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Impact of karst water on coal mining in North China

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Abstract Coalfields in North China encompass more than ten Provinces. They contain six to seven coal seams in the Permo-Carboniferous strata. The lower three seams account for 37% of the total reserves and are threatened with intrusion of karst water from the underlying Ordovician limestone. Hundreds of water inrush incidences have occurred, in which a large amount of water suddenly flows into tunnels or working faces under high potentiometric pressure. Over 50 mines have been flooded over the last 30 years. Large-scale dewatering or depressurizing of the karst aquifer was considered essential to avoid water inrushes and keep the mines safely operational. This practice, however, has caused sinkholes, dry springs, water supply shortage, and groundwater contamination in the surrounding areas. One alternative water control measure is to make full use of the rock layer between the coal seam and the karst aquifer as a protective barrier to prevent or constrain water flow from the underlying aquifer into the mines. Grouting is effective when the hydrogeological conditions are favorable to this technique. Proper design of the grouting program and experience of the contractor are also important for a successful application.

Keywords Coal mining · Karst water · Water inrush · Dewatering · Grouting · North China

Introduction

In China, karst occurs and is distributed widely in rocks that range in age from Archaeozoic to Cenozoic, but are predominantly Paleozoic. Carbonate rocks occupy an area of approximately 3.25 million km^2 of the country, including 1.25 million km^2 of bare karst and 2 million km^2 of covered or buried karst (Yu 1994). Groundwater in the karstified carbonate rocks is a valuable natural resource for the local people. Unfortunately, many mineral deposits such as coal, iron, lead and zinc, gold, aluminum, and copper lie in between, or above, or below the karst aquifers. The karst water-impregnated deposits constitute the majority of the mines that have a pumping rate greater than 60 m^3/min. At least 30 coalfields in North China and 20 coalfields in South China are currently threatened by karst water, as shown in Fig. 1.

The coal seams in North China lie in the Permo-Carboniferous strata (Fig. 2). The Taiyuan Formation of the Carboniferous system has a thickness of 95–163 m and consists of argillaceous shale and sandstone. From the top and moving downwards, the coal seams are Xia-jia, Da-xing, Xiao-qing, Shan-qing, Ye-qing and Yi-zuo. Their total average thickness is 9 m. Their roofs consist of mainly thin-bedded limestone with a varying thickness from 2 to 7 m. The water in the thin-bedded limestone may pose a threat to coal mining only when they are hydraulically connected with surface water or the underlying Ordovician limestone through faults or paleo-collapses. Figure 3 shows various recharge sources to the thin-bedded limestone.

