors of engineering and geological conditions by an expert. The judgment matrix is also obtained.

$$S_{B1} = \begin{vmatrix} 1 & 1 & 1 & 3 & 5 \\ 1 & 1 & 1 & 3 & 5 \\ 1 & 1 & 1 & 3 & 5 \\ 1/3 & 1/3 & 1/3 & 1 & 5 \\ 1/5 & 1/5 & 1/5 & 1/5 & 1 \end{vmatrix}$$

(3) Judgment matrix calculation

The weight coefficients could be determined by calculating the largest eigenvalue of S $\lambda_{\max}$ and the corresponding eigenvector A.

The largest eigenvalue $\lambda_{\max}$ of SB1 is 5.1544 and the corresponding eigenvector A = (0.2763, 0.2762, 0.2762, 0.1238, 0.0470).

(4) Consistency check

The consistency indicator $CI = \frac{\lambda_{\max} - n}{n - 1}$ and the random consistency index $CR = \frac{CI}{RI}$ are obtained, where RI is the average random index. When $CR < 0.1$, the sorting of judgment matrix elements has consistency, that is, the weight distribution is reasonable. When $CR \geq 0.10$, the

Table 2 Influencing factors and the weights of water-conserving mining

Compound factor weight B		Sub-factor weight C		Sub-factor weight D		Sub-factor weight E	
1. Engineering and geological conditions B1	0.347	(1) Overburden thickness C1	0.096		0.096		0.096
		(2) Lithology C2	0.070		0.070		0.070
		(3) Physical and mechanical properties C3	0.084		0.084		0.084
		(4) Strata combination C4	0.080		0.080		0.080
		(5) Geological structure C5	0.017	(1) Faults D1	0.013	(1) Fault density E1	0.006
						(2) Fault length E2	0.003
						(3) Fault throw index E3	0.004
				(2) Folds D2	0.004	(1) Fold section coefficient E4	0.0022
						(2) Fold plane coefficient E5	0.0018
2. Hydrogeological conditions B2	0.539	(1) Aquifer C6	0.202	(1) Recharge D3	0.082		0.066
				(2) Thickness D4	0.040		0.032
				(3) Permeability parameters D6	0.039		0.031
				(4) Groundwater depth D7	0.016		0.013
				(5) Vertically adjacent aquifers water difference D8	0.026		0.021
		(2) Aquifuge C7	0.337	(1) Thickness D9	0.179		0.179
				(2) Horizon D10	0.031		0.031
				(3) Water-physical properties D11	0.127	(1) Permeability E6	0.071
						(2) Expansibility E7	0.033
						(3) Water sensibility E8	0.023
3. Mining method B3	0.114	(1) Mining methods C8	0.019		0.019		0.019
		(2) Mining parameters C9	0.095	(1) Effective mining height D15	0.067		0.067
				(2) Working face inclination D16	0.0076		0.0076
				(3) Mining depth D17	0.0085		0.0085
				(4) Advance velocity D18	0.004		0.004
				(5) Working face dimensions D19	0.003	(1) Inclination length E9	0.002
						(2) Strike length E10	0.001
				(6) Coal pillar stability D20	0.006	(1) Coal pillar sizes E11	0.0032
						(2) Coal mechanical properties E12	0.0028
Total	1.0	Total	1.000	Total	1.0000	Total	1.0000

sorting and values of elements should be adjusted and the weights need to be redistributed.

The CI of S_{B1} is 0.0386. The average RI of fifth-order matrix is 1.11 (Saaty and Ozdemir 2003). Then $CR =$ $0.0386/1.11 = 0.0348 < 0.10$, indicating that the weight distribution is reasonable. The weight of engineering and geological conditions in three primary factors is 0.347. Then $0.347 * A = (0.0959, 0.0959, 0.0959, 0.0429, 0.0164)$, which is the final weight of the five secondary factors among the primary factors given by the expert.

3.2 Weight calculation

Many experts and scholars engaged in water-conserving mining have been invited to evaluate the importance of influencing factors at all levels. The AHP is used to analyze and calculate their weights. Table 2 shows the average values of weights of the influencing factors.

(1) Among the three primary influencing factors B1 (engineering and geological conditions), $B2$ (hydrogeological conditions) and $B3$ (mining methods), $B2$ is the most important, followed by $B1$ and $B3$.

(2) Among the secondary factors of $B1$ (engineering and geological conditions), C5 (geological structure) has the minimum weight, and the weights of $C1$ (thickness), $C2$ (lithology), $C3$ (physical and mechanical properties) and $C4$ (strata combination) are actually close.

(3) Among the secondary factors of $B2$ (hydrogeological conditions), the weight of the aquifuge $C7$ is larger than the aquifer $C8$. Among the third-tier factors of $C7$, the thickness $D9$ has the maximum weight.

(4) Among the secondary factors of mining methods $B3$, the weight of the effective mining $D15$ is obviously bigger than other factors, which is consistent with the result obtained by the traditional height empirical formula of the water flowing fractured zone, which chooses mining height as a parameter.

4 Discussions

Some influencing factors of water-conserving mining could be described quantitatively, such as the overburden thickness, while some factors could only be described in qualitative. While some factors could only be described in qualitative, such as strata combination. In the following studies, the fuzzy mathematical method will be used to provide normalized data for those indexes which are difficult to describe quantitatively. Then the objective weighting methods will be combined to provide more scientific weight distribution of water-conserving mining influencing factors.

5 Conclusions

(1) A four-level structure model of water-conserving mining has been established. The model includes three primary factors (engineering and geological conditions, hydrogeological conditions and mining methods), nine secondary factors such as the overburden thickness, sixteen third-tier factors such as the water-physical properties of the aquiclude and twelve fourth-layer factors such as coal pillar sizes.

(2) The analytic hierarchy process (AHP) is used to construct the judgement matrix and the weight of each influencing factor has been obtained.

(3) The overburden thickness, the aquiclude and the mining methods are the most important secondary factors among the engineering and geological conditions, hydrogeological conditions and mining methods, respectively.

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