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Characterization and Remediation of Karst Collapse Columns for Mining Safety and Environmental Protection: A Case Study in Renlou Coal Mine, China

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Abstract

Karst collapse columns are unique collapse structures in karst terranes. Coal mining in China has exposed numerous such features of tens of meters in diameter and hundreds of meters in height. Hydraulically conductive collapses functioned as groundwater pathways between underground workings and aquifers, resulting in water inrushes during coal mining. Over the last 60 years, water inrushes through these collapses have caused fatalities, economic losses, and degradation in the environment. Determination of locations and hydrogeological characteristics of the karst collapse columns are essential in preventing water inrush incidents through them. Advanced geophysical prospecting, directional drilling, aquifer testing and accompanied dye tracing are effective approaches to detecting and characterizing these structures. Five geophysical techniques consisting of both surface and underground geophysical surveys and directional drilling of three exploratory boreholes up to 986 m deep identified a concealed collapse feature of more than 135 m high in Renlou Coal Mine, China. The roof of the collapse feature was at approximately 785 m deep, and there was an open void of 1.5 - 2 m high at the top. Geotechnical properties, results from packer testing and tracer testing, monitoring of potentiometric pressures, and geochemical fingerprinting suggested that this collapse column was hydraulically conductive and still actively developing. Water in the confined thin-bedded limestone and Ordovician limestone aquifer that either overlies or underlie coal seams could flow into the underground working areas if this feature were not identified in advance but encountered during mining. A grouting program was designed and implemented to construct a water plug in the collapse that effectively cut off the hydraulic connections from the aquifers to the underground workings. Successful construction of the water plug in the collapse was confirmed by performance monitoring of the aquifers.

Keywords: karst collapse columns, water inrushes, coal mines, 3D seismic, directional drilling, grouting

1. Introduction

More than 90% of China's coal output is produced in north China, and approximately 300 billion tons of proven reserves are threatened with the underlying Ordovician karst aquifers. In the past 60 years, more than 1,300 groundwater inrush accidents occurred in coal mines in China and many of these water inrushes were through a unique type of karst features known as paleo-collapse structures or paleo-collapse breccia pipes or karst collapse columns (used in this paper and abbreviated as KCC) (Li et al., 2017; Wu et al., 2013). These KCCs functioned as hydrogeologically conductive pathways for the groundwater flow from the Ordovician karst aquifer to working faces under mining influences (Zhou, 1997; Benson et al., 1991). Unlike cover collapses or sinkholes that are often caused by human activities (Newton, 1987; Beck, 1991; Beck & Wilson, 1987; Zou, 1994), KCCs are rock collapses that occurred in the geological past (White, 1988; Sangster, 1988; Li & Zhou, 1989; Vegter & Foster, 1992). Depending on the internal cementation of the KCCs, they can be active or inactive in the groundwater circulation system. Inactive KCCs can be reactivated by human activities such as dam construction, mining underground minerals, pumping groundwater, and development of landfills. They may also be reactivated by natural events such as earthquakes and neo-tectonic activities.

Usually the infill materials in the karst collapse structures are tabular 5–40 cm angular fragments which display random orientation. Sides are subparallel and contacts between host and fills are sharp and irregular. In most cases, the matrix consists of clastic sediments without cement or mineralization. These structures are generally perpendicular to the ground surface. However, they could become inclined as a result of tectonic movements but remain perpendicular to the surrounding strata. Voids may be present at the top of the structures and drill bits can drop noticeably during borehole drilling. Closed depressions sometimes form in the surficial sediments.

The effects of KCCs can be observed in the various karst features of the carbonate aquifers and the yields of oil and gas reservoirs. They can also be seen in the interrelationships between important mineral deposits and karst aquifers which pose safety and environmental problems in mining engineering.

2. Karst Collapse Columns Encountered during Mining in North China

Geology and climate are two major factors affecting the development of karst features. Usually, there have been several phases of karstification during geological history. In China, for example, the most striking karstification is found in (1) the Caledonian Orogeny unconformity between the Ordovician limestone and middle carboniferous series in northern China; (2) the unconformity between the Lower Permian limestone and the Upper Permian Series in southern China; (3) the pre-Jurassic karstification in the Sichuan basin; and (4) the pre-Tertiary buried karst in northern China.

KCCs are widely distributed in north China as a result of these episodic karstification in the geological past. They have been found in over 50 coalfields and their total number exceeds 3,000 with an intensity of up to 70 collapses/km^2 (Zhou, 1997). Table 1 summarizes some of KCCS reported in north China's coalfields. In some mining panels, such collapse structures comprise 30% of the total mined areas. Figure 1 shows some common profiles of KCCs reported in north China. While the majority of the KCCs are buried underground, some are exposed to surface and expressed as depressions. The main characteristics of the KCCs include the following:

- They are recognizable in plan view as patches of breccia with miscellaneous lithological composition, generally derived from overlying strata and completely enclosed in lower bedrock.
- Diameters range from tens to hundreds of meters with the largest measuring 1,050 m (Dong, 2016).
- In profiles, they take the form of vertical cylinders several hundred meters deep.
- No bedding is apparent inside these structures and the different rocks are intermixed and poorly sorted. They generally contain higher proportions of displaced blocks and the adjoining strata are offset as a result of dissolution-collapse. Fragments tend to be sharply angular, typically rotated, show little sign of wear and appear to have dropped from their original stratigraphic position.

The KCCs encountered in north China are of different hydrogeological types depending primarily upon the lithology of their internal rock blocks, extents of weathering and cementation, and the secondary structures associated with the collapses (Zhou & Beck, 2012). Based on the exposed karst collapses from drillings and excavations, the KCCs can be permeable, impermeable and poorly permeable. In different karst collapses or different locations of the same collapse, the rock blocks may have different hydrogeological properties. In Yangquan Coal Mine of Shanxi province, none of the intercepted 960 KCCs was permeable to groundwater, whereas all of the six collapses encountered in Tangjiazhuang Coal Mine were hydraulically conductive. On average, 62% of the encountered KCCs are permeable or poorly permeable (Li & Zhou, 2015). Figure 2 shows profiles of the three types of KCCs. All of the three collapses were exposed in Fangezhuang Coal Mine of north China. KCC No. 9 is permeable; No. 2 is impermeable; and No. 1 poorly permeable. The permeable KCCs consist of weathered rock blocks, but they are typically unconsolidated and not cemented. The impermeable KCCs consist of weathered rock blocks that are often cemented by weathered shale and mudstone. The poorly permeable KCCs consist of partially cemented rock blocks with secondary fractures around the border of the collapses.