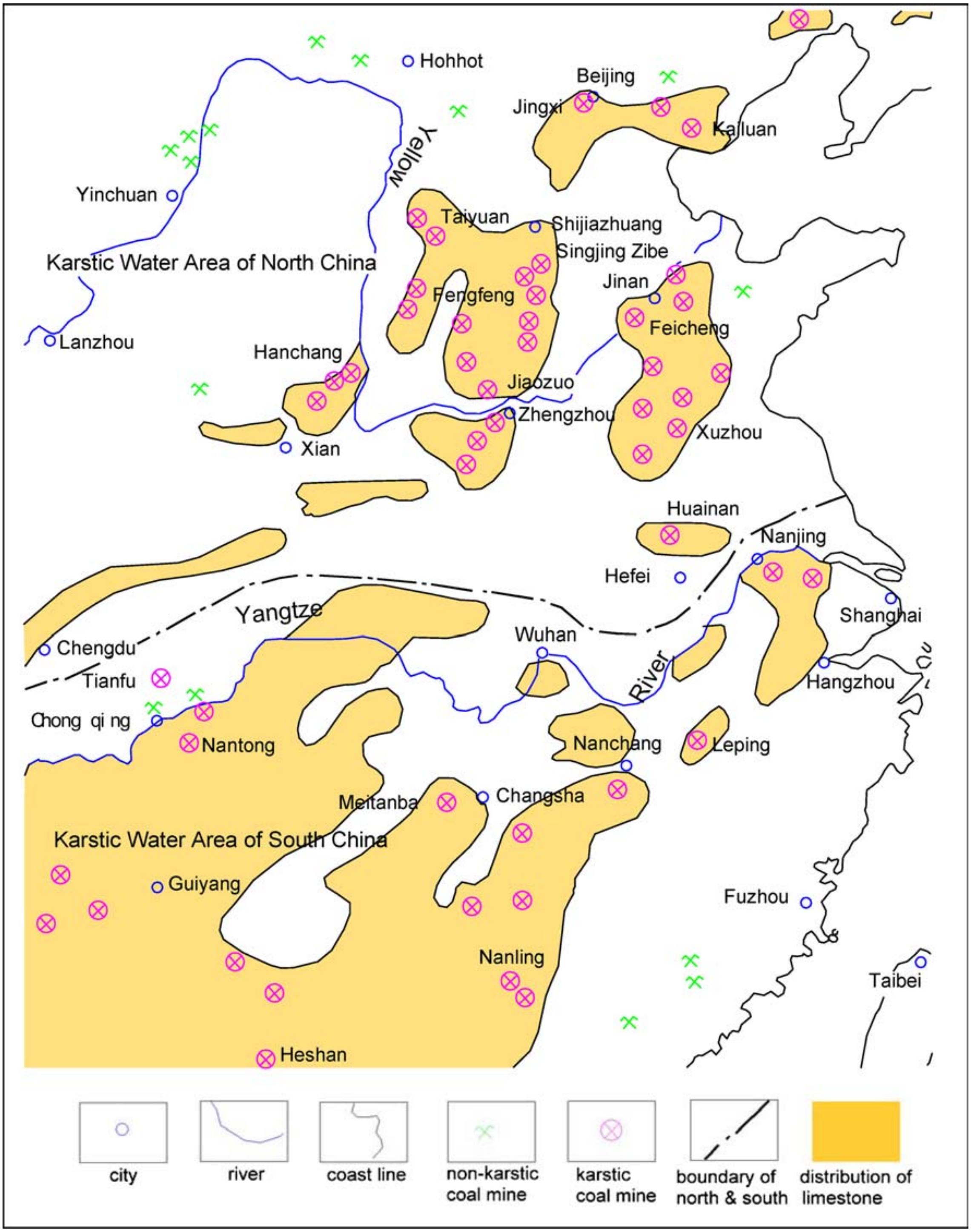


Fig. 1 Coalfields affected by karst water in China

The Shanxi Formation of the Permian system has a thickness of 90 m. It includes one coal seam—Da-mei with the thickness of 6–7 m. Beneath the Taiyuan Formation, the Benxi Formation is 18–53 m thick and consists of arenaceous shale, bauxite shale and iron ores. The underlying Ordovician limestone is a highly permeable confined aquifer and is characterized by heterogeneity and anisotropy in transmissivity and porosity. Its average thickness is 650 m. Because of the potential impacts of the confined water in the Ordovician

