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Vulnerability Measurement of Groundwater Inrush Channel in Mining Areas and Environmental Governance Measures – A Case Study on Taoshan Mine, China

Wei Xiao Gang*(**), Dai Jun Wu*, Li Guang Hui†, Hu Zhi Kai*** and Qin Sai*****

*Key Laboratory of Earthquake Engineering and Engineering Vibration, Institute of Engineering Mechanics, China Earthquake Administration, Harbin 150080, China

**College of Civil Engineering and Architecture, Zhengzhou University of Aeronautics, Zhengzhou 450046, China

***Kexing Construction Engineering Group Co., Ltd., Zhengzhou 450046, Henan, China

†Corresponding author: Li Guang Hui: 15136136550@163.com

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ABSTRACT

The unrestricted resource behaviour of mines has caused considerable geological environmental problems. Specifically, the increasing water-induced accidents in mines affect safety production and environmental safety in coal mines. To further decrease water inrush disasters to the maximum extent, vulnerability assessment of groundwater inrush channel in coal mines has become a primary problem of chain-cutting disaster mitigation. In this study, first, influencing factors against formation and project of water inrush channel in coals were analyzed comprehensively. Second, 14 indexes, which influence the vulnerability of the water inrush channel, were selected from three perspectives of coal seam features, coal quality features, and hydrogeological features. A case study based on data of 56# coal seam and 68 coal seam of Taoshan Mine, China was carried out. The vulnerability of the groundwater inrush channel in the Taoshan Mine was estimated by analytic hierarchy process (AHP) and fuzzy comprehensive evaluation. Results demonstrate that coal quality features, hydrogeological features, and coal seam features are major factors that influence the vulnerability of the water inrush channel. Among them, coal quality features contribute 48.36% of explanations to the vulnerability of the water inrush channel. According to the vulnerability grade evaluation results of fuzzy mathematics, the membership degree of belonging to "III" was 0.3731, which was the highest. This finding indicates that the vulnerability of the water inrush channel in Taoshan Mine belongs to grade III, which is a moderate state. Research conclusions have important references to perfect the evaluation index system for the vulnerability of water inrush channel in coal mines, provide early warning analysis of water inrush disasters in coal mines, and realize the mining–environmental protection coordinated development.

INTRODUCTION

China has tremendous coal mines. The ecological environment in coal mines is damaged seriously. Geological environmental protection and governance of coal mines are a large system project, which is characterized by a long period, large task, and complicated problems. Thus far, China has not issued a perfect geological environmental governance system of coal mines, divided the geological environmental protection and governance in coal mines clearly, and released relevant technological standards at an appropriate time. The geological environmental protection and governance of coal mines still cannot be balanced. With the long-term development of coal resources, excessive mining phenomena occur, thereby causing a series of environmental and geological problems, such as water and soil pollution, land resource damages, geomorphologic landscape damages, and collapse of water inrush channel. Recently, China has never stopped evaluations on the geological environmental impacts of coal mines. Systematic evaluations of geological environmental problems of coal mines by introducing scientific and reasonable evaluation systems can not only provide technical support to management planning of coal mines and solve environmental problems in coal mines but also are one of the important topics of modern environmental geological studies.

In particular, water inrush accidents in coal mines have been increasing continuously. To realize essential safety and decrease disasters to the maximum extent, studying water diversion structures of the disaster causing ring in the coal disaster chain has become a primary problem to chain-cutting disaster mitigation. With the increase in exploitations in complicated and difficult-to-mine coal bodies, the underground hydrogeological conditions become more complicated. Traditional flooding disaster control technology of coal mines cannot adapt to new exploitation environment and deviate from the engineering practices. New detection technology and method are necessary. The vulnerability of water inrush channel of coal mines refers to the possibility of disaster activation of the geological physical environment and engineering response features of water diversion structures in strata when the water inrush channel is used as the carrier and mining face approaches the underground water source as well as the difficulties of system recovery after the disaster. An evaluation index system for the vulnerability of water inrush channel in coal mines was established. The higher vulnerability grade indicates that disasters can easily occur in coal mines, and specific defence measures are required.