Table 1. Select KCCs that were reported in north China's coalfields

Province	Location	Number of KCCs	Max. size of collapses (m)			Water inrush
			length	width	height	
Shaanxi	Xishan Coal Mine, Taiyuan	1300	40			
	Yangquan Coal Mine	960	300		600	
	Huoxian Coal Mine	405	60			2
	Zhuangjiazhuang Coal Mine, Fenxi	360	30			1
	Shenlin Coal Mine	75	30			
Hebei	Jingxing Coal Mine	120	300	23	300	1
	Fenfeng Coal Mine No. 1	6	200	40		
	Fengfeng Coal Mine no. 4	20	73	150		
	Yangquhe Coal Mine	6	204	57		
	Fangezhuang Coal Mine, Kailuan	9	95	74	280	4
	Tangjiazhuang Coal Mine, Kailuan	6	116		50	
Henan	Hebi Coal Mine	22	200	60	398	
	Tongyie Coal Mine, Anyang	22				1
	Lifeng Coal Mine, Jiaozuo	1				1
Jiangsu	Dahuangsha Shaft, Xuzhou	17	200	146		1
	Qingshanzong Shaft No. 1	1				1
	Qingzhuan Coal Mine	1	38	19		
	Liuxing Coal Mine	1		20		
	Jincheng Coal Mine	27	125	62		
	Xinhe Coal Mine	3	136	100		
	Jiahe Coal Mine	1	135	100		1
	Wangzhuang Coal Mine	1	122	93		
	Quanzhao Coal Mine	7	60	40		
	Hanqiao Coal Mine	4	170	100		
	Dongzhuang Coal Mine	1	280	200		
	Yian Coal Mine	1				

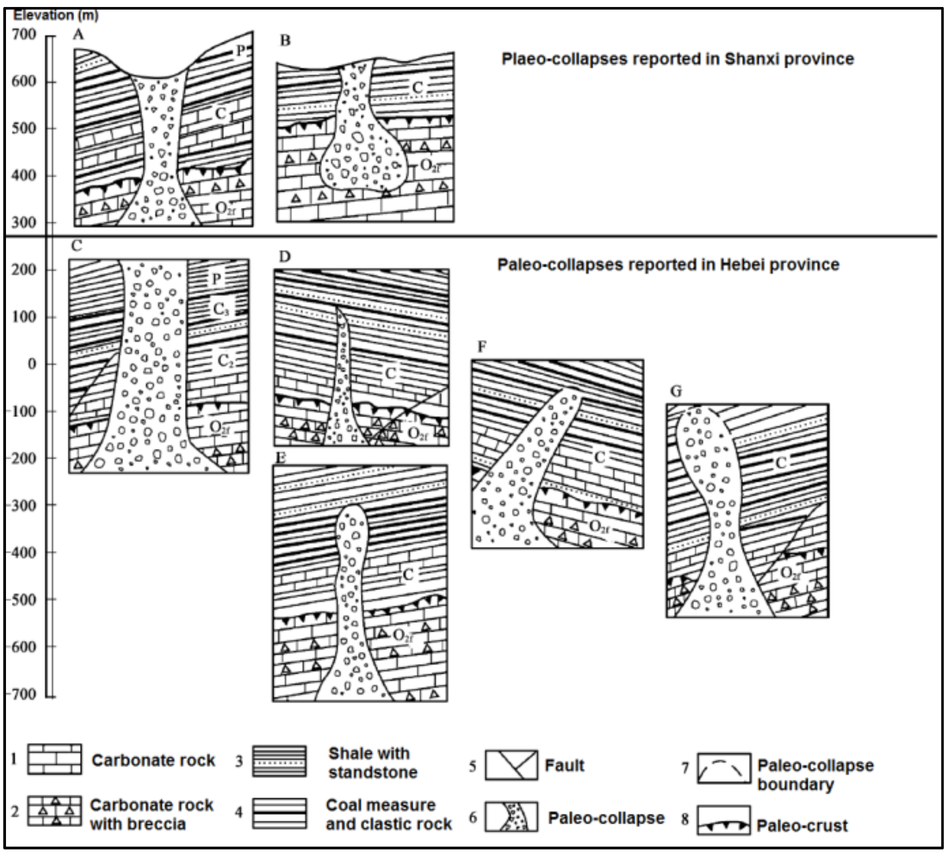

Figure 1. Select KCC profiles reported in north China (modified from Lu and Zhang, 2008). Elevation in meters is shown on the left side of the figure

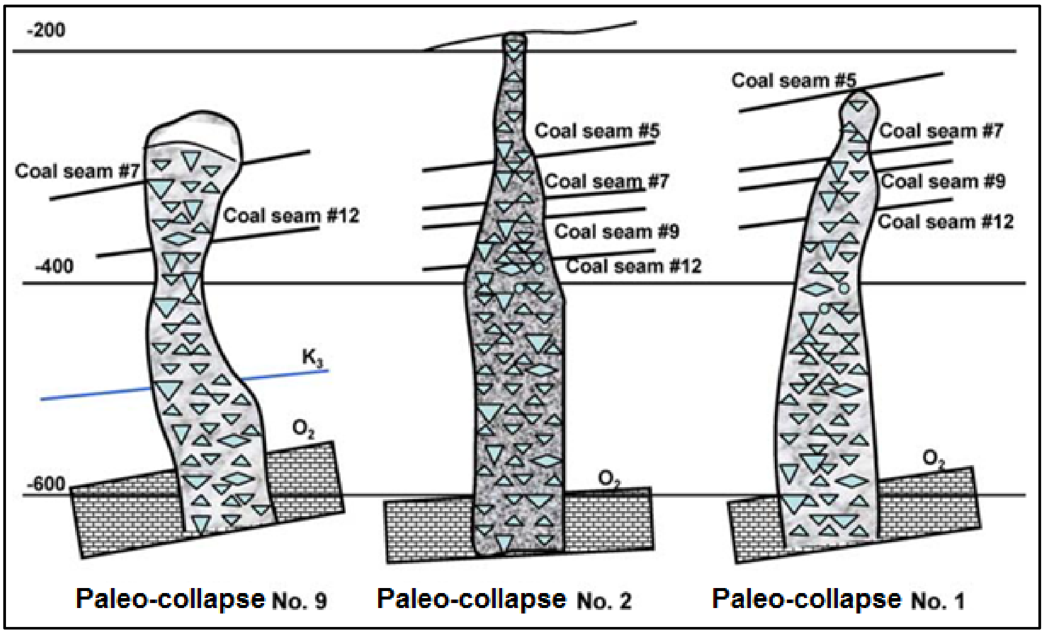

Figure 2. Longitudinal cross sections of KCCs No. 9 (permeable), No. 2 (impermeable) and No. 1 (poorly permeable) in Fangezhuang Coal Mine (modified from Yin and Zhang, 2005). Elevation in meters is shown on the left side of the figure

3. Formation Mechanisms of Karst Collapse Columns

Formation of KCCs may involve polygenetic processes. However, the bottom of these collapse structures is usually in the underlying karstified Ordovician limestone, and the lithological character of the breccia gives a strong impression of collapse of upper strata. Gypsum in the Ordovician limestone is recognized as playing an important role in KCC formation (Li & Zhou, 1990). Sulfate-reducing bacteria (SRBs) may help initiate and accelerate the dissolution process of the carbonate rocks (Lu & Zhang, 2008). Figure 3 presents a schematic diagram depicting the compound dissolution process in which the limestone is dissolved by both carbonic acid and sulfuric acid. In additional to presence of natural acid-producing gases, gypsum can produce H_2S by SRBs and additional CO_2 by interacting with carbonate rocks.

In Shanxi province, gypsum is present in the Middle Ordovician Fengfeng Formation. It contains up to 60% of secondary gypsum, present as thick massive beds, nodular gypsum and gypsum interbedded with mudstone and dolomite. The formation rests on the Majiagou Formation which also contains some gypsum and is the major regional aquifer. In the Tiejingou deposit near Yangquan the Fengfeng Formation ranges in thickness from several tens to more than one hundred meters. Within the formation large palaeokarst caves, situated in the present vadose zone, have collapsed and are filled with breccia. However, karst fissures are still undergoing dissolution and enlargement. The active dissolution of gypsum, indicated by sulphate-rich springs, confirms that the gypsum karst is still evolving.

