

Geological barrier– a natural rock stratum for preventing confined karst water from flowing into mines in North China

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Abstract Coalfields in North China encompassing more than ten Provinces contain six to seven coal seams in the Permo-Carboniferous strata. The lower three seams, accounting for 37% of the total reserves, are threatened with karst water from the underlain 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 and over 30 mines have been flooded over the last 20 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 has caused sinkholes, dry springs, water supply shortage, and groundwater contamination in the surrounding areas, which is environmentally not permitted. One of the alternative water control measures is to make full use of the rock layer between the coal seam and the karst aquifer as a geological barrier. Similar to the application in the nuclear industry where a geological barrier is used to contain radioactive wastes, the barrier of this application is considered a hydraulic barrier as well with the objective to prevent or constrain water flow from the underlying aquifer into mines. Its effectiveness to constrain water flow is described by a parameter referred to as hydrofracturing pressure (P_{hf}). When the water pressure in the underlying aquifer exceeds P_{hf} , a wedging

effect takes place within the fractures of the geological barrier and, as a result, water inrush occurs. In-situ hydrofracturing tests were used to determine P_{hf} in bauxite and silty sandstone at tunnels. The P_{hf} in the silty sandstone is larger than that in the bauxite but they both vary with depth (distance from the bottom of the tunnel). Based on the test results, a new safety criterion for water inrush was derived for mines and it has been successfully applied to mining practices with the minimum effort of dewatering in the karst aquifer. The same criterion can also be applied to tunneling and quarrying in areas with similar geological conditions.

Keywords Geological barrier · Hydrofracturing · Karst water · Mine · Water inrush

Introduction

In China, karst develops and distributes widely in rocks that range in age from Archeozoic to Cenozoic, but are predominantly Paleozoic. Carbonate rocks occupy an area of about 3.25 million km² of the country: of this bare karst is some 1.25 million km² and the rest is covered or buried karst (Yu 1994). Groundwater in the karstified carbonate rocks is a valuable natural resource for local people. Unfortunately, many mineral deposits such as coal, iron, lead and zinc, gold, aluminum, and copper are located in between, or above, or below the karst aquifers. The majority of the well-known deposits with large quantities of water (pumping water over 1 m³/s) are karst water-impregnated deposits.

The coal seams in the coalfields of North China lie in the Permo-Carboniferous strata, as shown in Fig. 1. The Taiyuan Formation of Carboniferous system has a thickness of 95–163 m, consisting of argillaceous shale and sandstone. From top to bottom, the coal seams are Xia-jia, Da-xing, Xiao-qing, Shan-qing, Ye-qing and Yi-zuo and their total average thickness is 9 m. Their roofs consist of mainly thin-bedded limestone with varying thickness from 2–7 m. Except for the lowest layer of limestone that may have hydraulic connection with the underlain Ordovician limestone, water in the rest of the thin bedded limestone is generally static. It is relatively easy to dewater or drain.

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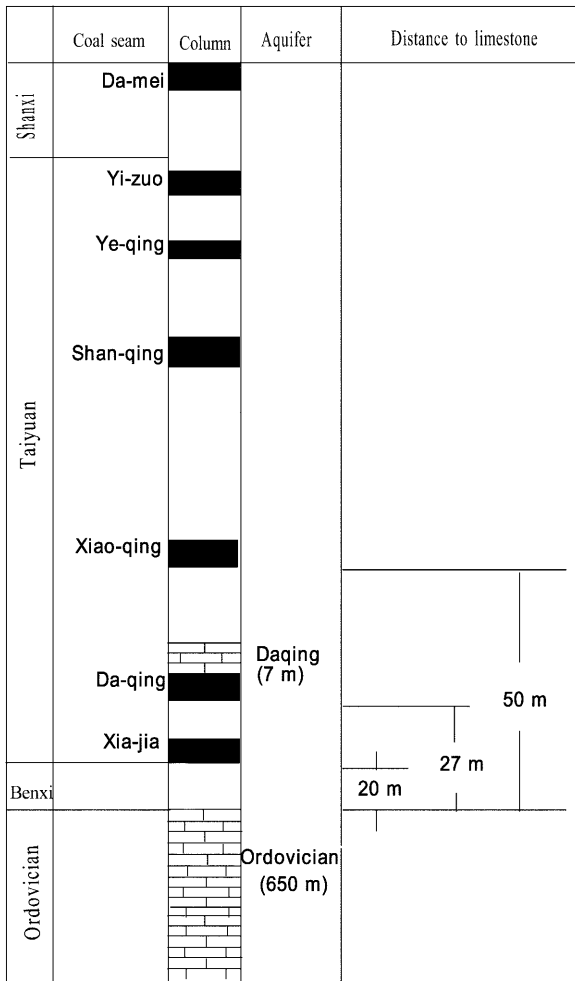


