The advance detection and treatment of karst collapse columns – A case study of the Renlou Coal Mine in Anhui Province, China

Yajun Sun[1], Zhimin Xu[1], Yuhua Wu[2], Shitian Zheng[3]

[1]*School of Resources and Geosciences, China University of Mining and Technology, Xuzhou 221116, China*
[2]*Wanbei Coal-electricity Group Co.Ltd, Suzhou 234000, China; 3.CCTEG XI'AN Research Institute, Xi'an 710000, China*

Abstract

Karst collapse columns are widely developed in Renlou Coalmine, Anhui Province, China. More than 10 collapse columns are detected so far in this mining area. In 1996, the first testing Panel 7222 encountered water inrush disaster because of the karst collapse column. The maximum volume of the water inrush quantity came up to 34570 m^3/h, which caused mine flooding and enormous economic loss. In this paper, a potential karst collapse column found during the excavation of No. Ⅱ 5_1 tunnel in 2010 is selected as a case study to establish the advanced detection and treatment approaches for karst columns. The approaches proposed by this paper include three strategies: the first is the preliminary monitoring and anomaly analysis of water quantity, quality, temperature and pressure. Secondly, based on the monitoring work, geophysical prospecting is applied to determine the abnormal position of the collapse column. Thirdly, the accurate position and the range of column are confirmed by ground or underground drilling to the geophysical anomaly areas. Finally, the advanced detection approach in the way of grouting is applied, which blocks the hydraulic connection with the high pressure bottom Ordovician aquifer and plugs the collapse column. The approach eliminates the potential risk of water inrush during the roadway excavation.

Keywords: coal mining; tunnel excavation; karst collapse column; combined detection and investigation; grouting treatment

Among the water inrush disasters that occur in coal mines, those that do so through karst collapse columns in Ordovician limestone aquifers are some of the most influential and serious types, as they have caused several of the largest water inrush accidents in history (Yin et al. 2004). Buried collapse columns are usually found at depth and are therefore difficult to detect. However, research on the prevention of water inrush incidents and the control of collapse columns has focused on post disaster governance, while few studies have investigated the advance exploration and treatment of collapse columns. In recent years, coal mining problems have been encountered continuously in high and superhigh-pressure confined aquifers, and the influences of Ordovician limestone aquifers have become increasingly serious. Hence, the effective advance detection and preventative treatment of collapse columns have become some of the most important fields of research in controlling water inrush events.

During the construction of the Renlou Coal Mine, two hidden water-conducting karst collapse columns were discovered and harnessed (Duan et al.2005; Kong et al. 2012), which indicates that there are geological conditions for the formation of collapse columns in the mine (Fang et al. 2008).

In 2010, during the construction of the II5_1 track, water was discharged through the upper anchor bolt eye, and various forms of exploration, such as underground and surface geophysical exploration, geochemical exploration and drilling, were carried out. A comprehensive analysis confirmed the existence of a water-conducting collapse column. To quickly and efficiently prevent a disaster associated with the collapse column, the advanced detection and comprehensive identification of the ultrahigh-pressure water-conducting collapse column concealed at depth were carried out: through comprehensive exploration and control technology with advance geological prediction, water quality warning systems, geophysical exploration and drilling verification. Predisaster detection and control of superhigh-pressure water-conducting collapse columns concealed at depth provide an important geological basis for grouting and preventing the future occurrence of serious disasters.

Background conditions

Mine traffic location

The Renlou Coal Mine is located in the Linhuan Coal Mine area in northern Anhui Province. The extent of the mine area is as follows. The northern boundary is bounded by the SunTuan Mine area, the F7 fault is adjacent to the XuTuan Mine area in the south, and the F23 fault bounds the area to the southeast, while the plane projection of the -800 m contour line of coal seam 31 bounds the area to the east, and the outcrop of coal seam 11 bounds the area in the west. The Renlou Coal Mine is 4–7 km wide from east to west and 8–11 km long from north to south with a defined area of 42.0705 km^2, the mining depth ranges from -315 – -720 m.

Hydrogeological background

The coal field within which the coal mine is located is completely concealed by a loose aquifer of Quaternary age. The coal-bearing strata belong to the Carboniferous Permian system. The coal-bearing basement is Ordovician karst limestone. The top of the direct water-filled aquifer of the mine is a coal-bearing stratum, while the bottom is a fractured sandstone. The indirect water-filled aquifer is composed of the Quaternary aquifer at the bottom of the Quaternary system, a coal-bearing fissured sandstone, the Taiyuan group limestone and the Ordovician limestone aquifer (290 m from the 7_2 mined coal seams). If no large vertical water structure is present, it is extremely unlikely that water from the Ordovician limestone will be directly exposed.

