Influence of Karst Collapse Column on Coal Mine Safety Mining - A Case Study of the Yangjian Mine in Shuozhou Mining Area, Shanxi Province, China

Zhimin Xu, Yajun Sun, Shang Gao, Hongying Chen, Minghao Yao

School of Resources and Geosciences, China University of Mining and Technology, Xuzhou, 221116, China, e-mail: xuzhimin@cumt.edu.cn

Abstract

Karst collapse columns are a special geological body, commonly found in the Carboniferous-Permian coalfields in northern China and posing a major hazard to mine safety. Mining activity near the collapse columns, especially ones that conduct water, can cause serious water inrush accidents, causing heavy casualties and property losses. To assess the influence of karst collapse columns on coal mining safety, the case of the Yangjian Coalmine in Shuozhou, Northern Shanxi Province, China is investigated. Five collapse columns were detected in Panel 90102 during tunnel excavation and advanced exploration. The extent of karst development, the water-bearing conditions and the conductive state of the columns, as well as the composition and physical properties of the rocks, were explored. Then the hydrogeological characteristics of the five collapse columns were summarized. Based on analysis of the water pressure of the Ordovician limestone aquifer and the thickness of the aquiclude, the influence of each collapse column on the safe mining of Panel 90102 was evaluated. To mitigate the water inrush threat from the collapse columns, a drilling and grouting reinforcement treatment for two water-conducting columns were implemented to block the Ordovician aquifer water from flowing onto the mine floor. This approach improved the safety of the mining operation in Panel 90102.

Keywords: karst collapse column; coal mining; floor water inrush; comprehensive prospecting; grouting

Introduction

Coal is a commonly used energy source in China and the country's coal deposits are extensively mined. Mining operation safety is an important issue, one of the hazards being water inrush in the coal panel floor. In the coal mines of northern China, the Ordovician limestone aquifer is the main aquifer affecting the coal seams; this aquifer has a high artesian head and the water flow is controlled by faults and karst collapse columns. Mining activities can transform the aquifer into an underground watercourse for the water-bearing rock of the base plate, endangering mine safety. (Wu et al. 2016) Statistical data shows that karst collapse columns exist in 45 coal mines in more than 20 large coal fields in China. The disaster in the Fangezhuang Coalmine in Kailuan is an example of the dangers of karst collapse columns. Due to the exposure of the collapse column, the most serious water inrush accident in the history of the world's coalmining occurred in panel 2171 of the mine in 1984. The maximum water inflow into the mine was 123,180 m^3/h, and three nearby coalmines were flooded. This resulted in direct economic losses of more than 1 billion yuan, and the loss of coal production of nearly 8.5 Mt. (Zhong. 2001) Another water inrush accident occurred on March 1, 2010 in the Luotuoshan coalmine, located in Wuhai, Neimenggu Province. This was a result of the exposure of a hidden subsided column during the excavation of coal roadway #16. Seventy minutes after the water inrush, the volume of the submerged roadway was 67,000 m^3, and the peak rate of the water burst was 60,036 m^3/h, which caused 31 deaths. (Zhang. 2015)

Karst collapse columns are commonly

found in the northern China coalfield and pose a serious threat to mining activity. Therefore, since the 1960s, hydrogeologists in China have been studying the causes, form, distribution and detection means of karst columns. Detection and prediction of collapse columns involve mainly two aspects: (Cao et al. 2012; Fengtian et al. 2016; Jiang et al. 2015) (1) geophysical exploration, for example, the use of radio-wave detection, surveying potential collapse areas using the direct-current method and transient electromagnetic method. Hydrogeological anomalies can be examined using advanced geophysical methods after a preliminary exploration. These methods can be combined with on-site drilling to verify the geological anomalies, enabling accurate control of the mine area surrounding collapse column. (2) Basic research is carried out to investigate the development of collapse columns, their mechanism of formation, the water inrush and the structure of the rock and the surrounding rock. To study the water inrush affected by the karst collapse column, laboratory simulation tests and numerical simulations are performed to explain the structural characteristics and the development of the collapse column. Based on the geophysical data and study results, damage control methods such as injected grouting transformation and leaving water pillars (Liang. 2015) have been used to prevent and mitigate karst collapse column water damage.

This paper focuses on the influence of karst collapse columns on the mining safety in the Yangjian coalmine, which is located in the Shuozhou mining area of northern Shanxi province. We use various exploration methods to identify the collapse columns, evaluate the risk of water inrush, and treat the rock surrounding the columns to prevent water inrush and tunnel collapse.