Shanxi province is in a semi-arid environment undergoing uplift. Palaeokarst, such as that originally developed under phreatic conditions in the Ordovician Fengfeng Formation, has been uplifted above the water table and preserved. In the Fengfeng Formation the dissolution of the gypsum has caused the formation of extensive breccia beds with associated breccia pipes or collapse columns that have propagated upwards through the active coalfields (Li & Zhou, 2006). Preservation of gypsum karst is likely when climatic conditions change causing a reduction in the availability of water to the natural systems. In this way the gypsum karst of southwest Oklahoma (Johnson, 1990) was preserved. Pollen/spore samples from underground deposits have yielded a temperate, but dry forest/grassland assemblage when the collapses occurred (Lu & Copper, 1997).

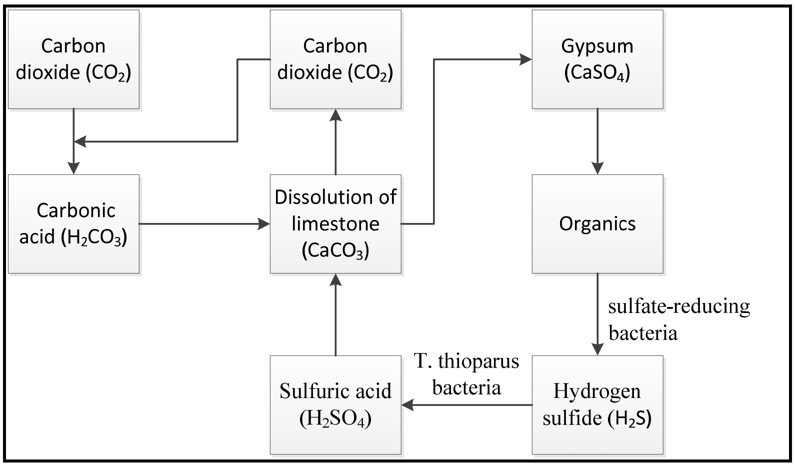

Figure 3. Schematic diagram of compound dissolution of limestone and gypsum

In active karstification situations gypsum can dissolve very rapidly and caves can quickly enlarge, or amalgamate, become unstable and collapse. When this occurs collapse columns or breccia pipes can propagate upwards and cause surface collapse. The sizes of the breccia pipes and collapses relates directly to the thickness and strength of the gypsum deposits. The more massive, thick and homogeneous the deposit, the larger are the caves that can be supported and consequently the larger the collapses and breccia pipes. When the gypsum between the collapse columns also dissolves an irregular bed of breccia may form.

The nature of the underlying and overlying strata adjacent to the gypsum also has a profound influence on the way gypsum karst develops. In sequences where the adjacent rocks are largely impervious the karst can only develop along the joints in the gypsum. In phreatic situations, where the gypsum is underlain, or overlain, by porous dolomites or sandstones, water enters the gypsum in a diffuse way. When this happens, dissolution progresses on many fronts and maze cave systems can develop, such as those observed in the Ukraine (Andrajchouk & Klimchouk, 1993). In this situation much of the dissolution occurs at the contacts with the adjacent strata which may also be karstified. In the maze caves the passages range from joint-controlled networks of small stable caves with little dissolution, to networks of actively dissolving conduits with large and unstable cavities; these commonly have subsidence associated with them.

Where gypsum is in contact with adjacent carbonate rocks, the water chemistry associated with the dissolution phenomenon is different to that for gypsum alone, or for limestone alone. The presence of gypsum together with carbonate rocks will usually cause a compound karstification effect. Waters rich in calcium carbonate can aggressively dissolve gypsum and simultaneously deposit calcite (Wigley, 1973). When this occurs the breccias caused by the dissolution of the gypsum may be cemented. Carbonate-cemented breccias, possibly formed by this mechanism, occur in the Fengfeng Formation. Gypsum dissolves easily in flowing water and increases the amount of sulphate in the water. When anhydrite hydrates to gypsum, the expansion can cause brecciation of the mineral, brecciation of the adjacent rock, and injection of fibrous gypsum veins; such deposits are present in the Ordovician Fengfeng Formation.

The solubility of gypsum in calcium carbonate-rich waters may be decreased by the common ion effect. Conversely, the presence of sodium, magnesium and chloride ions (possibly derived from interbedded dolomites and halite beds) can enhance the dissolution of gypsum. Experimental work shows that the presence of sulphate in the water increases the dissolution rate for dolomite. For water with an SO_4^{2-} content of 1 mg/l the dissolution amount for dolomite was 1.67 mg/l while that for limestone was only 0.94 mg/l (Lu & Cooper, 1997). The result of this groundwater chemistry on karstification is that very intense and pervasive leaching of the carbonate deposits, especially dolomites, can occur resulting in a honeycomb structure of very little strength. The dissolution of the gypsum, when it is complete, can leave just an insoluble residue, commonly of silt or clay.

After the gypsum dissolved and was removed by groundwater, numerous cavities or fractures were left behind. Solution of the gypsum layers and continuous dissolution of the limestone eventually led to the collapse of the overlying strata. Development of a KCC is envisaged as a more or less continuous process which progresses upward from an initial conduit (cave) until an equilibrium pressure arch configuration is attained. This occurs when a collapse reaches a lithologic unit of sufficient strength, or the cavity is completely filled with breccia and thus becomes self-supporting.

4. Impacts of Karst Collapse Columns on Mining and the Environment

The absence of coal seams and the sudden inrush of karst water from the Ordovician limestone have been encountered in the mines of the Permo-Carboniferous coalfields of north China. The KCCs functioned as groundwater pathways for some of these events. Figure 4 shows three scenarios in which the pressurized karst water in the Ordovician limestone flows into the mining areas through KCCs. The relative location of a mine to the active flow zone or karst conduits in karst aquifers determines the amount of water that can flow into the mine. In the presence of a large water-pressure difference, hydrofracturing will facilitate upward flow of the Ordovician karst water into mines. Mining drifts do not have to intercept the KCCs directly to cause a geohazards but may instead intercept faults or fractures connected to them. However, once a water inrush occurs and significant water flows into the workings, the whole mine may become flooded. In cases where different aquifers, several hundred meters apart, become hydraulically connected, the impacts on safety, economy and the environment can be alarming.

Table 2 lists 14 water inrushes through KCCs in coal mines, including the largest inrush in the world, which occurred in Fangezhuang Mine in 1984. Karst water gushed into the mine at a flow rate of 34 m^3/s at a depth of 313 m below sea level (bsl). The surface level is 27 m above sea level (asl). The whole mine was flooded within 21 h and as a result, the regional water table in the Ordovician limestone dropped from 5.94 m asl to 111.09 m bsl. The cone of depression covered approximately 84 km^2 with a north-south axis of 25 km long. The fall in the water table in the Ordovician limestone caused serious problems for local residents, including drying up of their water supply wells, contamination of the groundwater and formation of cover-collapse sinkholes. The water inrush led to the development of 17 cover-collapse sinkholes with diameters from 2.5 to 3 m and depths of 3 to 12 m.