Water outflow along the II 5_1 track roadway

On June 8, 2010, when the roadway was constructed to 28 m before G33, the upper shoulder bolt eyelet produced water at a rate of approximately 1 m3/h with a total hardness of 8.34°dH and no permanent hardness. When the excavation reached 31.5 m before G33 on June 9, the water volume increased, and the total water inrush rate through the upper three water exploration bolt eyelets reached nearly 30 m3/h. The permanent hardness of the effluent began to appear on June 10. By November 7, 2011, the total hardness of the water was 60.5°dH, the permanent hardness was 48.8°dH, the water temperature was 41°C, and the water inrush

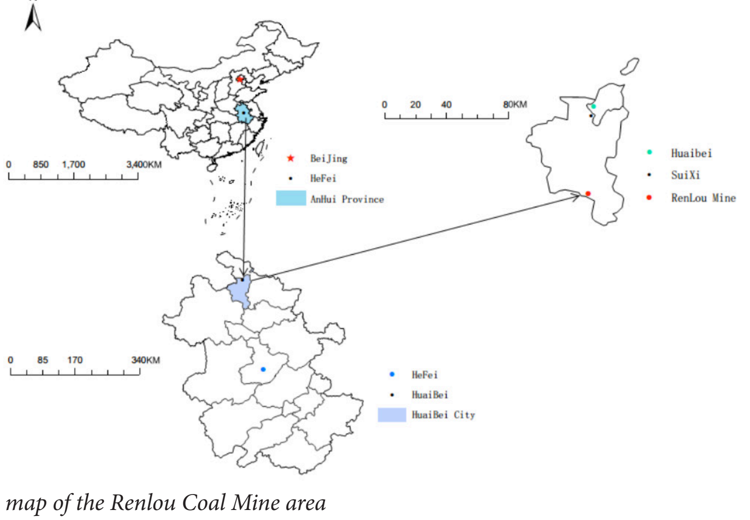

Fig.1 *Location map of the Renlou Coal Mine area*

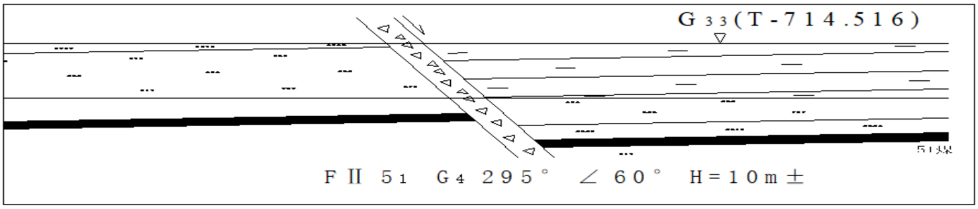

Fig. 2 Sectional view of the upper section along the heading of the II5$_1$ track roadway

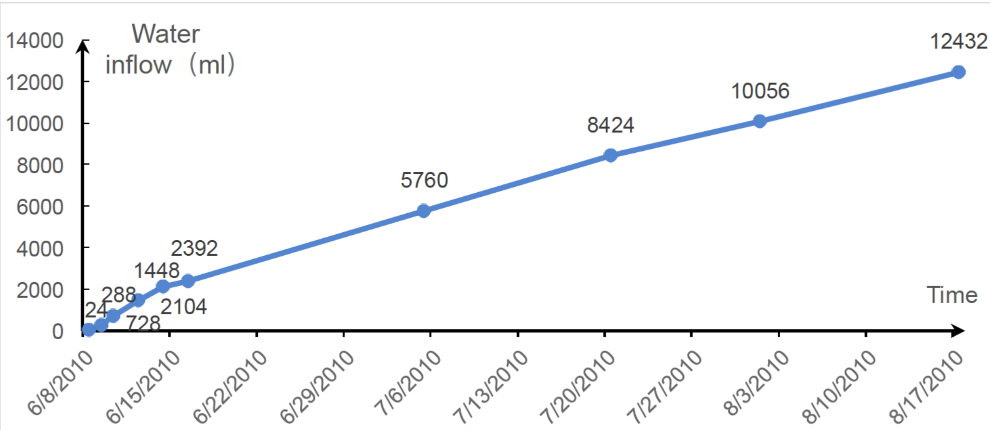

Fig. 3 Total water volume at the exit point of the II5$_1$ track roadway

rate was 8 m3/h. The permanent hardness of the water from the upper side of the roadway rose from zero, and the total hardness and permanent hardness of the water increased.