PAST STUDIES

Studies on the vulnerability of water inrush channel in coal mines are relatively weak. In engineering practices, the concept of vulnerability assessment is introduced for rapid, reliable, and comprehensive detection of water inrush channel. Vulnerability, as an important index to measure risk performance, characterizes the ability of the system to resist disasters and maintain stability, including adaptability, risks, and restorability. Janssen et al. (2006) introduced the relevant concept of environmental vulnerability in the global environment changes for groundwater vulnerability, the vulnerability of water inrush channel in coal mines and comprehensive environmental governance in coal mines. Wu et al. (2008) believed that in Northern China, coal exploitation was often influenced by groundwater inrush from underground karst aquifer, established a geographical information system (GIS) for water inrush vulnerability evaluation, and determined weight coefficients of different influencing factors by using the artificial neural network. Qiang et al. (2009) believed that water inrush was a geological disaster that influenced coal mine safety production in China seriously. Based on powerful spatial data analysis functions of GIS, they established a neural network model of water inrush risk assessment and carried out a case study by using the water inrush vulnerability index histogram. Rupert (2010) corrected the point rating scheme based on practical groundwater quality data to improve the validity of the underground water vulnerability map significantly by using the parameter statistical technology and geological information system. Qiang et al. (2011) pointed out that water inrush from seam floor was a complicated nonlinear phenomenon, and it was controlled by various factors. In addition, a case study based on data of three coal seams in Tashan Mine, China was carried out using the vulnerability index method of GIS. Research results demonstrated that the vulnerability index method of GIS had many potential advantages in evaluating the possibilities of water inrush. Fijani et al. (2013) proposed a model based on artificial intelligence to improve the groundwater vulnerability evaluation method of the aquifer in Maragheh–Bonab Plain, Iran. Qiang et al. (2013) believed that water inrush disasters influenced the safety production of many coal mines in China, explored influencing factors of water inrush by AHP, established a vulnerable index histogram, and proposed control measures to each risk grade. Based on the south region of Perak, Malaysia, Mogaji et al. discussed the groundwater vulnerability prediction model by using the ordered weighted average DRASTIC (The term "DRASTIC" stands for seven parameters in the model which are depth to groundwater table (D), net recharge (R), aquifer media (A), soil media (S), topography (T), impact of vadose zone (I), and hydraulic conductivity (C) method of GIS (Mogaji et al. 2014). Xiao et al. (2014) estimated water inrush evaluation of seam floor in 9# coal seams of Shanxi Liulin Hongsheng Jude Coal Industry Co. Ltd. through the vulnerability index analysis. They compared the evaluation results with the results of the traditional water inrush coefficient evaluation technique. The results demonstrated that the vulnerability index method, which considered various factors, was more advantageous. Liu et al. (2014) proposed an AHP vulnerability index method based on GIS to evaluate the water inrush phenomenon of many aquifers in seam floor under complicated hydrological conditions and used it to evaluate the water inrush vulnerability of aquifers in a coal mine. The results demonstrated that the proposed method solved the water inrush indication problem of seam floor under complicated hydrogeological conditions. Li et al. (2014) established a vulnerability index model of water inrush channel of coal mines according to the coupling theory of GIS and AHP, evaluated the probability of water inrush in major minable seam roof and floors of the well field, and proposed suggestions for safety production and water disaster control. Abdullah et al. (2015) designed the groundwater pollution vulnerability diagram by using the standard DRASTIC method and applied the linear structural density diagram into the standard DRASTIC model to assure the accuracy of effects of potential pollution vulnerability. Wu et al. (2015) evaluated the water inrush vulnerability of aquifer in Mengkeqing Mine, predicted mine inflow under natural conditions and mining conditions, and proposed corresponding control measures. Li et al. (2016) evaluated water inrush risk in mines by hydrochemical method and evaluated water inrush risk by analyzing concentrations of conservation ions through detailed hydrochemical investigation and sampling. Wu, Qiang et al. (2017) believed that hydraulic pressure and water yield of the aquifer, equivalent thickness of the water-resistant layer, and geological structural property are the main factors to control water inrush; they evaluated water inrush risks by vulnerability index (VI) method by combining GIS and AHP. Based on existing studies, the vulnerability of the water inrush channel of coal mines is developed and perfected with the comprehensive environmental governance of coal mines gradually. The possibility of disaster activation of the geological physical environment and engineering response characteristics of water diversion structure in rock strata as well as difficulties of system recovery after a disaster are influencing factors of vulnerability of water inrush channel in coal mines. Hence, an index system for the vulnerability of water inrush channel in coal mines was set up by combining the development law of water inrush channel, incidence on the underground project after disasters, and difficulties in governance technology. This index system was used to evaluate the vulnerability grade of the water inrush channel, and some specific defence measures were adopted. These concepts have extremely important effects on guaranteeing safe production and realizing environmental protection of coal mines. The vulnerability of the water inrush channel of coal mines was assessed based on existing studies. Evaluation indexes of the vulnerability of water inrush channel in coal mines were determined, and an index system was constructed. The weights of influencing factors were concluded by AHP, and vulnerability grade was judged by combining fuzzy mathematics. Finally, specific comprehensive environmental protection measures of coal mines were proposed.