Hydrogeological conditions of the study area

The Yangjian coalmine is located in Shuocheng District, Shuozhou City, north of Shanxi Province, China (Fig.1). The Danshui ditch fault is the main geological feature in the region, while secondary faults are also common. Generally, the geological and hydrogeological conditions in the area are complex, leading to the development of collapse columns. The coal-bearing strata in the area are Carboniferous Permian strata, deposited directly above the Middle Ordovician. The Middle Ordovician consists of thick limestone, located more than 50 m below the upper main mining seam. The location of the fault and high pressure in the aquifer are the main threat to the mining operations. The stratigraphic column (Fig.2)

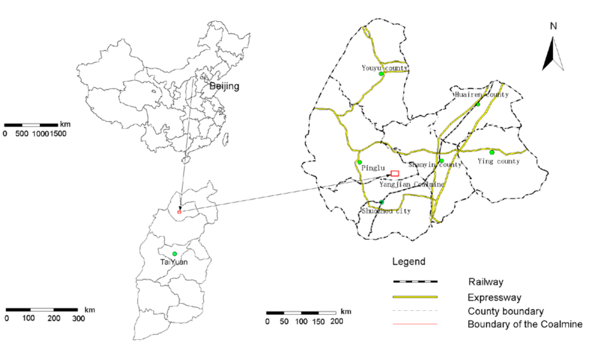

Fig 1. *Location of Yangjian Coalmine*

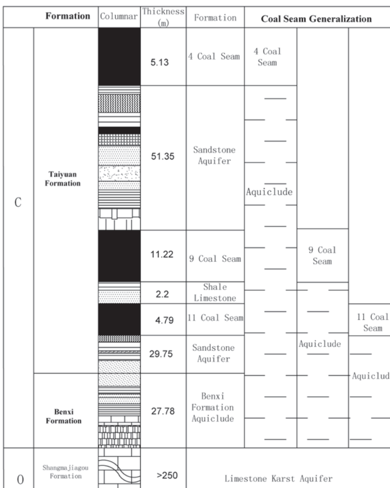

Fig 2. *Hydrogeological column generalization of Yangjian Coalmine*

shows that the main water-filled aquifer is the Ordovician limestone karst aquifer which is more than 800 m thick. The water abundance in the aquifer is not uniform, an aquifer pumping test showed units-inflow range of 0.12–93.36 L/s·m, indicating an extremely uneven flow. The Ordovician limestone water pressure in the mine floor reached a maximum value of 2.265 MPa, posing a serious threat to mine safety.

Materials and Methods

Considering the geological conditions in the Yangjian coalmine, a thorough investigation of the effect of the mining operations on geological anomalies, such as potential collapse columns, should be carried out. In this study, we evaluate the risk of water inrush in the Yangjian coalmine to facilitate disaster prevention and control and ensure safe mining operations.

Panel exploration methods

In recent years, geophysical techniques have become more common in studies of collapse columns. In this paper, the electromagnetic wave perspective method (Dong et al. 2003; Jiao et al. 2014) is used for surveying the study area. The principle is the use of electromagnetic waves to detect anomalies in the underground rock formation. Rocks will exhibit different electrical properties (resistivity and dielectric constant) depending on their ore content. The level of absorbed electromagnetic energy will change, with low-resistance rock layers having higher absorbance of electromagnetic waves than high-resistance rocks. When the wave encounters the interface of a fault structure, the electromagnetic wave will be reflected or refracted at the interface, resulting in energy loss. In mine geology, if the electromagnetic waves emitted by the transmitting source encounter a fault, collapse column, water-bearing fracture, coal seam thinning area or any other structure as they propagate through the coal seam, the wave energy is absorbed or completely shielded. The monitoring receiver will receive a weak signal or no signal, which is interpreted as an anomaly, indicating the possible location and range of an abnormal body.

Exploration drilling is the most direct method of mine water-hazard exploration; it can also reveal water-rich anomalies. Core data analysis can determine the composition and physical properties of the strata, including water conductivity, thus leading to early detection of a developing collapse column and enabling a comprehensive risk assessment of the column. At the same time, core drilling can reveal other hydrogeological conditions and water sources, providing useful information for mitigating water-triggered threats to the safety of the coal mining area (Li et al. 2011b).