Geological prediction analysis

The main roadway is located in the Gongguang coal protection pillar. The minimum vertical distance between the bottom boundary of the new overlying strata "fourth aquifer" and the roadway roof is approximately 440 m, and the minimum vertical distance between the underlying Taiyuan Formation limestone and the roadway floor is approximately 210 m.

The strata of the II5$_1$ mining area compose a nearly monoclinic structure with a yield of 90°<16° ±. The exposed lithology of the roadway is mainly fine sandstone and mudstone. The DF8 normal fault is exposed at 3 m (lower) and 12 m (top) before G33; its occurrence is 295°<60°–69°, and its fault throw is 10 m. The fault fracture zone is 1 m with no water seepage through it (Fig. 2). The lithology in the middle and lower parts of the head section is characterized by several small faults in the fine sandstone, and there is no deep fault structure in the area.

In summary, there are material bases and hydrodynamic conditions for karst development in the coal field. At the same time, through a comprehensive analysis, we can exclude water-conducting faults as the cause of the abnormal water inrush along the II5$_1$ track roadway. Therefore, through the abovementioned geological prediction and comprehensive analysis of the fractures and faults in the vicinity of the mining area, the inrush of water along the II5$_1$ track roadway eliminates the possibility of water being conducted through a fault, and a collapse column is suspected to connect a deep water source with the II5$_1$ track roadway.

Water quality warning identification

Analysis of the inrush water value

When the construction of the II5$_1$ track roadway reached approximately 28 m before G33, water began to rush out of the upper shoulder anchor hole, and the initial water volume was approximately 1 m^3/h. When the excavation reached approximately 31.5 m in front of G33, the amount of water increased. The total water volume rushing out of the three anchors in the upper construction area was nearly 30 m^3/h, and the single-hole (aperture of 32 mm) maximum water output was 16 m^3/h. After performing the initial grouting to plug the water, the water volume was stable at 8 m^3/h, and there was no decrease in the inrush rate (Figure 3). According to the increase in the amount of effluent water and the stability of the water volume after plugging, the comprehensive analysis suggests a relatively stable supply from the water source.

Analysis of the water temperature change

On June 8, 2010, the water temperature was 33°C, after which the effluent water temperature gradually increased to 41°C on November 29, 2011 (Figure 4). According to the normal geothermal gradient of 3°C/hm at the Renlou Coal Mine, the normal ground temperature is 34–36°C; hence, there is an abnormality in the head-on effluent temperature along the $II5_1$ track roadway. Based on a comprehensive analysis of the abnormal increase in the water temperature, which is higher than the normal ground temperature, the water is preliminarily determined to be sourced from a deep, high-temperature water supply.

Water quality warning

On June 8, 2010, water emerged from the anchor hole of the upper shoulder at 28.5 m before G33 in the main roadway with a total hardness of 8.34°dH and no permanent hardness. The water began to show permanent hardness on June 10. By November 7, 2011, the water had a total hardness of 60.58°dH and a permanent hardness of 48.81°dH. From

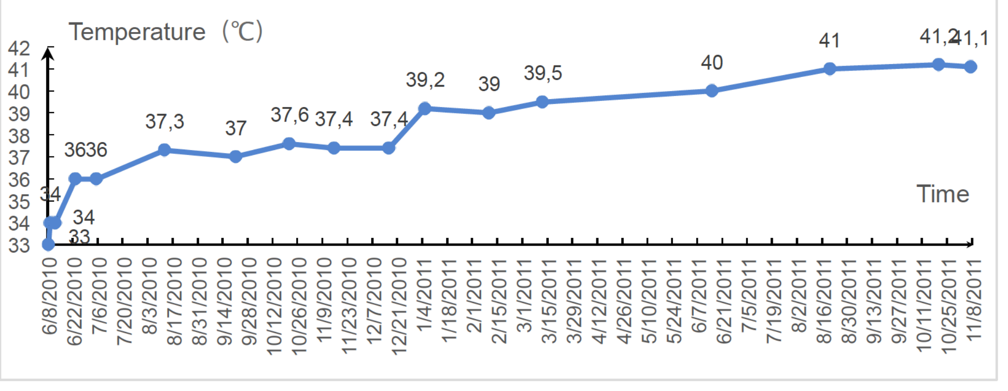

Fig. 4 *Curve of the change in the head-on water bursting point temperature along the* $II5_1$ *track roadway*