Table 2. Case histories of water inrushes through KCCs in north China

Mine	Date	Flow rate (m^3/s)	Description	Damage
Taoyuan Coal Mine	2013	2.8	Karst water from the Ordovician limestone flowed into the cut-hole of 1035 working panel through a concealed KCC.	Mine was flood with 1 person missing.
Shenjia-zhuang Coal Mine	2012	0.36	Karst water from the Ordovician limestone flowed into mine through a concealed KCC that has developed to 50 m below the coal seam.	Mine was flooded.
Huangsha Coal Mine	2011	3	Karst water from the Ordovician limestone flowed into working panel 112106 at depth of 800 m through a compound structure consisting of a KCC and a fracture.	Mine was flooded.
Luotuoshan Coal Mine	2010	2	Karst water from the Ordovician limestone flowed into mine via 870 m return airway of #16 coal seam.	Mine was flood with 32 fatalities.
Dongpang Coal Mine	2003	19.5	Karst water from a karst collapse structure flowed into the mining area.	Mine was flooded.
Wucun Coal Mine	1999	0.67	Karst water from a karst collapse structure flowed into the mining area.	Panel was flooded.
Renlou Coal Mine	1996	19	Karst water flowed into $7_2 22$ working face at depth of ~380 m through a KCC. The collapse connected thin-bedded limestone and Ordovician limestone with the mining area.	Mine was flooded, shut down about 6 months.
Huaxian Coal Mine	1984	0.06	Karst water from a karst collapse structure flowed into surrounding fractures and then into the horizontal drift in the Ordovician limestone.	Drift was abandoned.
Fagezhuang Coal Mine, Kailuan	1984	34	This is the biggest water inflow incident in the world. The mining coal seam was 180 m above the Ordovician limestone, but they are connected by a karst collapse structure. The reactivation of the collapse may be associated with a recent earthquake in this area. Grouting boreholes revealed that the top of the sinkhole was unfilled with sediments.	Mine was flooded, resulted in 9 fatalities, 17 cover sinkholes, and the adjacent three mines were threatened.
Fagezhuang Coal Mine, Kailuan	1983	0.23	A small fault with displacement of 0.2–0.5 m was intercepted by a working stope. Karst water flowed through a karst collapse structure into the fault and then to the working stope.	Working stope was flooded.
Fagezhuang Coal Mine, Kailuan	1978	1	Water flowed into the mine from the sandstone, which is 160 m above the underlying Ordovician limestone. A sluice gate was constructed to isolate the water inflow area and a 0.2-m fracture was revealed, connected with a karst collapse structure.	Part of a drift and a working stope (70,188 m^3) was flooded
Lifeng Coal Mine, Jiaozuo	1967	2	Karst developed very well in the area. Intensive mine water drainage reactivated the karst collapse structure.	A working stope was flooded, and 1 fatality occurred.
Huoxian Coal Mine	1967	0.13	Karst water flowed into an excavating drift through a karst collapse structure and a connecting fault.	Drift was abandoned.
Tongyie Coal Mine, Anyuang	1965	0.39	A water inspection borehole drilled into a karst collapse structure from a drift. The initial water flow rate was 0.5 m^3 min^{-1} and water flow rate increased to 23.3 m^3 min^{-1}. An exploration borehole revealed 17 cavities within 50 m of the collapse with the maximum bit-drop of 2.59 m.	Mine was flooded.

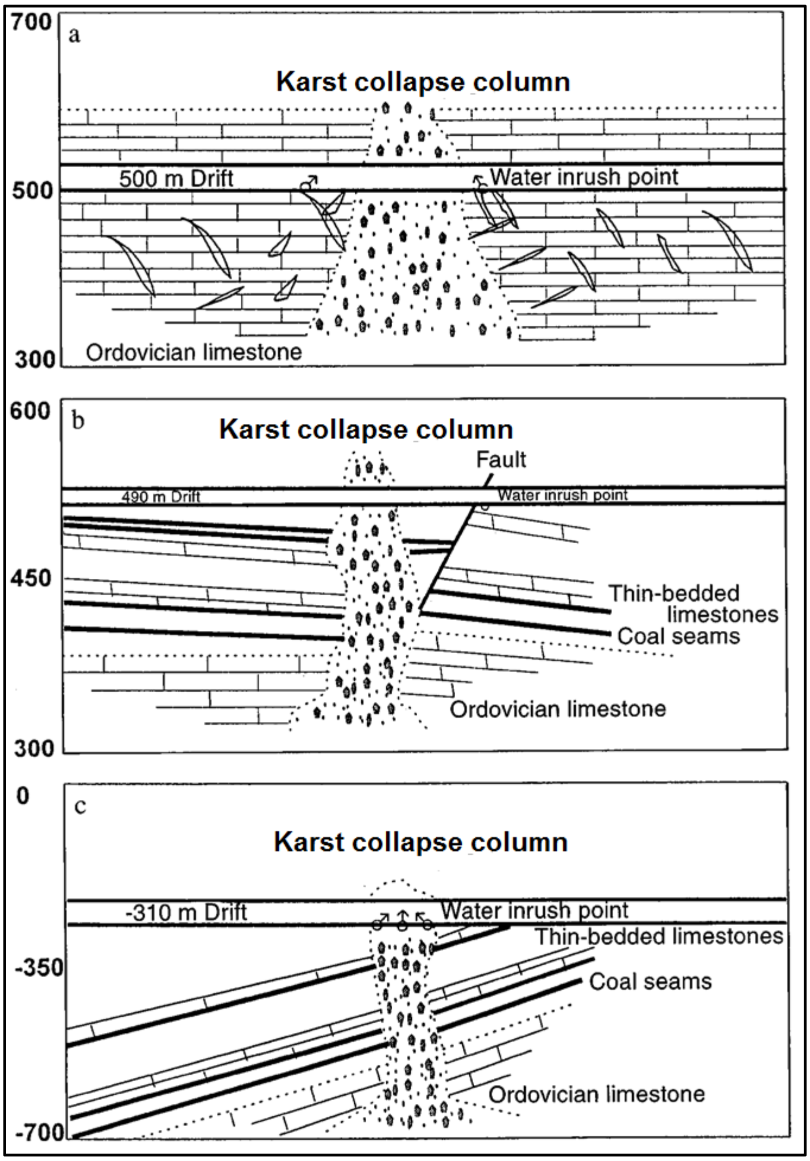

Figure 4a–c. Scenarios where karst water from Ordovician limestone flows into workings through KCCs. 4a through karst collapse-connected fissures; 4b through karst collapse-connected faults; 4c through karst collapse columns (modified from Zhou, 1997). Elevation in meters is shown on the left side of the figure

Table 2 also includes a water inrush that occurred at the mine of this case study, Renlou Coal Mine, Anhui province in 1996. The water inrush occurred in working panel $7_2$22 of 380 m deep. Figure 5 shows the lithology in the mine and the water-inrush point. The panel was flooded within 10 h. The final water level was stabilized at 15.59 m asl, which is approximately the same elevation of the water level in the Ordovician limestone. The maximum water inflow was 19 m^3/s. The water inrush resulted in a water level drop of 7.04 m in an Ordovician limestone monitoring well 16.2 km away. Investigations in response to the water inrush and subsequent grouting confirmed that the water pathway was a KCC. The column was nearly vertical and oval-shaped with long axis of 30 m and short axis of 25 m. Although none of the boreholes reached the bottom of the KCC, the collapse column was at least 300 m high, having its root in the Ordovician limestone and roof in the Quaternary and Tertiary formations. The top section of the KCC consisted of an open void, which suggests that the KCC was still actively developing upward. The mine was restored six months later after a successful grouting program.

A second relatively smaller water inrush occurred at working panel $7_2$18 in the same coal mine in 1999. Timely recognition of water inrush indicators including pressure increase in front of the tunnel, deformation of tunnel support structures, water flow increasing from 5 to 9 m^3/h allowed quick responses so that the risk for a catastrophic water inrush was mitigated by systematic investigation and grouting. No serious damages occurred at the second encounter with production rate slightly affected. The investigation confirmed that this water inrush was also through a KCC that was oval-shaped with its long axis of 40 m and short axis of 30 m. It has developed to a position approximately 20 m below #8 coal seam. This collapse was also actively developing upward.