MODEL AND INDEX SYSTEM

Fuzzy Hierarchy Comprehensive Evaluation Method

Fuzzy hierarchy comprehensive evaluation is used to quantize the fuzzy indexes of the evaluated object by constructing a grade fuzzy subset (this approach determines the degree of membership). Then, various indexes are combined by the fuzzy transformation principle.

First, the domain of discourse of factors of the evaluated object was determined; it refers to the P evaluation index, as follows:

$$u = \{u_1, u_2, \cdots\cdots, u_p\} \quad \ldots(1)$$

Second, the domain of discourse of comment grades was determined, as follows:

$$v = \{v_1, v_2, \cdots\cdots, v_p\} \quad \ldots(2)$$

After constructing the grade fuzzy subset, evaluation factors u_i ($i = 1, 2, \ldots, p$) of the evaluated object are quantized one by one. In other words, the degree of membership ($R|u_i$) of the evaluated object to the grade subset was determined from a single factor to obtain the fuzzy relation matrix, as follows:

$$R = \begin{bmatrix} R| & u_1 \\ R| & u_2 \\ \cdots & \\ R| & u_p \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ r_{p1} & r_{p2} & \cdots & r_{pm} \end{bmatrix} \quad \ldots(3)$$

In the matrix R, the element in the row i and column j (r_{ij}) indicates the degree of membership of the evaluated object to the grade fuzzy subset (v_j) from the factor (u_i). The performances of the evaluated object on u_i is depicted through the fuzzy vector $(R|u_i) = (r_{i1}, r_{i2}, \ldots, r_{im})$ by the actual value of one index in other evaluation methods. Finally, the weight vector of the evaluation factors was determined. In the fuzzy comprehensive evaluation, the weight vector was determined as follows:

$$A = (a_1, a_2, \ldots\ldots, a_p) \quad \ldots(4)$$

In Eq.(3), element a_i in the weight vector A is the degree of membership of factor u_i to the fuzzy subset (important factors to the evaluated object). The relative importance sequence of evaluation indexes was determined by AHP; thus, the weight coefficient can be obtained. All evaluation indexes were normalized before synthesis. $\sum_{i=1}^{p} a_i = 1,\ a_i \geq 0,\ i = 1, 2, \cdots\cdots, n$. A and R of the evaluated objects were synthesized by using an appropriate operation, through which the vector of fuzzy comprehensive evaluation results (B) of the evaluated objects were obtained.

$$A \times R = (a_1, a_2, \cdots\cdots, a_p) \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ r_{p1} & r_{p2} & \cdots & r_{pm} \end{bmatrix} = (b_1, b_2, \cdots\cdots, b_m) = B \quad \ldots(5)$$

where b_i is obtained from operation of A and column j of R. It expresses the degree of membership of the evaluated object to the grade fuzzy subset v_j, in general.