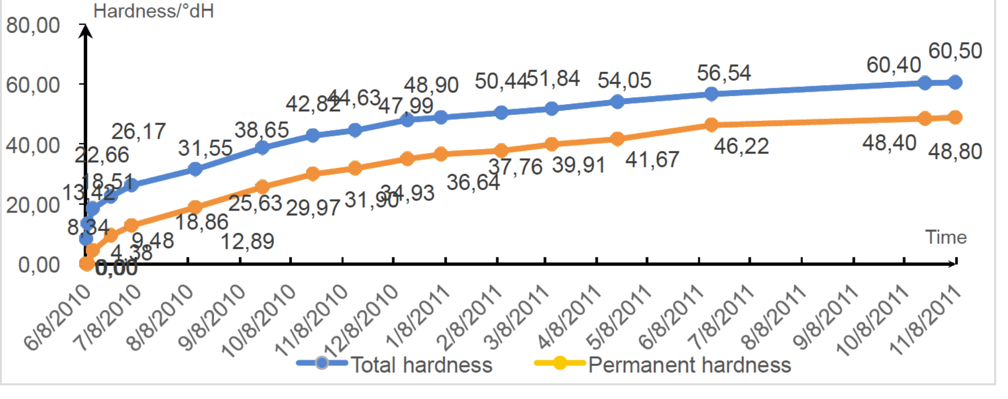

Fig. 5 *Curve of the change in the water quality at the water inrush point along the* $II5_1$ *track roadway*

June 8, 2010, to November 2011, the total hardness increased from 8.34 to 60.58°dH, and the permanent hardness increased from 0 to 48.81°dH. The full hardness and permanent hardness of the water displayed an increasing trend (Figure 5).

An analysis of the main hardness of the effluent water quality along the II5$_1$ track roadway conducted from scratch shows that the water hardness and permanent hardness were generally increasing. This implies that there may be a deep water supply with a high hardness (Ge et al. 2007). Comprehensively, according to the increase in the effluent water volume, the rise in the water temperature and the abnormal water hardness and water pressure along the II5$_1$ track roadway, it is concluded that the water outlet point may be connected to a deep water reservoir with a high temperature, a high hardness and a stable source of replenishment (Gui 2005). Combined with the abovementioned geological prediction results, hidden karst collapse columns are suspected at the point of water inrush along the II5$_1$ track roadway, seriously threatening the safety of further mine production.

Integrated geophysical exploration

A comprehensive surface downhole geophysical exploration method was designed in which the ground was probed by three-dimensional seismic and transient electromagnetic instruments. Five kinds of geophysical methods, namely, the transient electromagnetic method, high-resolution electric method, parallel electric method, seismic survey method and ground-penetrating radar method, were used to perform advance exploration of the subsurface along the II5$_1$ track roadway, including the front and the sides of the II5$_1$ track roadway (Liu et al. 2008). The exploration encircled the abnormal target area, providing the basis for drilling verification.

Surface geophysical exploration

Three-dimensional seismic exploration and transient electromagnetic detection were carried out at ground level along the main road, and the detection results revealed the following:

1. On the west side of the water inrush point, the reflected waves at the top interface of the Ordovician limestone are disorganized and broken, indicating a fissure development zone.
2. There is a suspected collapse column approximately 350 m ahead of the main roadway.
3. There are water-rich areas in different layers to the southeast of the main roadway, and there are abnormal superpositions. To the southwest, there are water-rich areas distributed at the 5$_1$ coal roof and the 7$_2$ coal floor.