Fig. 1
Geological column in coalfields of North China

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

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

One of the major impacts of the groundwater on the mining activities is the unpredictable occurrence of water inrush, in which a significant amount of water suddenly invades the underground working areas from the underlying aquifer under potentiometric pressure. Large water inrushes have occurred and over 30 mines have been flooded in the last 20 years. Dewatering or depressurizing of the Ordovician limestone has been essential to keep the mines safely operational. However, this practice has resulted in many engineering and environmental problems in the surrounding areas such as sinkholes, dry springs, shortage of water supply, and surface water and groundwater contamination (Zhou 1997a).

Water inrush is the result of interaction between water and rocks in the geological stratum between the coal seams and the Ordovician limestone. It occurs when the strength of the stratum is not strong enough to resist the water pressure. The position of the water inrush is often related to geological structures. Adjacency, intersection and pinch of faults, anticline and synclinal axes are more susceptible to water inrush. In the studied area, over 78% of water inrushes are related to faults and the northeast fracture group controls 62% of them.

Figure 2 shows the data points of water inrushes collected at Fengfeng coalfield. The vertical coordinate represents the thickness of the rock layer between the coal seams and the Ordovician limestone, and the horizontal coordinate represents the potentiometric pressure of the karst water. The invasion points are concentrated mostly on the upper right, while the safety points on the lower left. Between them, there is a natural limit approaching a straight line. Clearly, the rock layer between the coal seam and the threatening aquifer acts as a geological barrier or a hydraulic barrier that prevents the water in the Ordovician limestone from invading and flowing into the underground cavities.

The effectiveness of the geological barrier depends on its thickness, lithology, and integrity. Water inrushes are unlikely to occur when the geological barrier is thick. The four upper coal seams are free from water invasion because the geological barrier is over 100 m. Hard rocks, such as limestone and sandstone, have high intensity; for

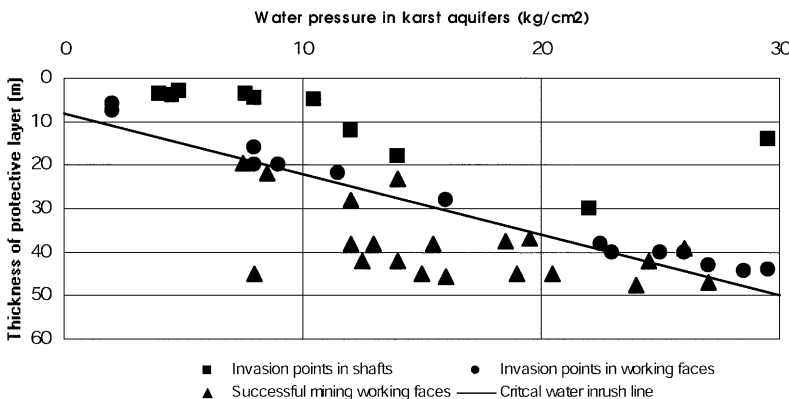


Fig. 2
Thickness of geological barrier vs. water pressure in Fengfeng Coalfield

example, a layer of medium-grained sandstone of 2 m can bear 7 kg/cm^2 of water pressure. Flexible rocks such as shale do not have the same intensity as hard rocks. However, they may have a higher capacity for water resistance, as found in another North China's coalfield (Fig. 3). The interception for shale seems to be larger than that for the hard rock, but the slope is relatively sharp, indicating water inrush could occur under higher water pressure for the same thickness of geological barrier. When the geological barrier consists of inter-bedding layers of flexible and hard rocks, water invasion can hardly take place. As shown in Fig. 4, the interception for such an arrangement of rocks is very small: only 3 m. Coals were mined successfully under a water pressure of 8 kg/cm^2 when the geological barrier was 13 m thick.