These water inrush incidents suggest that the hydrogeological conditions in Renlou Coal Mine meet the three basic requirements for a water inrush through KCCs:

- Presence of a karst aquifer that can supply a sustainable water source;
- Active KCCs that are permeable to water; and
- Significantly higher water pressure in the karst aquifer than the elevation of the underground working area, providing the necessary force for water flow.

Therefore, proactive detection of any concealed KCCs and determination of their hydrogeological characteristics have become essential components of a comprehensive investigation program in preventing water inrush incidents and ensuring normal coal production in the mine.

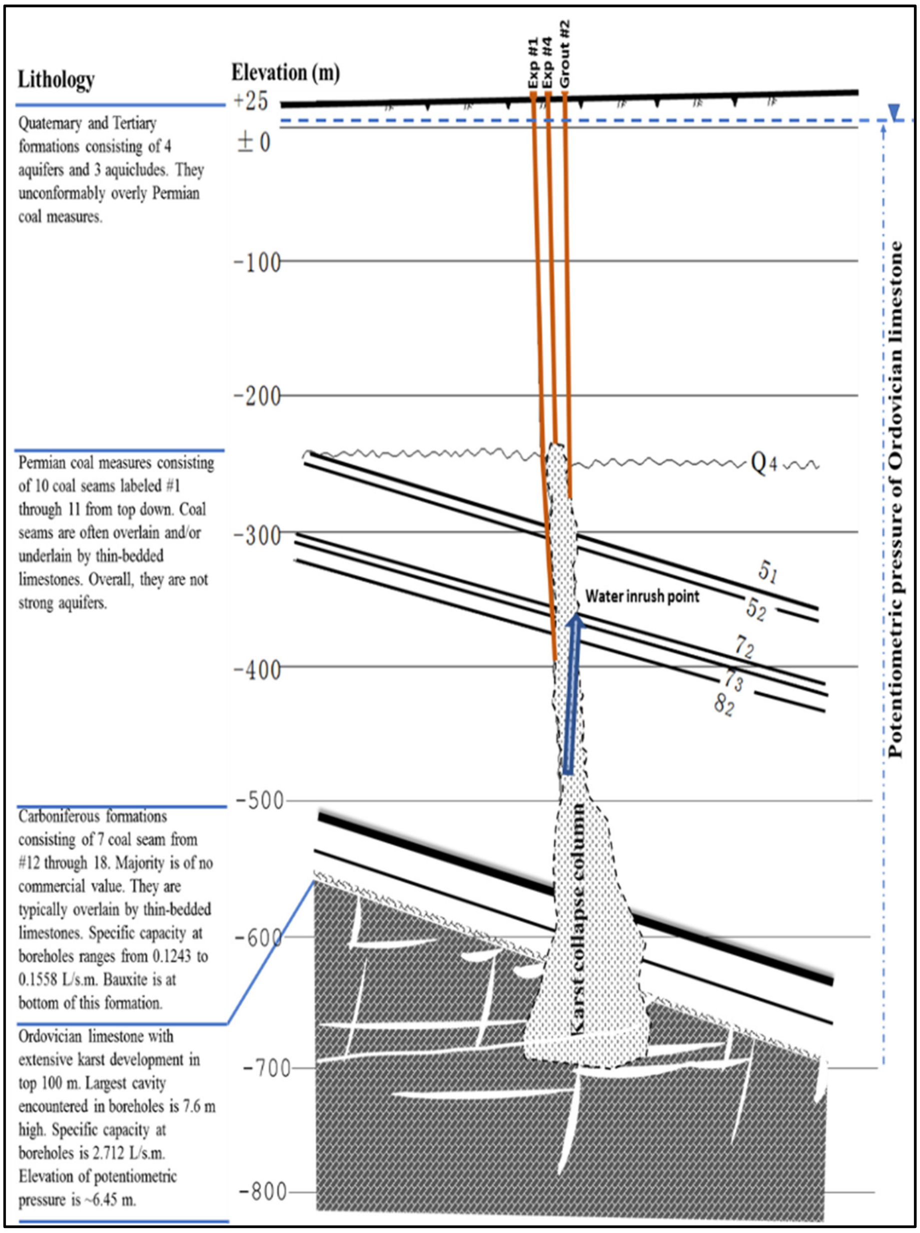

Figure 5. Schematic depicting lithology and 1996 water Inrush at Renlou Coal Mine, China

5. Detection and Remediation of a Concealed Karst Collapse Column in Renlou Coal Mine

In June 2010, an anchor hole advanced in II 5_1 Tunnel encountered groundwater. The tunnel was at elevations from -718.6 to -720.1 m bsl and was excavated for mining #5_1 coal seam. The tunnel was 440 m below the Quaternary and Tertiary formations and at least 300 m above the Ordovician limestone. The stratigraphy encountered by the tunnel consisted of fine sandstone and mudstone with petrified plant parts. Under normal conditions, water in these formations was limited and did not pose safety threat to underground workings. The tunnel also intercepted a normal fault, DF_8, with 5 m displacement. No water seepage was observed through the fault.

5.1 Water Source Discrimination by Temperature and Hardness Measurements

As shown in Figure 6, two exploration boreholes, 4-3 and 4-3', were advanced at different angles to investigate the source and pathway of the groundwater encountered at the anchor hole. At an angle of 47°, borehole 4-3 intercepted fault DF_8, whereas at an angle of 40°, borehole 4-3' intercepted a high-angled (75°) fracture. The maximum groundwater flow rate at borehole 4-3 was 2 m^3/h, and the maximum flow rate at borehole 4-3' was 16 m^3/h.

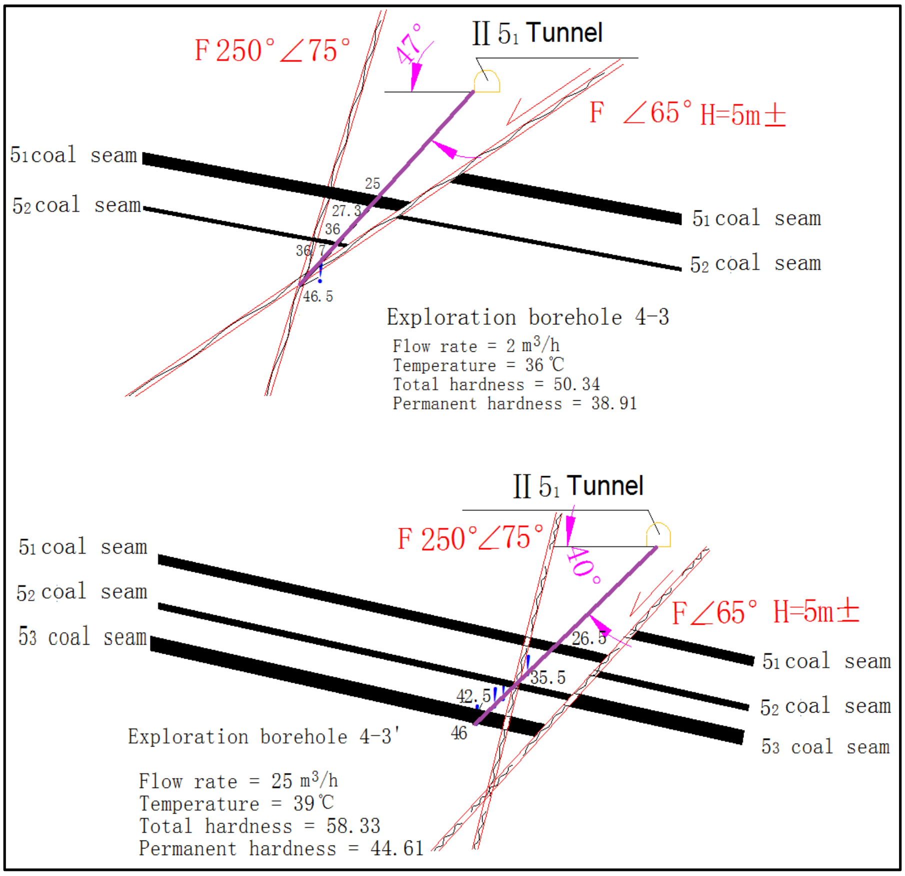

Figure 6. Layout of boreholes 4-3 and 4-3' for exploration of water sources

Figure 7 shows changes of water temperature and hardness at borehole 4-3 from June 2010 to November 2011. Data at borehole 4-3' had similar trends. Over a period of 17 months, the water temperature gradually increased from 33 to 41°C. The normal earth temperature at this elevation in the mine is approximately 35°C. The higher than normal temperature in the inflow water indicated that the water source was from deeper formations.