Subsurface geophysical exploration

1. Transient electromagnetic method. There is an abundant water body at distances in

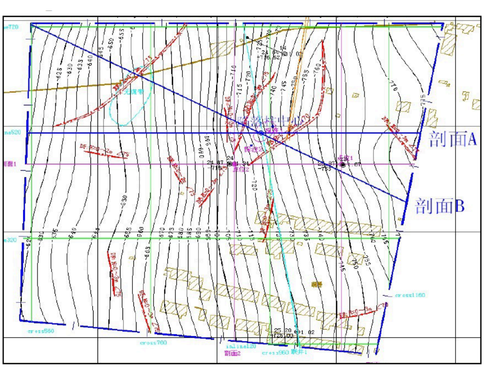

Fig. 6 *Surface three-dimensional seismic results*

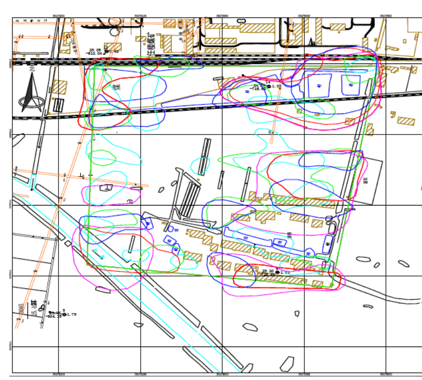

Fig. 7 *Comprehensive results of the surface transient electromagnetic survey revealing water-rich anomalous areas*

front of the main road ranging from 60 to 110 m, at horizontal distances ranging from 20 to 65 m, and below the floor of the roadway below 30 m.
2. Transient electromagnetic and parallel electrical methods. There is an abundant water body at distances in front of the main road ranging from 0 to 50 m and at horizontal distances ranging from 70 to 110 m, 65 to 110 m and 30 to 80 m. There are 2 water-rich areas.
3. Seismic surveying and high-density resistivity methods. Fissures are developed at 160 m behind the roadway and within 50–80 m from the roof of the roadway. Approximately 130–20 m in front of the roadway, fissures are developed, and the presence of water is strong with a hydraulic connection to a deep aquifer.
4. High-resolution method. There are 3 low-resistance anomalous areas in the range from 10 to 90 m in front of the G34 wire point.
5. Transient electromagnetic method. There is a substantial low-resistance anomaly.
6. Ground-penetrating radar method. There are 3 anomalous areas in the apical plate, 1 anomalous area in the bottom plate, and 1 anomalous area in front of the tunneling direction.

Comprehensive analysis of the above various geophysical exploration results and other data: the conductor of the $II5_1$ track roadway is a water-conducting collapse column, and preliminary analysis shows that this column is located 65–115 m behind the roadway at horizontal distances of 38–65 m.

Drilling control

On the basis of the preliminary analysis of the concealed collapse column in combination with the comprehensive geophysical exploration results, the key target areas for drilling verification were delineated. Drilling verification methods were employed to determine the spatial position and development of the collapse column. Ground drilling verification holes, downhole roadway drilling holes, ground-oriented exploration holes (Ge et al. 2007; Zhou et al. 1996), etc., were implemented. Drilling verification was performed in anomalous areas defined by the integrated geophysical exploration results to identify the spatial patterns and boundaries of the water inrush and the concealed water-conducting column.

1. Underground drilling exploration. A total of 19 boreholes in 3 groups were used for the up roadway, and 6 boreholes were drilled for the haulage roadway.
2. Surface-guided directional drilling. Four column exploration holes (the first hole revealed the collapse column) and 1 underground branch hole based on the abnormal area delineated by geophysical exploration were drilled. The four column exploration holes all exposed the collapse column.

Combined with the drilling verification described above, the collapse column was accurately mapped, and the spatial position, boundary and height of the collapse column were controlled. At the same time, the drilling verification also showed that the identification and comprehensive detection results of a