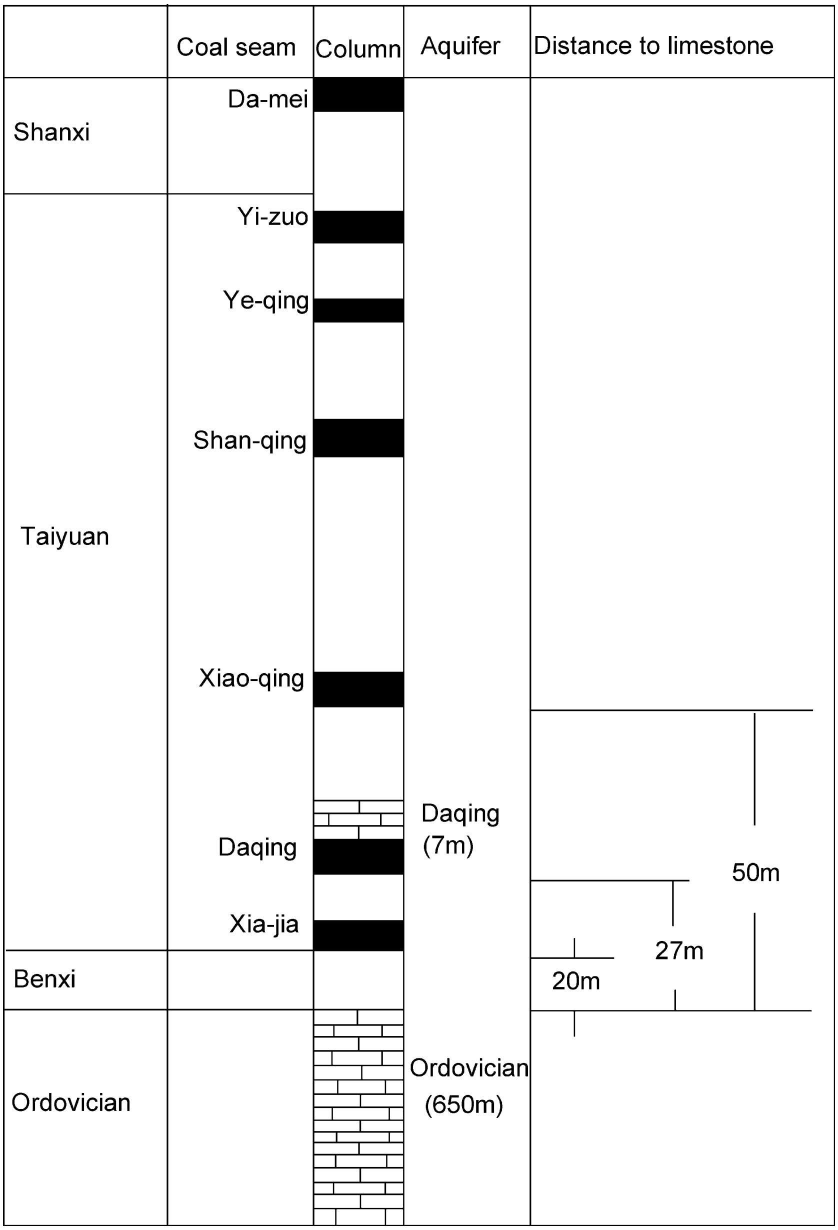


Fig. 2 Typical coal seams overlying the Ordovician limestone in North China

limestone on the mining activities, the three lower coal seams, accounting for 37% of the total reserve, are listed as prospective reserves.

Water inrush

One of the major impacts of groundwater intercepted by mining activities is the unpredictable occurrence of water inrush, during which a significant amount of water suddenly invades the underground working areas from the underlying karst aquifer under potentiometric pressures. The inflow is often several or even tens of times larger than the pumping capacity of the affected mine. Mines can be flooded within hours. Out of the 137 disastrous water inrushes reported by Li and Zhou (1988), 73% have water flows between 10 and 50 m^3/min, 16% have water flows between 50 and 100 m^3/min and 11% have water flows greater than 100 m^3/min. Over 50 mines have been flooded. The largest water inrush in China and in the world occurred in the Fangezhuang Mine of North China, in which the water flow was approximately 2,000 m^3/min.

In North China, over 130 mines are threatened by karst water. Water problems have caused lower production from some of the mines, environmental con-