Risk assessment of floor water inrush

The risk assessment of floor water inrush is a quantitative assessment of the risk of water outburst in each point (or each panel) using a mathematical model that reflects the influencing factors and mechanisms of action of each water inrush case in a specific mining area. (Zhu et al. 2013) In China, combined with existing experience in groundwater hazard control technology, the most commonly used and applicable method for assessing the risk of floor water inrush is to calculate the water-inrush coefficient.

$$T = \frac{P}{M} \tag{1}$$

where T is the water-inrush coefficient for aquifers below the coal layer floor, in MPa/m; P is the aquifer pressure, in MPa; and M is the floor aquiclude thickness, in m.

The Chinese Mining Bureau of Science and Technology provided guidelines for critical values based on data from coal mines in northern China. Based on Table 1, the critical water-inrush coefficient can be determined as

Table 1 *Critical water inrush coefficient T*

The integrity of the floor	Safety	Danger
Complete backplane (normal block)	≤0.1 MPa/m	>0.1 MPa/m
Incomplete floor belt (construction block)	≤0.06 MPa/m	>0.06 MPa/m

0.1 MPa/m in a normal geological block and 0.06 MPa/m in a tectonic failure block.

The floor water inrush is usually the result of the combined effect of many influencing factors, resulting in complex geological conditions which vary between the different mining areas. In addition to determining the water-inrush coefficient, the assessment of water inrush risk involves considerations of the tectonic setting of the mine, collapse columns and other structures that may affect the water inrush.

Controlling floor water inrush

In this paper, the karst collapse column is treated by grouting technology. (Li et al. 2011a; Oda M. 1986; Yang et al. 2002; Zhang et al. 2012) The basic principle of the grouting transformation is that concrete slurry is injected into the water-occupied layer, The basic principle of grouting transformation is that the slurry is injected into the fault fissures or channels in the rock under high pressure, so that they become the whole of water blocking, in order to improve the geological conditions and the ability of anti-destructive of the aquifers. This method is widely used in China to control groundwater inflow into mines. The pulp used for grouting can be divided into ground pulp and underground slurry, both types of pulp being very efficient grouting slurries.

Results and discussion

Results of collapse column survey

For the electromagnetic wave investigation, the fixed-point method was used in this study. With the wave transmitter fixed at a certain point of the roadway, the receivers record the magnetic field intensity point by point within a certain range along another roadway. To determine the position and distribution range of the anomaly area, the position of the transmitter and receiver were swapped and the process repeated. Thirty-eight transmission points were set along Panel 90102 at 50 m intervals, with the receiving points being 10 m apart. Each transmission point is recorded by eleven receiving points, totaling 418 data points.

The tomographic image (Figure 3) shows a higher intensity in the soft layer. Combined with hydrological and ground pressure data, two abnormal areas were identified, which included five collapse columns (XL_1–XL_5), see Figure 4.

According to the geophysical exploration results, 53 drilling sites were set in the transport roadway of Panel 90102 to verify the geological conditions surrounding the five collapse columns identified in the electromagnetic survey. The engineering parameters are shown in Table 2. Of the 53 boreholes, 43 revealed abnormalities

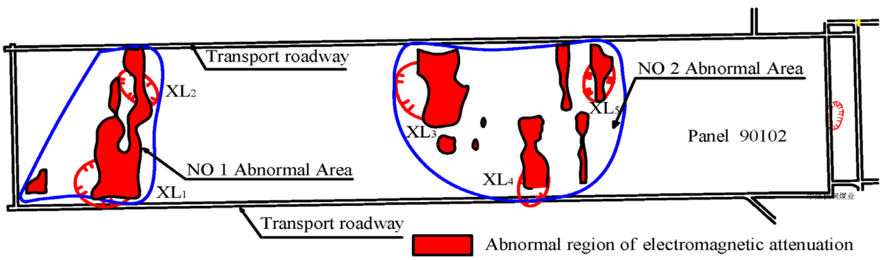

Fig3. Perspective of tomography in tunnel of panel 90102

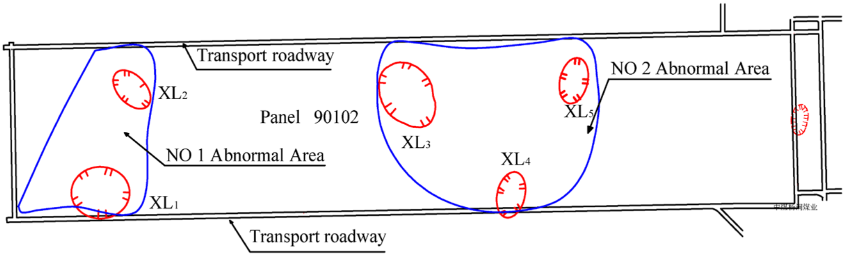

Fig4. Perspective of geophysical prospecting results in tunnel Panel 90102

Table 2 Drilling conditions in Panel 90102

Drilling location (track alignment)	In 260 m	In 340 m	In 418 m	In 420 m	In 850 m
Number of boreholes (unit)	12	13	8	7	13
Amount of work (m)	923	1248	888	499	1040