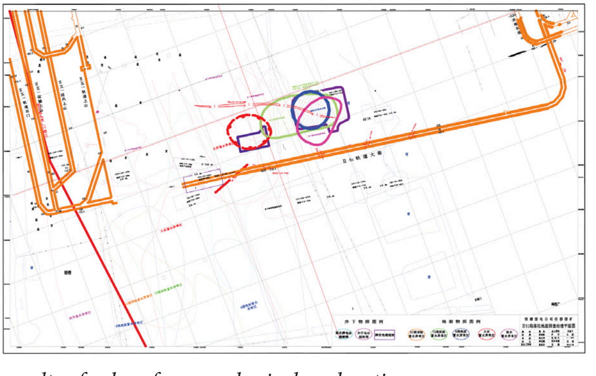

Fig. 8 Comprehensive results of subsurface geophysical exploration

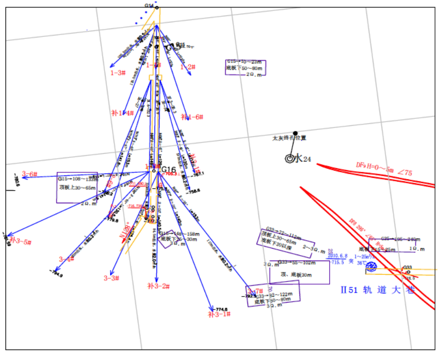

Figure 9 *Drilling plan for the II5$_1$ up roadway*

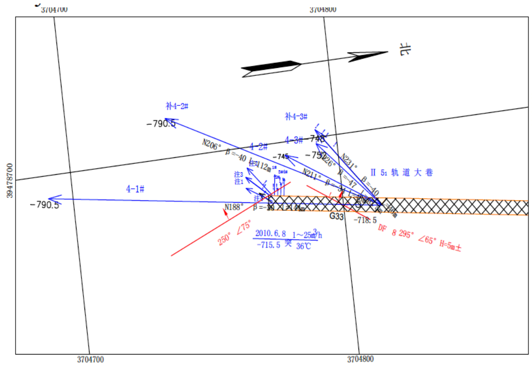

Fig. 10 *Drilling plan for the II5$_1$ track roadway*

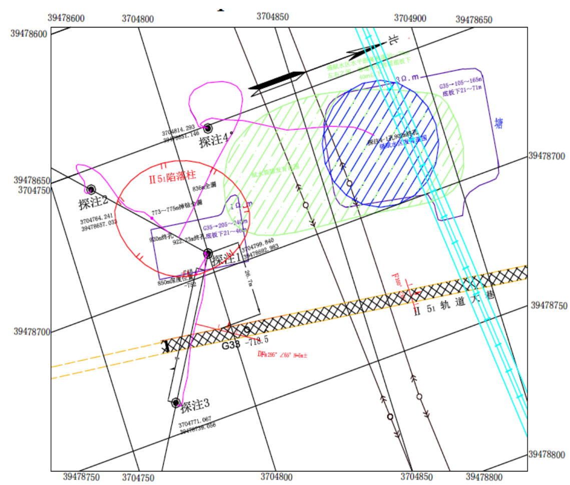

Fig. 12 *The collapse column boundary*

concealed collapse column are reliable and effective, providing an important reference for the spatial location and determination of concealed collapse columns.

Conclusions

1. Through an analysis of the development of a collapse column in the mining area and the water inrush conditions of past collapse columns in combination with the water inrush conditions, the hazard of the concealed collapse column was determined, thereby providing a theoretical basis for early treatment.
2. Aiming at the preventative exploration and treatment of the collapse column, geological prediction, water quality warning systems, geophysical exploration and drilling verification were conducted. Through systematic exploration, the spatial position and development pattern of the collapse column were accurately detected.
3. To investigate the collapse column through drilling, high-precision directional drilling technology and the porous joint exploration method were adopted to effectively and accurately control the boundary of the collapse column, thereby providing a basis for subsequent treatment.

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

Duan ZW (2005) Quick recognition and detection of hidden conducting karst collapse column in Renlou coal mine. Journal of Xi'an University of Science and Technology 24 (03):268-270+335. (Chinese)

Fang P, Wang HL (2008) Karst in the fall of distribution of causes. Coal Engineering (11):84-85. (Chinese)

Ge JD, Wang JM (2007) Chemical early warning study on water-conducting collapse column in Renlou Coal Mine. Coal Engineering (09):85-88. (Chinese)

Gui RH (2005) Study on hydrogeochemical characteristics and discriminating model of groundwater in Wanbei Mining Area. [D]. University of Science and Technology of China. (Chinese)

Ge HQ (2007) Application of directional drilling technology in treatment of collapse column. Coal Geology of China 19(1):19-20. (Chinese)

Kong YF, Yang BS (2012) Water disaster prevention of insidious water conducting collapse column and exploration and governing technology in advance. Journal of Anhui Institute of Architecture & Industry(Natural Science) 20(05):24-28. (Chinese)

Liu ZX, Liu SC, Yu JC (2008) Application of integrated mine geophysical techniques in detecting collapse columns. Geophysical and Geochemical Exploration 32(02):212-215. (Chinese)

Yin SX, Wu Q, Wang SX (2004) Studies on Characters and forming mechanism of karstic collapse columns at mine area of north China. Chinese Journal of Rock Mechanics and Engineering 23(01):120-123. (Chinese)

Zhou TF, Yang DS (1996) Research and application of directional drilling technology for screw drill. Exploration Engineering (Rock & Soil Drilling and Tunneling) (04):53-55. (Chinese)