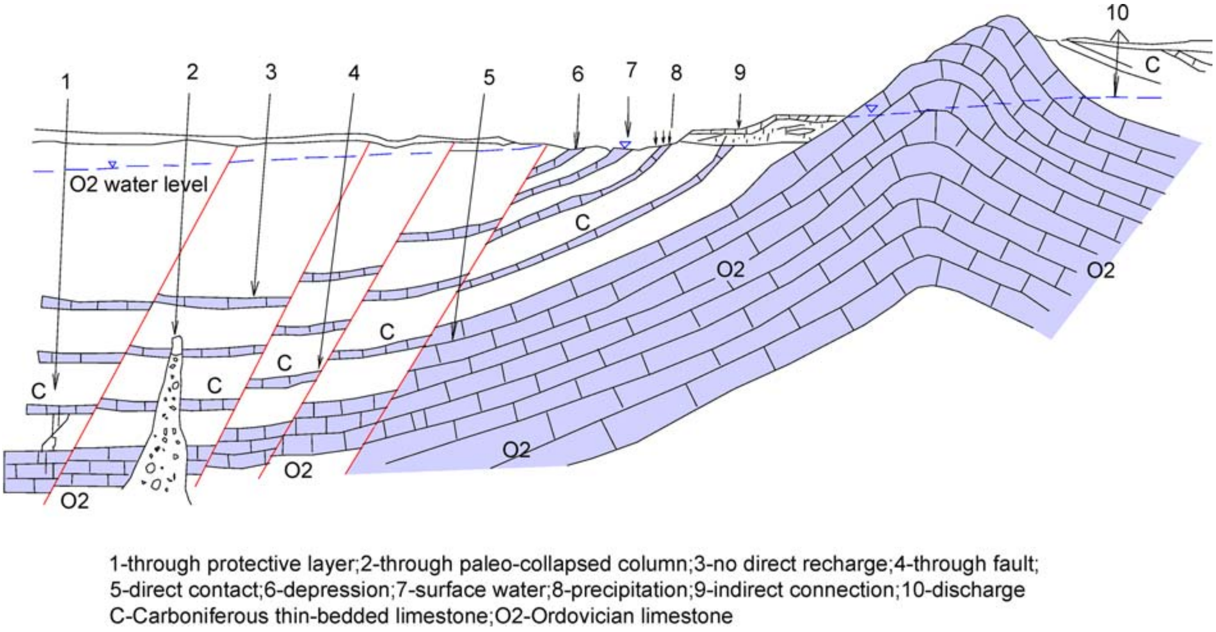


Fig. 3 Recharge sources to Carboniferous thin-bedded limestone

cerns and even loss of lives. It is believed that the water problem can become more severe as the mining levels lower. It is estimated that more than 15 billion tons of coal may not be exploited if the water threat is not addressed (Li 1990).

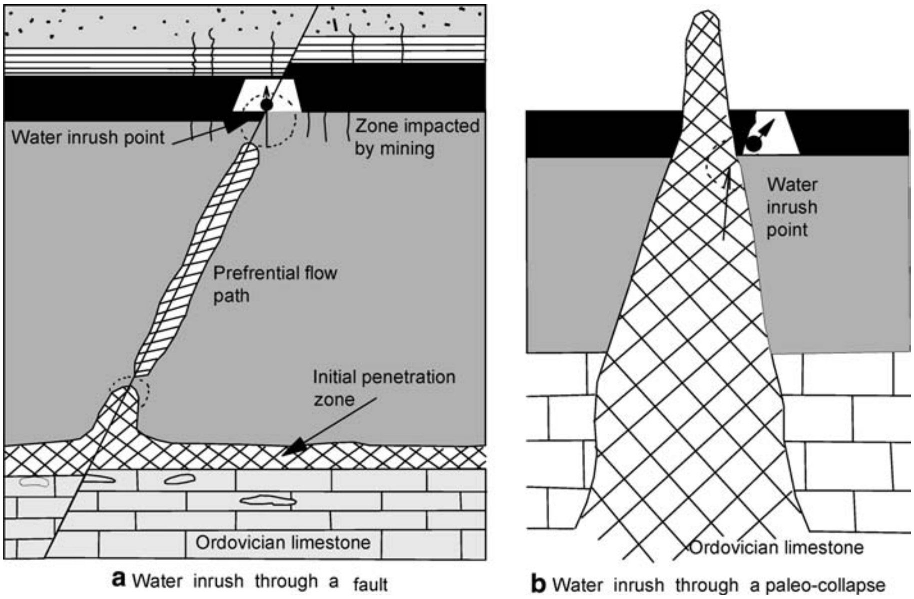
Effect of geologic structures on water inrush

The position of water inrush is often related to geologic structures. Faults, fracture zones, anticline and synclinal axes are more susceptible to water inrush and constitute the weak zones and preferential flow paths for the confined karst water. Because of fault displacements, in some locations the coal seams are in direct contact with the limestone aquifers. Faults can also connect different aquifers. Figure 4 shows the typical flow paths of the karst water to the underground workings. In the coalfields of North China, over 78% of the water inrushes are related to faults and fractures. In Hungary, 75–80% of the inrushes occurred along faults, 16–21% in fractured zones, and only 4% were not related to geologic structures (Kesseru 1997).

Paleo-collapse columns are another geologic feature through which water inrushes occurred. Paleo-collapse columns were encountered in over 20 coalfields in North China, including those in Shanxi, Hebei, Hena, Shandong, Shaanxi and Jiangsu Provinces. Over 400 paleo-collapse columns have been exposed in the working stopes in the Duerping Mine of Xishan Coalfield, Shanxi Province. Most of the paleo-collapses originate in the Ordovician limestone and develop into the overlying Permo-Carboniferous coal strata. A paleo-collapse feature can be over several hundreds meters high. These paleo-features complicate the mining operations and some of them are permeable to water. The largest water inrush mentioned above was through a massive paleo-collapse column, which was 280 m high and 50 m in diameter.