Index System

Influencing factors of the vulnerability of water inrush channel in coal mines were summarized based on academic studies on permeability law of water inrush formation and engineering practice experiences. Meanwhile, an index system of the vulnerability of groundwater inrush channel in Taoshan Mine was proposed, considering the possibility of available index data (Table 1).

Indexes are divided into qualitative indexes and quantitative indexes in studies on the vulnerability of groundwater inrush channel in coal mines. The qualitative indexes in Table 1 contain mine ventilation system, coal seam stability, water-resisting layer, water filling characteristics, number of coal seams, and fault nature. The data of all six indexes were statistical evaluation results through a questionnaire survey of geological experts and research members. The data of the remaining quantitative indexes were collected from the geological survey and research reports in Taoshan Mine.

EMPIRICAL STUDY

Taoshan Mine is located in the eastern regions of the Western

Table 1: Index system of the vulnerability of groundwater inrush channel in coal mines.

Level-1 indexes	Level-2 indexes	Units	Variable No.
Coal seam features	Mine ventilation system	State grade	X1
	Relative gas emission volume	m^3/t	X2
	Coal seam stability	State grade	X3
	Coal seam thickness	m	X4
Coal quality features	Water content	Ma%	X5
	Ash content	Ad%	X6
	Volatile content	V_{daf}%	X7
	Gel layer	Ymm	X8
	S	St,d%	X9
	P	Pd%	X10
Hydrogeological features	Water-resisting layer	State grade	X11
	Water filling characteristics	State grade	X12
	Number of coal seams	State grade	X13
	Fault nature	State grade	X14

Production Zone in Qitaihe Mine, and the administrative region is classified to Taoshan District, Qitaihe City. Taoshan mine is bordered at Taoshan Fault in the east, and it is adjacent to the Xinfu Mine. In the coal mine, the striking length and inclined width were approximately 5 and 5 km, respectively. The inclined area and the area of mining right were approximately 25 and 22.9952 km^2, respectively. On the north edge, railways run through the Qitaihe Station, connect to the National Railway, and extend all regions in China. Highways extend to Yilan, Kiamusze, Jixi, Baoqing, Mishan and Harbin, and Duisu Port. Hence, the traffic conditions are very convenient. The mine exploitation began in 1958. The disk deviation well group was adopted, followed by technological reconstruction and construction. In the coal mine, the total thickness of the coal-bearing seam was approximately 1470 m, which covers 65 coal seams, and the average total thickness of coal seams was 38 m. The coal-bearing coefficient was 2.6%. The 56# coal seam and 68# coal seam were selected as the research object for fuzzy comprehensive evaluation of the vulnerability of water inrush channel.

Determination of the Weight of Evaluation Indexes Based on AHP

AHP transforms the semiqualitative and semiquantitative problems into quantitative computation by constructing a pairwise matrix, calculating weight vectors, consistency test, and weight sequencing, and making a comprehensive judgment on weights of evaluation indexes of water inrush channel. When selecting evaluation indexes, the principle of reflecting the primary and the most comprehensive information by the least indexes should be observed. An index system of the vulnerability of groundwater inrush channel was constructed based on the principle of AHP (Saaty et al. 1985). Calculation results are listed in Table 2.

Table 2 shows that coal quality features, hydrogeological features, and coal seam features can influence the vulnerability of the water inrush channel significantly. The coal quality features contribute 48.36% of the explanation to the vulnerability of the water inrush channel. The upper 40–48 coal seams in Taoshan Mine belong to the semi-bright coals, which are mainly dominated by bright coals. Bright coals have glassy lustre, stripped structure, endogenous fracture development, and high vulnerability. The middle 55–79 coal seams belong to semi-bright coals and semidark coals in stripped and lamellar structures. Massive structures account for a high proportion, and the coal seams have a large amount of internal dirt. Hydrogeological features contribute 34.87% of the explanation to the vulnerability of the water inrush channel. Taoshan mine has many small rivers and valleys, and it belongs to an aged river. After several diversion, the watercourse twists and turns, forming many cutoff lakes. The river width is 20-30 m, the water depth is approximately 4 m, and the maximum flooding water level is 165 m. Large and small gobs below the groove are superficial, and the surface soil is thin; thus, the water filling in the ore bed is affected to some extent, easily causing vulnerability of water inrush channel. Moreover, surface water bodies are a water filling factor in Taoshan Mine; they are mainly catchments during rainy seasons in several valleys. Surface runoffs penetrate underground through surface collapse pits in the gob and can influence water filling in coal mines. Coal seam features contribute 16.77% of the explanation to the vulnerability of the water inrush channel. Recently, Taoshan mine manage-

Table 2: Weights of Indexes of the vulnerability of water inrush channel.