Two types of hardness are presented in Figure 7, the total hardness was measured prior to boiling and permanent hardness was measured after boiling. Their unit is degree of General Hardness or German degree (dGH). Both types of hardness show a general trend of increasing. The total hardness increased from 8.34 to 60.58 dGH, whereas the permanent hardness increased from 0 to 48.81 dGH. The persistent increases in the hardness also suggest that the water sources were from the deeper formations. The measured temperature and hardness at end of the monitoring period were similar to those measured in the Ordovician limestone in the mine.

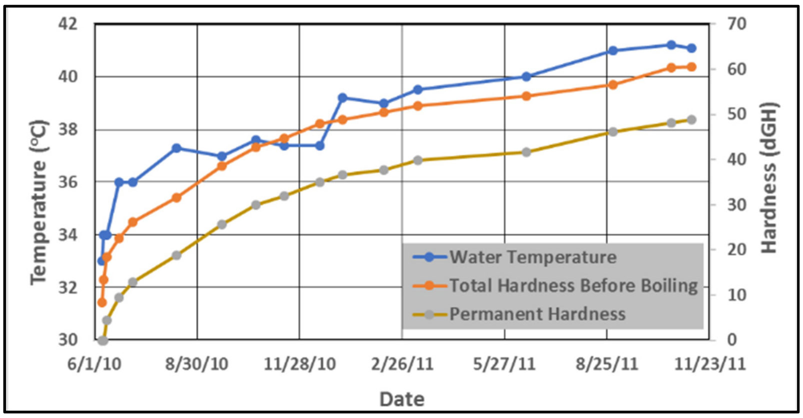

Figure 7. Water temperature and hardness measurements at boreholes 4-3

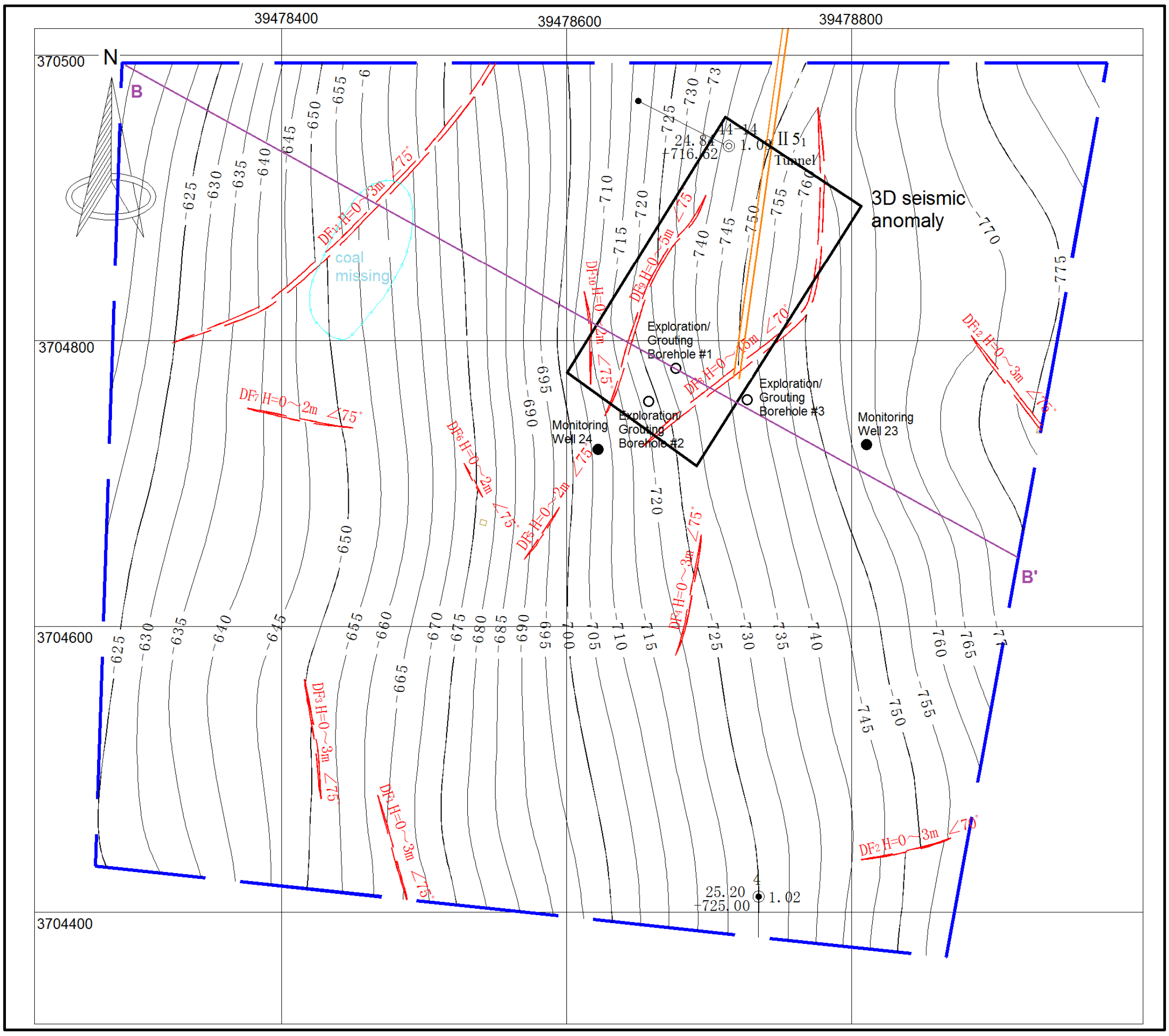

Figure 8. Contours of 5_1 coal seam elevation as interpreted from 3D seismic survey

5.2 Geophysical Investigations

Geophysical surveys were conducted to investigate any geologically and hydrogeologically anomalous areas. Time domain electromagnetic methods (TDEM) and 3D seismic were used on the ground surface, while TDEM, 3D seismic, earth resistivity imaging, and ground penetrating radar were used underground in II 5_1 Tunnel.

Anomalies identified and verified from multiple geophysical techniques were considered the targets for further investigations. Figure 8 shows an example of 3D seismic interpretation of the #5_1 coal seam elevation. The rectangular is a geophysical anomaly in which the coal seam elevations were distorted. A vertical profile of the 3D seismic is shown in Figure 9. The geophysical anomaly was interpreted to be associated with a KCC.