Control of protective barrier on water inrush

The effectiveness of a protective barrier depends on its thickness, lithology and integrity. Areas with thick barriers are less vulnerable to water inrush. Mining of the four upper coal seams in the Fengfeng Coalfield has been free of water inrushes because the protective barrier is more than 80 m thick. The thickness of the protective barrier for the three lower coal seams varies from 20 to 50 m, and mining has experienced water inrushes. Estimation of the thickness of the protective barrier is challenging because of the existence of the paleo-weathering surface of the Ordovician limestone. The Ordovician limestone was exposed to the surface for over 80 million years before the Carboniferous materials were deposited (Fig. 5). Therefore, the bedrock surface of the Ordovician limestone is very irregular and is characterized by pinnacles and cutters. Exploratory boreholes revealed both clay-filled and open voids on the bedrock surface. X-ray diffraction analysis of the clay in the fractures or voids indicated that the clay consists of



a Water inrush through a fault **b** Water inrush through a paleo-collapse

Fig. 4 Common passageways for water inrushes

both kaolinite and illite. The clay contained trace elements of boron (2,500 mg/l), thus defining its marine origin. The ratio of strontium and barium also confirmed a marine origin of the clayey materials.

Limestone and sandstone do not rupture easily under water pressure. A layer of medium-grained sandstone of 2 m can bear 7 kg/cm^2 of water pressure. Flexible rocks such as shale, however, are not as strong, but they may have higher capacity of water resistance. The lithology that provides the best protection against water inrush consists of inter-bedding layers of flexible and hard rocks. For example, in the Wangfeng Mine, 16 m of protective barrier successfully supported mining under a water pressure of 8 kg/cm^2.

The protective barrier does not have to be impermeable to water flow. If seepage occurs, the barrier reduces the potentiometric pressure. In-situ tests indicated that 1 m of bauxite could reduce up to 33 m of potentiometric pressure, whereas 1 m of coarse sandstone would only reduce 0.16 m of pressure (Li 1990).

Effect of mining activities on water inrush

Because mining activities destroy part or all of the protective layers, water inrush takes place when the groundwater is not under artesian pressure and water inrushes are more likely to occur at the working face than in the shaft. The space and span of a working face has a significant influence on the water-resisting capacity of the protective layer. Of the 56 water inrushes in Zibo, 90% took place in working faces of 20 m width (Li and Zhou 1988). During the mining of the Da-mei coal seam in Jiaozuo, the majority of water inrushes occurred in the faces of 20–25 m width. Water invasions in shafts may happen with a delay of 1–2 years after excavation of the shaft because of the long-term effect of shaft excavation on the floor.

The influence of mining activities on the protective layer has been studied using the gas-discharge data from coalmines (Li 1990). Gas flow was observed 20–80 m below the coal seam after mining. Because of the dif-