Obviously, water invasion occurs more easily under higher water pressure. When Shaqing coal seam was extracted at -90 m (above sea level) in one coalfield, water pressure in the Ordovician limestone was 22 kg/cm^2 and the protective layer was 40–45 m thick. No water inrush took place. However, when the mining level was extended to -170 m , the water pressure increased to 30 kg/cm^2 , and six water inrushes have taken place already, although the protective layer remained the same.

The non-zero interception to the vertical axis implies that water inrush could take place even when the groundwater is not under pressure. This is the result of mining activi-

ties. Part of the protective layer might be destroyed by mining operations. This is clearly illustrated by the different distribution of the invasion points at the working faces and in the shafts. For the same geological barrier, water inrushes are more likely to occur at the working face than in the shaft. The space and span of the working faces has a significant influence on water-resisting capacity of the geological layer. In addition, water invasions in shafts might happen after a delay of 1–2 years after excavation of the shaft because of the long-term effect of shaft excavation on the floor.

Impact of mining activities on geological barrier

With regard to the influence of mining activities on the protective layer, the data from gas-discharge in coal mines could be used as a reference to the destroyed thickness. Gas was liberated 20–80 m below the layer after mining. Because of different properties of gas and water, fractures caused by mining can conduct gas but may not be conducive to water. The thickness of the rock through which both gas and water can flow is the parameter of concern. Two water injection tests (nos. 1 and 2) were conducted in one coalfield to investigate the destroyed thickness. In