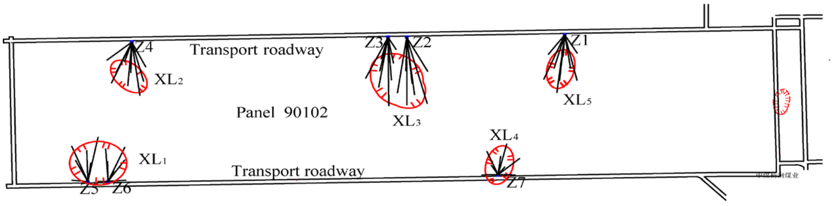

Fig 5. *Boreholes in Panel 90102*

in the rock and coal seams, indicating the development of the collapse columns. However, the collapse columns were found to consist of dense material due to reduced water flow, indicating the low water content and weak conductivity of the collapse column.

The core data showed five collapse columns (Fig.5) comprising mainly sandstone, mudstone and coal rock debris. No water flow was observed during more than three months of monitoring. During the excavation of the tunnel along the transport roadway of Panel 90102, XL_1 was exposed and water gushed through the floor of the tunnel. The exploration results are shown in Table 3.

Safety evaluation of floor water inrush

Panel 90102 has a bottom water barrier thickness of 50 m and bottom plate pressure of 1.3 MPa; considering only the water pressure and the thickness of the aquifer, the water inrush value is about 0.026 MPa/m, which is less than 0.06 MPa/m; therefore, the panel is considered safe. However, the theory of water-inrush coefficient method does not take into account the effects of the geological formations, groundwater conditions and other environmental factors. For example, if the Ordovician limestone aquifer has a high water content, even if the water-inrush coefficient is less than 0.06 MPa/m, water inrush events may occur in this area. Five collapse columns were exposed in Panel 90102. Geophysical prospecting data, drilling results and mining data from the top of the face #4 of the coal mine found five subsidence columns consisting of dense rock of low water content. However, collapse columns XL_1, XL_4 and XL_5 are connected to the aquifer through the floor of the working face, which makes the panel prone to water inrush. While the threat of the XL_5 collapse column has been ruled out, it is necessary to control the XL_1 and XL_4 collapse columns.

Treatment Scheme of Karst Collapse Column

Considering the special structure of Panel 90102, near water-rich anomalies and other characteristics, floor grouting reinforcement can be used to enhance the mechanical strength of the floor and increase the thickness

Table 3 Condition of Collapse column in Panel 90102

Name of subsided column	Size	Revealing features
XL1	Short axis 45 m, long axis 97 m	No water, relatively dense
XL2	Short axis 25 m, long axis 41 m	No water, relatively dense
XL3	Short axis 51 m, long axis 101 m	No water, relatively dense
XL4	Short axis 60 m, long axis 100 m	No water, relatively dense
XL5	Short axis 85 m, long axis 104 m	No water, relatively dense

of the floor aquiclude. In this technique, a number of grouting holes are drilled above the Ordovician limestone block, reinforcing the floor aquiclude and stabilizing the floor of the coal panel. By blocking the water from the Ordovician limestone aquifer, the collapse of the column can be prevented.

Panel 90102 of the Yangjian Coalmine has five collapse columns; of these, columns XL_1 and XL_4 need to be grouted. Here, we use XL_1 as an example, the grouting procedure described below. The minimum thickness of the safety floor aquiclude for XL_1 was calculated as 30 m. The probe hole is designed to reach the bottom of the column at a depth of 35 m, to ensure that it extends to the actual collapse column boundary, the designed hole depth out of the border after 6m for the final hole. According to the characteristics of floor of Panel 90102, it is determined that the horizontal plane of the grouting layer is the aquiclude of the Benxi Formation above the top of the Ordovician limestone block. The cement slurry is injected into the karst collapse column. To achieve the correct slurry diffusion range, the water abundance in the aquifer is not uniform was selected. The grouting holes are spaced 24 m apart, and the collapse column boundaries are located on the east and west sides of the subsidence column. Five holes are drilled along the west side and five holes along the east side as shown in Figure 6.