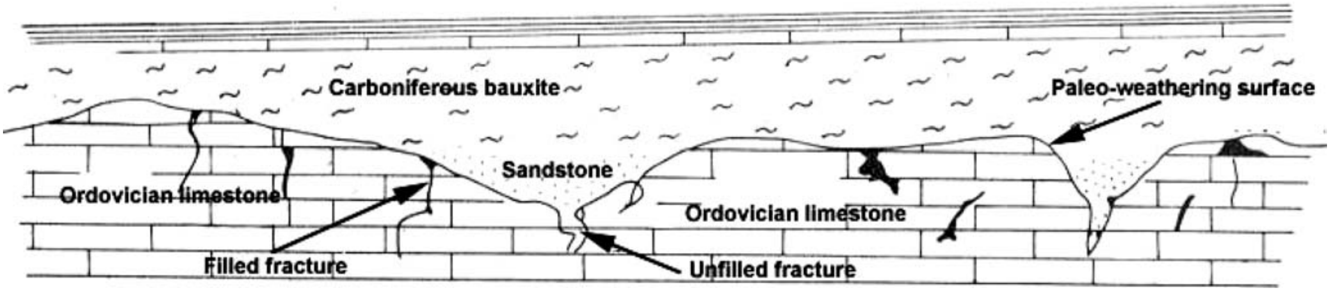


Fig. 5 Paleo-weathering surface of the Ordovician limestone

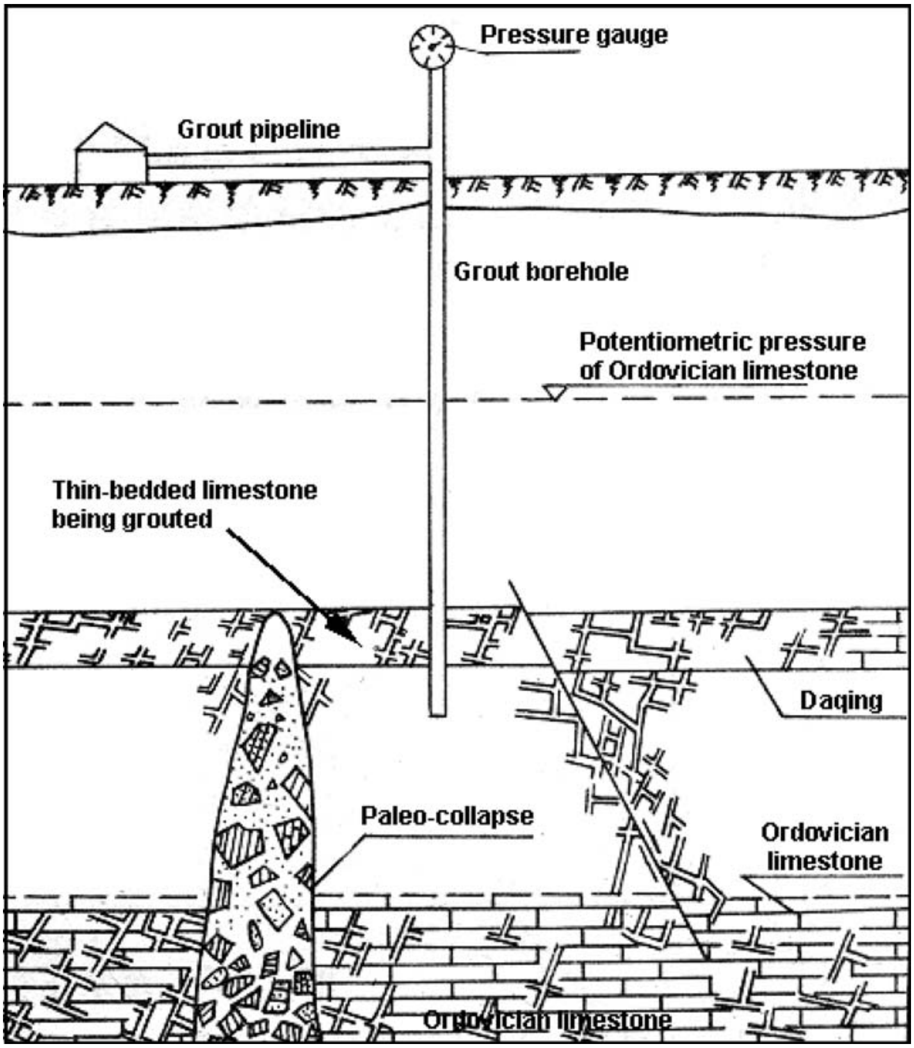


Fig. 6 Grouting operations to control karst water

ferent properties of gas and water, fractures that conduct gas may not transmit water. In-situ water-injection tests are the best way to investigate the destroyed thickness. In water-injection tests, boreholes were drilled into the protective layer of a mining slope, with each hole being terminated at a specific depth. The change in the volume of water flowing through the boreholes during mining indicates the extent to which the protective layer is affected by mining. On average, the thickness of the protective barrier destroyed by mining activity was approximately 8 m in North China.

Effect of the potentiometric pressure of Ordovician limestone on water inrush

Obviously, water invasion occurs more easily under higher water pressures. When the Shaqing coal seam was mined at 90 m depth (below ground surface) in the Fengfeng Coalfield, water pressure in the Ordovician limestone was 22 kg/cm^2 and the protective layer was 40–45 m thick. No water inrushes took place. When the mining level was extended to a depth of 170 m, the water pressure increased to 30 kg/cm^2, and six water inrushes occurred although the protective layer remained the same. In the Hanwang Mine of the Jiaozuo Coalfield, a 30 m increase of the water level caused by a water inrush in an adjacent mine resulted in four water inrushes.

The permeability of the protective barrier is in general low; however, fractures exist in the barrier. When the fractures in the barrier are connected with the underlying limestone, the karst water in the limestone penetrates upward into the barrier under potentiometric pressure. The initial conductive zone tends to be thicker in harder rocks with better-developed fractures. A greater conductive zone may also develop around paleo-collapsed features (Zhou 1997). Both the initial conductive zone and the mining activities reduce the effectiveness of the geologic barrier to prevent water from invading the mines.

Effective measures reducing water inrush risk

Reduction of water inrush risk in coalmines requires the determination of the hydrogeological conditions in the Ordovician limestone. Investigations should focus on the preferential passageways through which the karst water may flow. The potentiometric pressure of the Ordovician limestone and the thickness of the protective barrier should be known to provide a decision. Techniques used for such investigations include field mapping, karst features inventory, water-injection or water-releasing aquifer tests, tracing tests, hydrochemical analyses, and groundwater monitoring. Surface and underground geophysical surveys, such as well logging, seismic, radar and radioactive measurements, are also useful in determining high-risk areas.