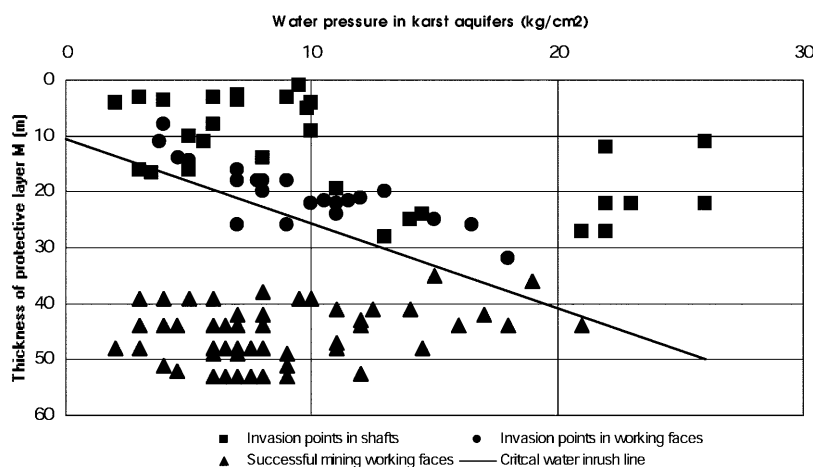


Fig. 3 Thickness of geological barrier vs. water pressure in Jiaozuo Coalfield

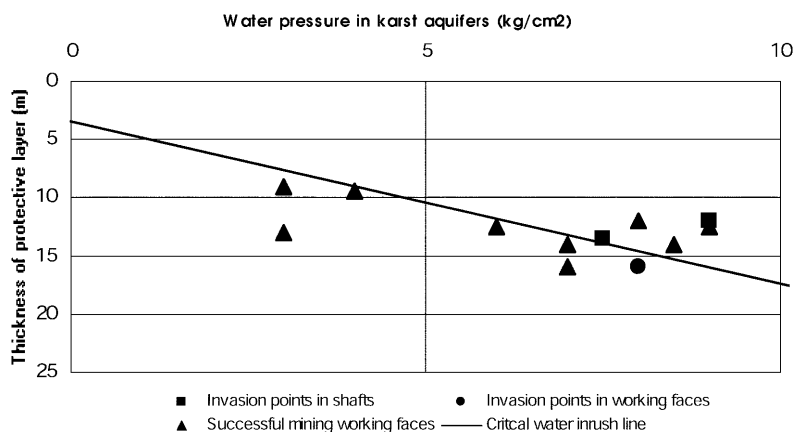


Fig. 4 Thickness of geological barrier vs. water pressure in Handan Coalfield

each water injection test, five angled boreholes were drilled into the protective layer of a mining slope (Fig. 5). The vertical distance between the boreholes was 1 m and the shallowest borehole (borehole 1) was 2.5 m below the slope floor. The geological barrier was composed of sandy shale, argillaceous limestone, and coal. A small fault with 0.5-m displacement was observed in the barrier. A long-wall extraction approach was employed for the tests. Figure 6 shows the influence of mining activities on the volume of water injected for water injection test no. 1. The distance to the mining face is expressed by the horizontal coordinate with zero at the face. To the left and right are the distances to the mining direction and to the extracted zone, respectively. The time (days) calculated according to the average speed of face advance during the test is shown in the figure as well. The volume of water (liters/hour) flowing through the boreholes at various depths and horizontal distance is shown on the vertical coordinate. Borehole 5 was discharging water before the test with a water pressure of 0.68–0.85 kg/cm². The water injection pressure applied to this borehole was 1.5 kg/cm². The

pressure applied to the other boreholes was 1 kg/cm². The water flow in borehole 5 increased when the central borehole was 14 m away from the working face after mining, whereas water flow in boreholes 2 and 3 seemed to decrease. The water flow in boreholes 2 and 3 had a slight increase at 52 m and the water flow decreased in borehole 4. Figure 7 shows the influence of mining activities on volume of water injected for test no. 2. Water pressure of 1 kg/cm² was applied to all the boreholes. In general, water flow started after water injection reached its maximum volume at the working face.

Change of the amount of water injected through the boreholes implies the effect of mining activities on the geological barrier. The thickness of the geological barrier destroyed by the mining could be analyzed by the water overflow from the abandoned galleries through the boreholes. Fluctuations of the water volume injected before and after mining decreased as the depth of the tested segment of the borehole increased. When the depth reached 7–8 m, the fluctuation became very small. In addition, the geological barrier that was initially impermeable began to conduct water through holes at 6–7 m below the slope after the mining. On average, the thickness of the geological barrier destroyed by mining activity was approximately 8 m in North China.

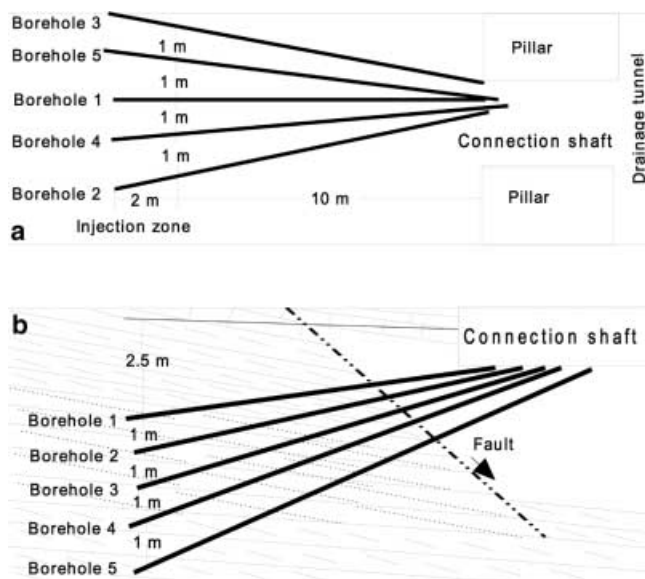


Fig. 5 Water injection tests. a Plane view; b profile view

Laboratory experiments on failure of geological barrier

Experiments were conducted in the laboratory to test the failure mechanism of the geological barrier under high water pressure in a tri-axial filter (Fig. 8). The rock sample is clayey limestone with two fractures perpendicular to each other and is 150 mm in diameter and 400 mm long. A water pressure (P_w) of 35 kg/cm² was applied to the sample. Stresses (σ) simulating the lateral earth stress of 200 m below the ground were applied to the cylinder of the sample. The applied stress was varied to simulate three mining-related stages—compression, dilation, and recovery. In the initial phase (0–1 min), the water flow rate was greater than 300 m³/min, where $P_w \gg \sigma$. With an increase in stress, the rock underwent a compression process