Variable No.	Name of variables	Level-1 weights	Level-2 weights	Total weights
X1	Mine ventilation system	0.1677	0.1113	0.0187
X2	Relative gas emission volume		0.0674	0.0113
X3	Coal seam stability		0.5329	0.0894
X4	Coal seam thickness		0.2884	0.0484
X5	Water content	0.4836	0.1590	0.0769
X6	Ash content		0.1845	0.0892
X7	Volatile content		0.1983	0.0959
X8	Gel layer		0.0494	0.0239
X9	S		0.1554	0.0751
X10	P		0.2535	0.1226
X11	Water-resisting layer	0.3487	0.1399	0.0488
X12	Water filling characteristics		0.4551	0.1587
X13	Number of coal seams		0.0723	0.0252
X14	Fault nature		0.3327	0.1160

ment agency has focused on safety management and adopted centralized inflow and zoned ventilation measures. The gross installed capacity of the major fan is 1615 kW. The total air inflows in the entire coal mine are 13100 m^3/min, and the total ventilation volume is 1435 m^3/min. The effective wind volume in the entire mine is 92%. As a result, the possibility of gas explosion is decreased. The level-2 weight of coal seam stability (X3) is 0.5329, which has occupied more than half of the weights of the level-1 index coal seam features. The reason is that the total coal seam thickness in wells is approximately 1470 m, which covers 65 coal seams. The average total thickness of the coal seam is 38 m, and the coal-bearing coefficient is 2.6%. The coal seam features have four stable coal seams and four relatively stable coal seams, and the remainder includes unstable coal seams.

Vulnerable Grade Evaluation Based on Fuzzy Mathematics

The fuzzy mathematics maximum membership principle was used to evaluate the vulnerability of the water inrush channel and obtain specific and explicit ambiguous problems. A comprehensive fuzzy mathematics model was constructed. In accordance with the index system and quota of the indexes, the standard eigenvalues of five levels of indexes were recognized, thereby obtaining the standard eigenvalue matrix A. Subsequently, fuzzy evaluation was implemented. The fuzzy subset was evaluated by combining the weights of AHP and the membership matrix. The principle of obtaining the larger product was used. After normalization, the maximum was selected as the evaluated grade of the vulnerability of the water inrush channel according to the maximum fuzzy mathematics membership principle. According to Eqs. (1)-(4), the fuzzy evaluation matrix of level-1 indexes was as below.

$$\begin{bmatrix} 0.3970 & 0.4234 & 0.0966 & 0.0257 & 0.0573 \\ 0.1367 & 0.1657 & 0.4775 & 0.2046 & 0.0155 \\ 0.2315 & 0.3243 & 0.3613 & 0.0829 & 0.0000 \end{bmatrix}$$

According to Eq. (5), the comprehensive fuzzy evaluation vector was [0.2134 0.2642 0.3731 0.1322 0.0171]. The results show that the five numbers are memberships of the vulnerability of water inrush channel to "I, II, III, IV and V", and the membership to "III" is 0.3731, which is the highest. Hence, the maximum membership principle indicates that the vulnerability of the water inrush channel in Taoshan mine belongs to Grade III, indicating the moderate state of vulnerability of the water inrush channel in Taoshan mine.