Dewatering

Dewatering or depressurizing of the Ordovician limestone has been essential to keep the mines safely operational. However, this practice is favorable where the karst hydrogeology is relatively simple, or in areas where the coal resources are very limited. In some mines, as much as 100 m^3 of water need to be pumped for every ton of coal. The feasibility of dewatering or depressurizing the Ordovician limestone depends on the hydrogeological condition of the aquifer, especially its boundary conditions. For example, in the Yangquhe Mine of the Fengfeng Coalfield, tracing tests using bromide revealed that the only recharge source to the Ordovician limestone in the mine area was from the northwestern corner where the limestone is shallow. As depth to limestone becomes greater, the water gradually becomes static. Accordingly, the water chemistry changes from the HCO_3-type through the SO_4-type to the CL-type. Water-releasing tests indicated that the Ordovician limestone underlying the coal seams could be economically drained. However, complete draining of an aquifer is generally not recommended. In addition to the expenses of dewatering, this method may result in many engineering and environmental problems, including sinkholes, dry springs, shortage of water supply, and surface water and groundwater contamination (Zhou 1997).

Mining under potentiometric pressure

Data on the water inrushes indicate that potentiometric pressure of the Ordovician limestone and the thickness of the protective barrier are the two main controlling factors. The ratio of the water pressure measured in boreholes and the effective thickness of the protective barrier is often referred to as the water inrush coefficient (Li 1990). In the studied area, approximately 90% of the water inrushes occurred when the inrush coefficient exceeded a threshold value. In the Fengfeng Coalfield, the critical inrush coefficient ranges from 0.65 to 0.8 $kg/cm^2/m$. In the Wangfeng Mine of the Handan Coalfield, the critical value is 0.8 $kg/cm^2/m$, whereas in the Jiaozuo and Zibo Coalfields the coefficient is approximately 0.66 $kg/cm^2/m$. Therefore, it is possible to extract coal by regulating the inrush coefficient. Both decrease of the potentiometric pressure and reinforcement of the protective layer can reduce the water inrush coefficient. As long as the water inrush coefficient does not exceed the critical threshold, coal seams can be mined without a significant risk of water inrush.

When the Xiaoqing coal seam was mined in the Wangfeng Mine, the protective layer was 22 m thick and the potentiometric pressure of the underlying limestone ranged from 13 to 18 kg/cm^2. The calculated inrush coefficient was 0.8–1.4 $kg/cm^2/m$, which was greater than the critical value of 0.8 $kg/cm^2/m$ in the mine. Water-releasing boreholes were used in tunnels to decrease the water level in each working area by 40–100 m so that the inrush coefficient was smaller than the critical value. No water inrushes took place during mining. The water-releasing boreholes were sealed after mining, and the water level was eventually restored to its original level. This mining approach is applicable to the three lower seams in most of the mines of the studied area. Working stopes with the water inrush coefficient smaller than the threshold are less vulnerable to water inrush. However, water inrush risk may exist because of uncertainty in the data and complex hydrogeology. Throughout many years of practice in the mining industries, a suite of techniques has been developed for use with this mining method (Li 1990) to ensure that the karst water is properly controlled.

Grouting

Grouting is an effective way to block or cut off the flow paths to coalmines. Cement or mud is injected into designated boreholes to establish grout curtains. Practices indicate that shallow (<100 m) blockage is more effective. Grouting is also used to interrupt the hydraulic connection between flooded mines and production mines. Grouting can prevent surface streams from recharging the karst aquifers and can rejuvenate dried springs. Figure 6 shows the general layout of the grouting technique to control mine water.

The first grout curtain was established in 1964 in the Qingshan Mine of the Xuzhou Coalfield, Jiangsu Province (Li 1990). The grouting took place in a thin-bedded limestone overlying the Ordovician limestone and the depth of the grouting holes varied from 15 to 85 m. Over the last 40 years, many grout curtains have been constructed in the mines in North China to control water inflows. The length of the completed grout curtains varies from 260 to 3,115 m. The deepest grout curtain was 600 m deep in the Ordovician limestone in the Zhangmatun Mine of the Shandong Province.

The successful application of grouting techniques to water control in mines requires a thorough understanding of the hydrogeology of the mine and immediate surroundings. Grouting is not the answer to all water problems. Grouting techniques are only applicable to the mines in which hydrogeological conditions are characterized by the following.