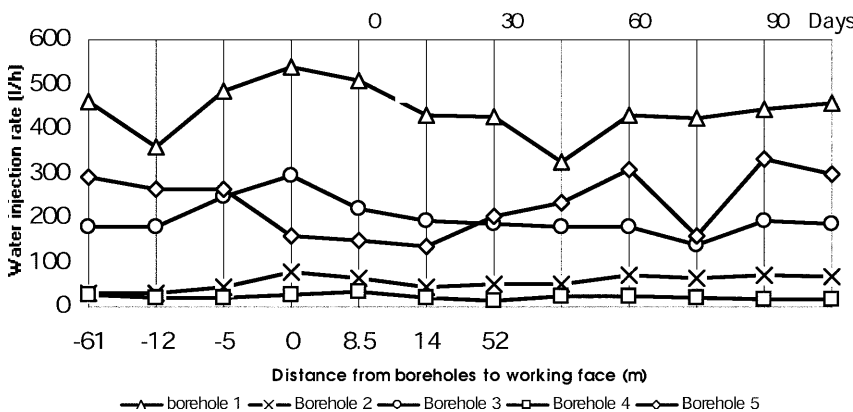


Fig. 6 Water injection rate during mining for test no. 1

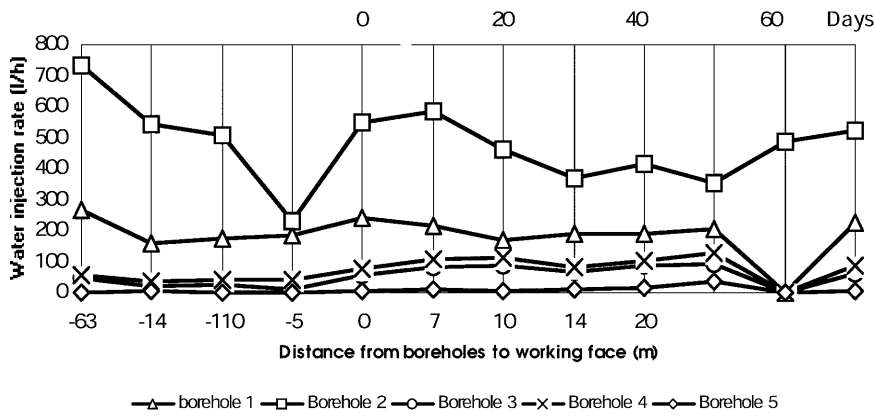


Fig. 7
Water injection rate during mining for test no. 2

(1–23 min) where $P_w < \sigma$. The fractures were gradually forced to close and the water flow decreased to zero. At the dilation period, the earth stress decreased because of the pressure release caused by excavation. When $P_w > \sigma$ (28–29 min), the fractures opened and water began to flow again. The maximum water flow was 120 m³/min. During the recovery period, the roof would collapse and the stress gradually increased to its normal levels. When $P_w < \sigma$ (>29 min), the fractures closed again and water flow receded.

The experimental results indicate that the failure of the fractured rock sample as a hydraulic barrier depends on the relationship between the water pressure and the lateral stress. Water flow was observed when the hydraulic pressure exceeded the lateral stress. This process is very similar to the spontaneous hydrofracturing in which a wedging effect takes place when the hydraulic pressure exceeds hydrofracturing pressure (P_{hf}). P_{hf} is approximately the same as the minimum earth stress in value, and it is regular practice to measure the minimum earth stress