POLICY SUGGESTIONS

Strengthening Geological Environmental Monitoring in Coal Mines

Strengthening geological environmental monitoring and management in coal mines. A responsibility system shall be implemented for geological environmental restoration in coal mines. The principle that the party that explores coal mines is held responsible for the protection and the party that destroys the coal mines is responsible for governance shall be observed. Responsibilities of all links shall be implemented thoroughly, and a management mechanism and system shall be established and perfected to strengthen monitoring and management of all coal mines, especially those that are destroyed seriously. Thus, regulations on the protection and governance of coal mines are developed. The monitoring of geological environmental restoration and governance in coal mines shall be strengthened. Relevant departments shall increase supervision and verification of mining application, expanding secondary mining scale and changing the mining mode. Mining protection and governance restoration scheme shall be formulated. Mining closing, mining termination, and land reclamation can only be implemented after acceptance by relevant departments.

Improving Environmental Engineering Governance of Coal Mines

Barren rocks at open mining edges are cleaned. Two sides are solidified, and the surface is greened. On one hand, catchwater should be constructed on top of mountains to stop water flow into the stope and further cause groundwater pollutions or trigger geological disasters. On the other hand, the land use scope of mining activities must be restricted. Land resources shall be used reasonably and standardly, and all random stacking phenomena shall be eradicated. Waste residues, which are produced in the mining process, are used scientifically, and resource recycling is realized. When coal mines are closed, waste residues can fill in the stope to prevent pollution from the source. The green vegetation in the mining area that protects some vegetation transplantation shall be adopted in the mining process rather than deforestation. This approach can prevent excessive vegetation damages, thereby causing great disasters. Moreover, trees and grasses shall be planted appropriately, the green area shall be expanded in the coal mine, and the vulnerable ecological problem in the mining area must be eliminated. After coal exploitation, a large-area gob can cause floor cracks, surface collapse, and settling. The collapse and fractures shall be filled up timely, and large-area settlement shall be flattened timely.

Strengthening Technological Content of Environmental Protection in Coal Mines

Details are introduced as follows: (1) increasing efforts in research and development of deep processing of mineral resources, expansion of peripheral industrial chains of mineral resources, and increasing mining products; (2) enriching deep processing technology of mineral resources and extending industrial chain; (3) adjusting mineral exploitation technology and introducing the automatic and scientific mineral mining system; (4) improving management level, decreasing number of operation posts, and attempting to realize unmanned mineral exploitation comprehensively; (5) promoting green clean mineral industrial development positively, shutting down mines with resource wastes and severe pollutions through technological reforms, optimizing management, and improving standards; (6) adopting comprehensive governance, controlling energy and water resources, which are collected from coal mines, performing full-process monitoring on wastes and emissions during mining activities, increasing monitoring strength, and urging enterprises to reform green clean mineral industries; (7) promoting green clean mining technologies positively and applying the philosophy of green cleaning mining industry into mining, transportation, and processing of coal mines.

CONCLUSIONS

Excessive or disordered coal resource exploitation leads to occurrences of geological disasters in coal mines, such as collapse, landslide, debris flow, and surface collapse. The ecological environment in mining areas and surrounding areas are worsened and the ecosystem is degenerated due to vegetation damages. Water inrush in coal mines is a typical natural disaster, which negatively affects normal production and environmental protection of coal mines. Influencing factors of formation and project of water inrush channel in coal mines are analyzed. Then, 14 indexes that influence the vulnerability of the water inrush channel are selected. A case study based on data of 56# and 68# coal seams in Taoshan Mine, China is carried out. The vulnerability of the water inrush channel is estimated by AHP and fuzzy comprehensive evaluation. Results demonstrate that coal quality features influence the vulnerability of water inrush channel mostly, followed by hydrogeological features and coal seam features successively. The vulnerability grade evaluation results of fuzzy mathematics suggest that the membership of “III” is 0.3731, indicating that the Taoshan Mine belongs to “III” in terms of vulnerability of the water inrush channel. This reflects that the vulnerability of the water inrush channel of Taoshan mine is in a moderate state. Finally, three governance measures of strengthening geological environmental monitoring, improving environmental governance, and increasing technological content for environmental protection in coal mines are proposed. In-depth studies on enriching influencing factors of vulnerability of water inrush channel, geological environmental comprehensive evaluation, and recovery and governance of geological disasters in coal mines are required in the future.

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