5.3 Borehole Exploration

Figure 8 shows the locations of three exploratory and grouting boreholes #1, #2, and #3, and two monitoring wells #23 and #24. The monitoring wells were installed to monitor potentiometric pressures of the Ordovician limestone. The exploratory boreholes were drilled in the order of #1, #2, and #3. They were drilled in the geophysically interpreted anomaly to investigate the subsurface conditions, in particular, to confirm presence of the KCC. If the KCC was confirmed, these boreholes were then used as grouting holes to construct a water plug within the collapse feature. Borehole #1 was vertical, while directional drilling was used in both boreholes #2 and #3 to intercept the KCC encountered in borehole #1. Figures 10 and 11 shows the profiles from borehole #1 through borehole #2 to monitoring well 24 and from borehole #1 through borehole #3 to monitoring well 23, respectively. Table 3 summarizes the pertinent observations in these three boreholes.

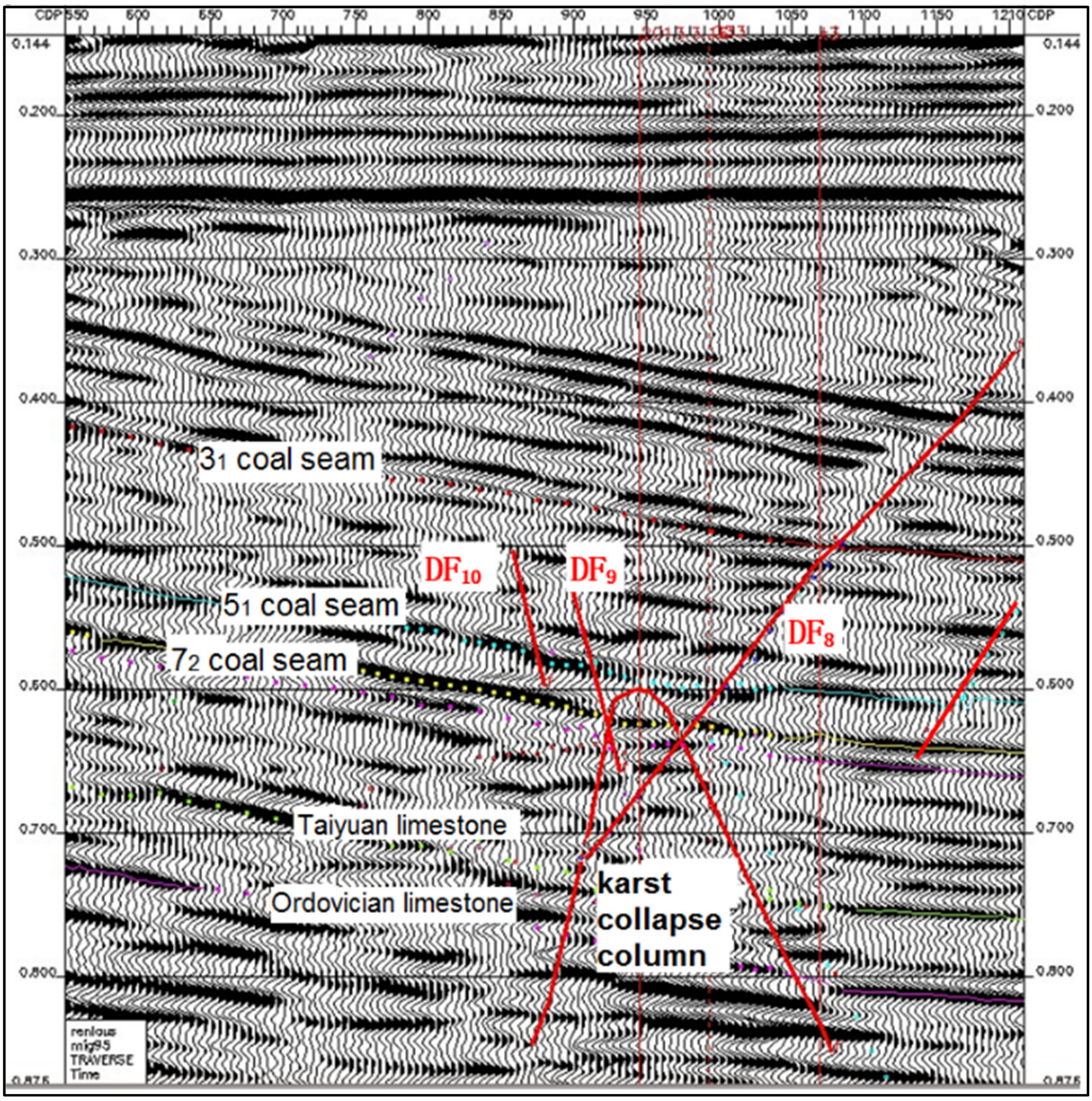

Figure 9. A cross-section of 3D seismic survey (location of the cross-section is shown in Figure 8)