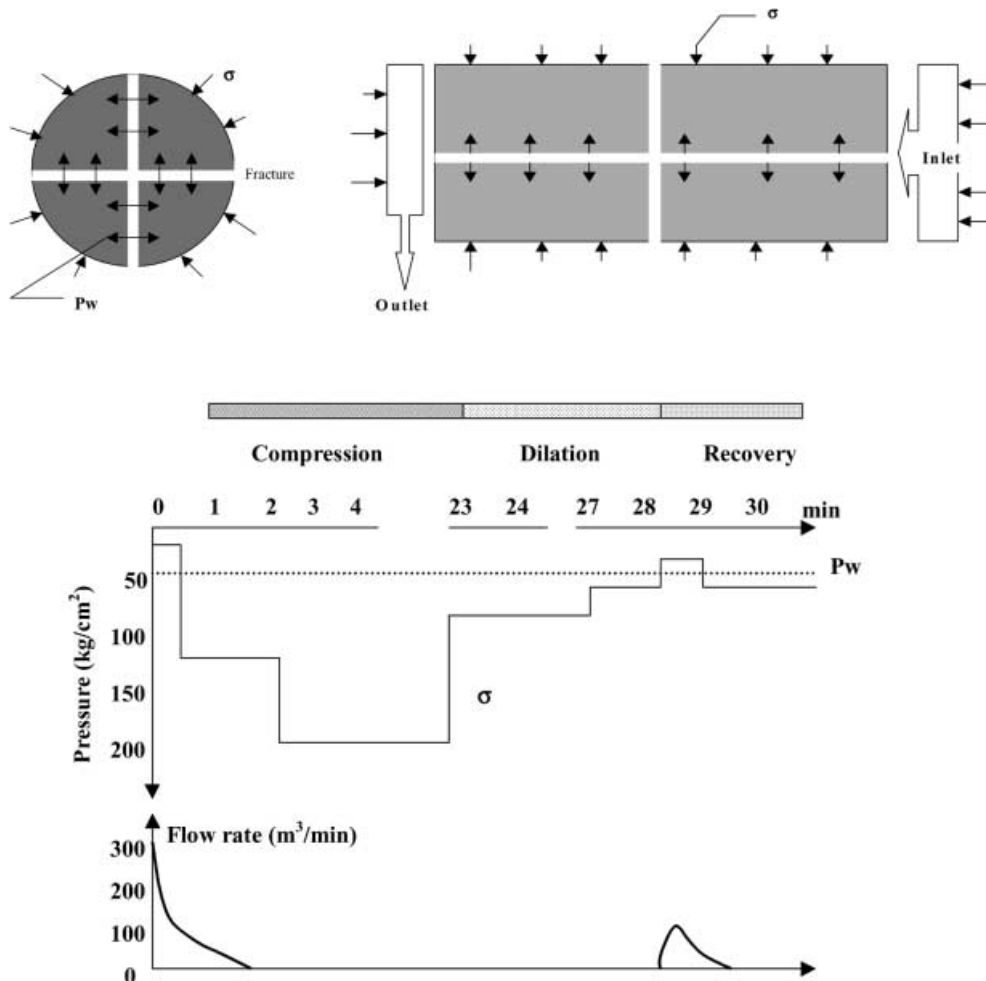


Fig. 8
Experiments of water inrush through a geological barrier

by hydrofracturing tests in boreholes (Kesseru 1997). Therefore, the effectiveness of the geological barrier can be quantitatively described by measuring its hydrofracturing pressure or the minimum stress. The presence of fractures is a prerequisite to spontaneous hydrofracturing.

Initial conductive zone in geological barriers

In the area under study, the permeability of the geological barrier is in general low; however, there is no distinctive contact plane between the barrier and the Ordovician limestone. The Carboniferous barrier unconformably overlies the Ordovician limestone. There was a long period during which the limestone underwent various weathering processes. The weathering processes resulted in an irregular limestone surface. In addition, the geological barrier has itself undergone numerous tectonic movements. 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 its potentiometric pressure. The area that has already been invaded by karst water prior to mining is