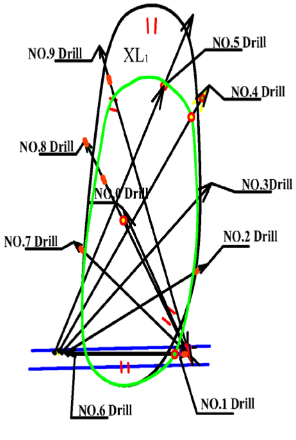

Fig 6. Design and layout of XL_1 collapse column

After the grouting operation, the scope of the collapse column in Panel 90102 is calculated (green line, Figure 6). The boundary contour of XL_1 is reduced by 16 m along the longitudinal axis. The water are not effluent from the drilling and the void has been filled in XL_1 collapse column. In addition, several water inrush points disappear in Panel 90102, which indicates that the effect of XL_1 collapse column treatment engineering is good.

Conclusions

1. Karst collapse columns pose a serious safety threaten on the coal fields of northern China. Hence, it is very important to examine the hydrogeological characteristics of karst collapse columns and implement effective means of controlling mine safety.
2. In this paper, the range, composition and physical properties, including water content and water conductivity, of karst collapse columns in northern China coal mine were identified by geophysical and drilling methods, and the water inrush safety was evaluated.
3. Based on this evaluation, the grouting reinforcement method was used to control the karst collapse column, which can effectively control water inrush and water damage in the floor.

Acknowledgements

This research was financially supported by the National Basic Research Program of China (No.2013CB227901), the National Key Research and Development Program of China (No.2017YFC0804101) and the National Natural Science Foundation of China (No. U1710253). The authors also thank the editors and reviewers for their constructive suggestions.

References

Cao Zhiyong, Wang Wei, Wang Yun. 2012. Numerical simulation and imaging of scattered wave of sunk piller in coal seam. Chinese Journal of Geophysics 55 (5): 1749-1756.

Dong Shouhua, Wang Qi. 2003. Application of tomography in radio wave tunnels perspective. Journal of China University of Mining & Technology 32 (5): 579- 582.

Fengtian Yang, Zhonghe Pang, Zhongfeng Duan. 2016. Distinguishing between faults and coal collapse columns based on sediment dating: a case study of the Huainan coal field, China, Environmental Earth Sciences (2016) 75: 959. DOI 10.1007/s12665-016-5761-8

Jiao Xianfeng, Jiang Zhihai, Liu Shucai. 2014. Characteristics of Abnormal Response of Wireless Electromagnetic Wave Perspective in Tundish of Coal Seam, Journal of Mining and Safety Engineering 31 (06): 1001-1004.

Li Jianghong, Zhang Yi. 2011a. Study on drilling technology of karst collapse column, Zhongzhou Coal (188): 17-19.

Li Shicai, Zhang Xiao, Zhang Qingsong. 2011b. Study on Diffusion Mechanism and Blocking Method of Water Injection Grouting for Water Bursting in Underground Engineering, Chinese Journal of Rock Mechanics and Engineering 30 (12): 2377-2396.

Liang Chongjuan. 2015. Characteristics of Water Damage and Its Application in Coal Mine Collapse Column, Energy and Energy Conservation 10: 29-30.

Oda M. 1986. An equivalent continuum model for coupled stress and fluid flow analysis in jointed rock masses, Water Resources Research 22 (13): 1845-1856.

Qiang Wu, Yuanzhang Liu, Xiaoli Wu. 2016. Assessment of groundwater inrush from underlying aquifers in Tunbai coal mine, Shanxi province, China. Environment Earth Science (2016) 75:737.DOI 10.1007/s12665-016-5542-4

Yang M J, Yue Z Q, Lee P K. 2002. Prediction of grout penetration in fractured rocks by numerical simulation, Canadian Geotechnical Journal 39 (6): 1384-1394.

Zhang Min, Wang Xing-hua, Wang You. 2012. Numerical evaluation of uplifting effect for upper structure by grouting, Journal of Central South University 19: 553-561. DOI: 10.1007/s11771–012–1039–9.

Zhang Wenzhong. 2015. Three dimensional large scale simulation experiment of collapse column water inrush. Journal of Taiyuan University of Technology 46 (6): 685-690.

Zhong Yaping. 2001. Studies on Integrate Technology of Water Prevention in Kailuan Mines. Beijing: China Coal Industry Publishing House Press.

Zhu Zongkui, Xu Zhimin, Sun Yajun. 2013. Study on risk assessment of floor water inrush based on dimensionless multi-source information fusion, Journal of Mining and Safety Engineering 30 (06): 911-916.