1. The fractures in the grouting rock are well interconnected so that a continuous grout curtain can be established. When the fractures are not connected, some of them may not be filled by grout, especially when the number of grouting holes is limited. As a result, gaps may be present in the grout curtain. One of the most favorable grout locations is the epikarst zone of the limestone.
2. The aquifer that poses the threat to mining has one or several distinct recharge sources and these recharges account for the majority of the water flowing into the mine.
3. Groundwater flows through one or a few preferential flow paths and these flow paths can be clearly delineated in three dimensions.

In addition to hydrogeological conditions, grouting design is another important factor in curtain effectiveness. The choice of grout depends on site-specific conditions, such as rock type, rock stress, groundwater quality, and the volume of water. The grouts commonly used in mines were clay grouts and cement slurries. Clay grouts are used to fill large volumes of small voids in weak zones. They can be produced locally in many mines. Colloidal suspensions can fill voids as small as 0.1 mm. The setting time can be infinite. Moderate strength can be obtained by adding 50–60% of cement, but in many cases low-strength is adequate for reducing flow. The grout curtain established in the Yanmazhuang Mine of the Jiaozuo Coalfield was composed of 93% of local clay. The curtain reduced the mine flow by 18 m^3/m.

Cement slurries are used to fill voids in competent rock, preferably free of clay. They can enter fractures or voids larger than 1 mm. Admixture of sodium silicate and bentonite can improve penetration. Sand, clay, or fly ash can be mixed with cement to produce sand–cement slurries, clay–cement slurries, or sand–cement–fly ash slurries. Their setting times vary significantly. The water–cement ratio is important in controlling the behavior of cement slurries. A high ratio may help the slurries to get into smaller openings further away from the grout holes, whereas low ratio slurries limit movement in the vicinity of the grout hole.

Chemical grouts such as acrylamides and chrome lignins, and resorcinol formaldehydes were also used on special occasions. They have very low viscosity. The setting time varies from a few minutes to hours, and admixture of the accelerator before injection can accurately control the setting time. Because chemical grouts are liquids rather than suspensions, they can be pumped into fractures or voids as small as 0.01 mm. They may shrink when they are not in the saturated zone or when they are exposed to brine water.

Because the grout contractors control the nature of grout and the rate at which the grout is injected into the boreholes, the experience of the contractor is very important. Grout pressure must be carefully controlled. Acceptance of a large quantity of grout without pressure increase may indicate that the grout is running through a sizable conduit. Procedures such as adding sand, sawdust, chopped plastic, or an admixture of accelerators, may be used to thicken the grout. In saturated zones, the grout pressure must exceed the hydrostatic pressure. Under normal circumstances, it should not exceed the vertical stress to avoid hydrofracturing. Hydrofracturing may create additional passageways for groundwater flow. On average, the grout pressure in the completed grout curtain in the coalfields of North China was controlled at 1.5–2 times the respective hydrostatic pressure.

However, hydrofracturing may be necessary to fill large clay-filled voids. When there are a limited number of clay-filled voids and the voids are relatively small, it is common to remove the clay fillings to provide a concrete diaphragm wall. It is, however, very challenging to build such a wall when many large clay-filled voids are present at depths. Under such circumstances, these clay fillings are generally not groutable. High-pressure cement grouting may provide an alternative technique to build a water-resistance barrier in clay-filled voids of a karst aquifer. The hydrofracturing caused by the high grout pressure can produce a series of cracks in the fillings. The cement grout enters these cracks thus forming a cement-reinforced network. Consolidation and chemical hardening of the clay fillings may also aid this process. As a result, the clay-fillings in the karst voids are crisscrossed by a rigid network of injected grout. As the clays become dense and hardened, an anti-seepage barrier may be formed.

Conclusions

Control of water inrush from the Ordovician limestone is the key to safely mine the lower three coal seams in the coalfields of North China. The thickness of the protective layer between the Ordovician limestone and the coal seam, the potentiometric pressure in the Ordovician limestone, characteristics of the paleo-weathering surface on the limestone, and mining activities may affect the occurrence of a water inrush. A decrease in the potentiometric pressure of the karst aquifer or reinforcement of the protective layer can help reduce the water inrush risk. Choice of the water control methods depends on the site-specific conditions. Grouting is an effective way to reduce the amount of water flowing into the mine. Knowledge of the hydrogeological conditions in the mining area, the proper design of a grouting program, and experience of the contractor are essential to ensure a successful application of the grouting technique.

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