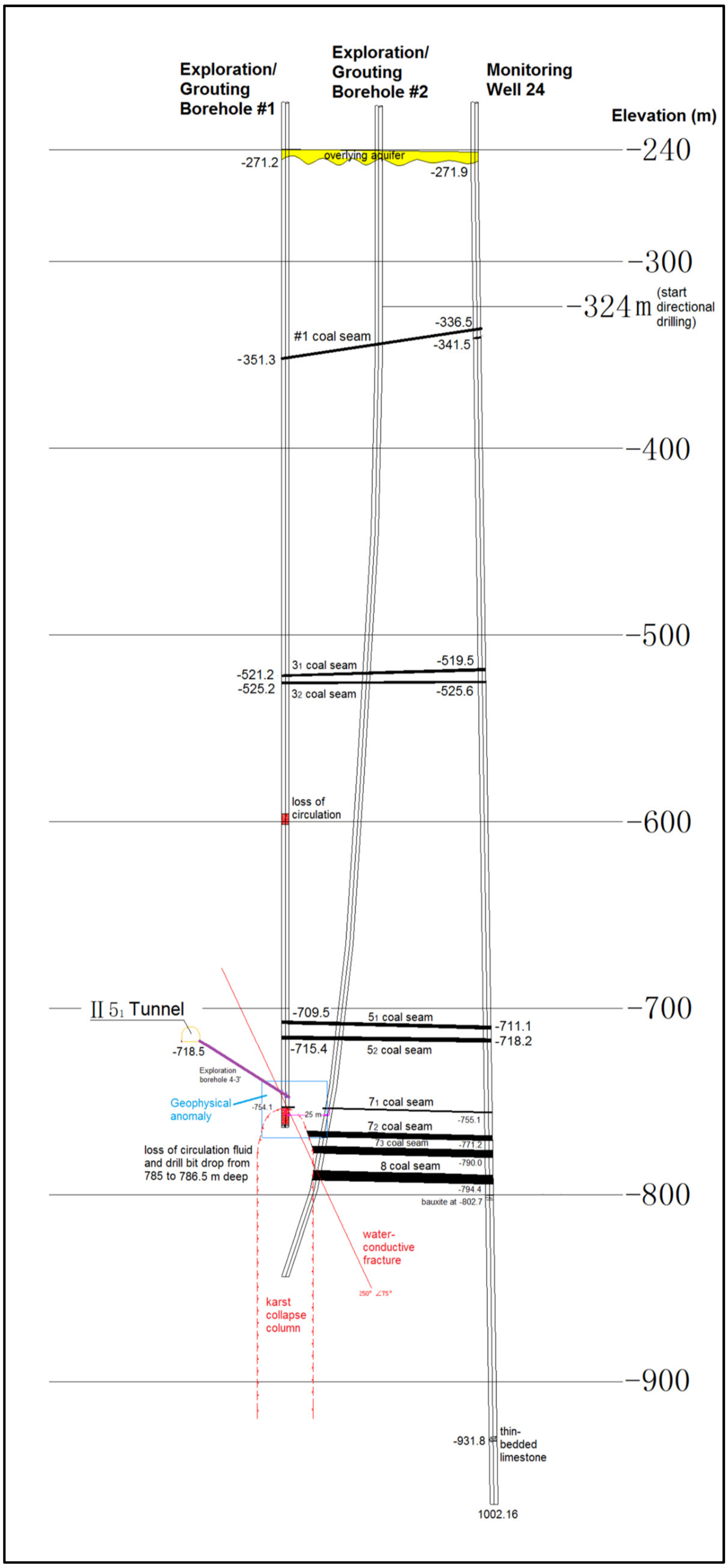

Figure 10. Profile of exploration/grouting boreholes #1 and #2

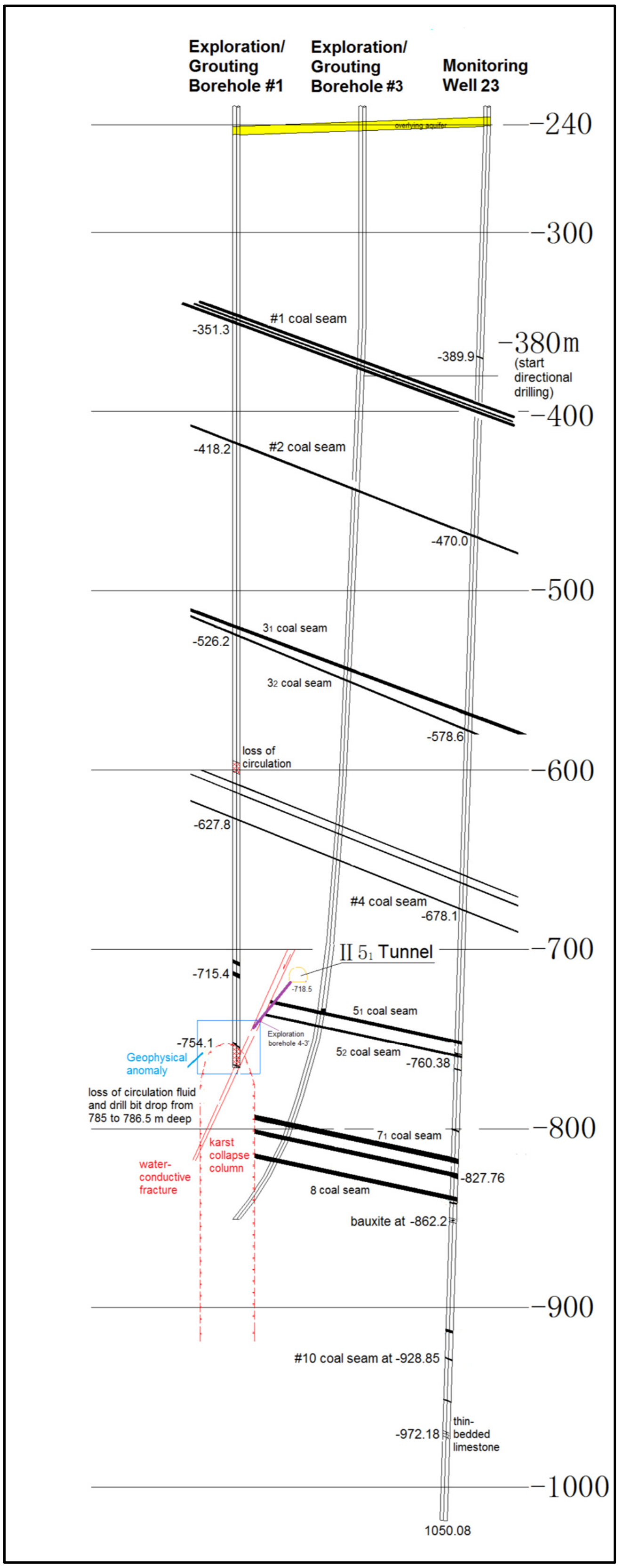

Figure 11. Profile of exploration/grouting boreholes #1 and #3

Table 3. Summary of drilling parameters at three exploration/grouting boreholes

Parameters	Exploration/Grouting Boreholes		
	#1	#2	#3
Total depth (m)	920.48	920.57	986
Directional drilling		At 350 m toward borehole #1	At 380 m toward borehole #1
Depth to bedrock (m)	271.2	273.7	273.1
Depth to #1 coal seam (m)	376.8	360.0 - 369.6	395.05
Depth to #5 coal seam (m)	740.8	764.9	758.7
Loss of circulation intervals (m)	▪ 627 – 694 ▪ 785 – 787	▪ 609 – 619 ▪ 773 – 775 ▪ 863 to 865 ▪ 885	▪ 739 983
Drilling bit drop (m)	1.5 m from 785 to 786.5; likely entering collapse body	2 m from 773 to 775; likely entering collapse body	
Grouting (t)	1,366 t (935 tons at 791 m; 81 t at 820 m; 159 t at 842 m; 191 t at 900 m)	1,920 t (445 t at 803 m; 245 t at 835 m; 180 t at 855 m; 110 t at 865 m; 270 t at 865.5 m; 140 t at 885 m; 70 t at 905 m; 420 t at 920.57)	295 t at 911 m
Post-grouting water intake capacity (L/min.m.m)	0.00099	0.00091	0.00214

Both boreholes #1 and #2 encountered drill bit drops and total loss of circulation. The bit drops at boreholes #1 and #2 were 1.5 m and 2 m, respectively. The loss of circulation was greater than 72 m^3/h where the drill bit drops occurred. The drops occurred at depths between 773 and 787 m. Such characteristics were atypical of the formations at these intervals unless a KCC or large fracture was present. The exploratory and geophysical results suggested that this feature was likely a KCC. The KCC had an oval shape, and its dimensions were estimated to be 55 m in the long axis and 40 m in the short axis. The bottom of the KCC was unknown and its roof was approximately 20 m below #5 coal seam.

Grouting at boreholes #1 and #2 further confirmed that both boreholes intercepted the top of the KCC. Grouting materials injected at borehole #1 were observed at borehole #2 as well as in II 5_1 Tunnel. Since borehole #3 was advanced after grouting at boreholes #1 and #2 was completed, it encountered cement-filled void and the amount of grout was significantly reduced in borehole #3. Water injection tests were conducted at all three boreholes before completing the grouting. The results (Table 3) demonstrated that the water intake capacity was less than the designed value of 0.01 L/min.m.m. The water intake capacity was calculated by water injection rate (L/min) divided by applied pressure (m of water) and test interval (m). Another indicator of the grouting success was that the post-grouting groundwater flow into II 5_1 Tunnel was minimal and the remaining water seeped from the overlying formations as verified with water quality parameters. The water levels in monitoring wells 23 and 24 were measured to ensure the long-term success of the investigation and remediation effort.

6. Conclusions

KCCs are karst features that were often encountered in mines of north China. Because these karst features could be several hundred meters high, they can connect multiple aquifers and lead water to underground workings under the following conditions:

- The KCC is active and permeable to water.
- The KCC is connected to water-bearing media (aquifers or water pools) that can supply a significant water source.
- The water pressure in the water-bearing media is higher than the elevation of the underground working area.

Because of potential damages that can be caused by these structures in mines, proactive detection of any concealed KCCs and determination of their hydrogeological characteristics are essential components of mine water control and prevention programs in China. Multiple techniques including geochemistry, geophysics, directional drilling, grouting, and water injection testing were proved to be effective in detecting and characterizing a concealed KCC in Renlou Coal Mine. The risks posted by the KCC were successfully mitigated by directional grouting.

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