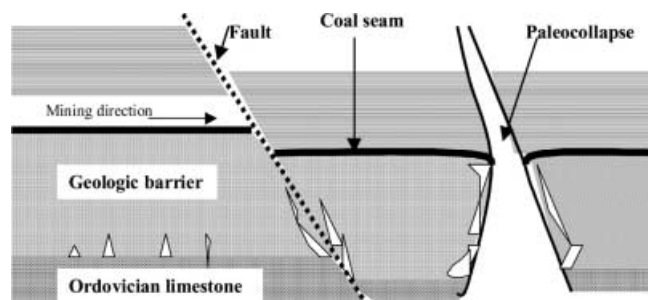


Fig. 9 Schematic illustration of initial conductive zone

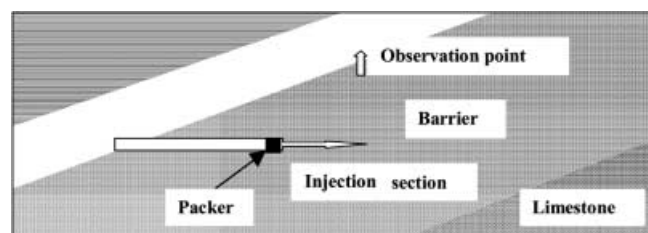


Fig. 10 In-situ hydrofracturing tests

Table 1

Measured height of the initial conductive zone

Thickness of geological barrier (m)	Potentiometric pressure of Ordovician limestone (kg/cm^2)	Height of initial conductive zone (m)	Characteristics of the geological barrier
21.4	11.0	0.92	Fine sandstone, bauxite, clay stone, very few fractures
19.7	10.5	0.0	
23.6	12.6	0.0	Fine sandstone, coal seam, bauxite, few fractures
21.6	12.6	< 7.6 ^a	
22.4	12.0	8.5	Fine to medium-grained sandstone, fractures well developed
20.1	12.0	6.67	
17.8	12.0	7.07	
20.8		< 6.3 ^a	

^a Inferred value

Table 2

Results of in-situ hydrofracturing tests

Geological barrier	Vertical depth (m)	Water pressure (kg/cm^2)	Duration of water injection (min)	Characteristics of Hydrofracturing	Hydrofracturing pressure (kg/cm^2)	
Shalestone and fine sandstone	0.5	3		Instantaneous seepage, while the water pressure decreased to $2 \text{ kg}/\text{cm}^2$	3	
	1.1	10	20	Water flow through two sets of joints	10	
		5	25	Seepage through one set of joints, while the water pressure decreased to $8 \text{ kg}/\text{cm}^2$	15	
	3	10	15			
		15	5			
		3	3	10	Water flow through joints	20
		5	20			
		8	15			
	Bauxite	0.5	3	20	Seepage through one set of joints	1.5
			5	1	Seepage through two sets of joints	4
15			15	Seepage through one set of joints	5	
0.7		5	1			
		1	5	15		
		15	15			

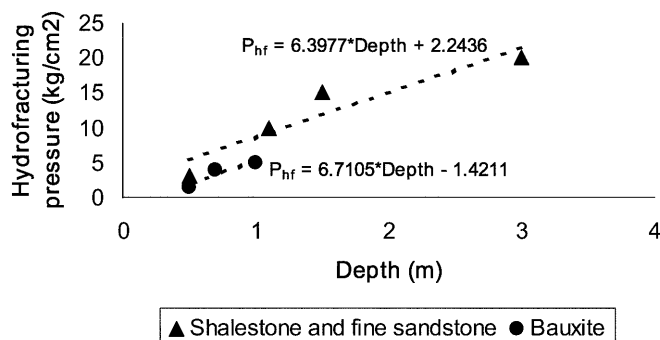


Fig. 11
Hydrofracturing pressure vs. depth

defined as the initial conductive zone. This zone cannot play an effective role in preventing karst water from flowing into the mines. However, the existence of this zone provides the essential condition for a wedging effect. At locations where this zone does not exist, the barrier would be able to bear very high water pressures and break only when the water pressure exceeds its shearing strength by bending of the barrier.

Continuous monitoring of the potentiometric pressure while drilling into the geological barrier is necessary to detect the height of this zone. Table 1 lists the exploratory results at one mine. Clearly, the initial conductive zone is closely associated with the lithology and structure of the barrier. It more likely develops in harder rocks with better-developed fractures. A high conductive zone may develop along fractures and around collapsed zones, which is schematically illustrated in Fig. 9. Therefore, fractures and paleo-collapses are likely to become avenues for groundwater flow or contaminant transport (Zhou 1997b).

In-situ hydrofracturing tests

In-situ hydrofracturing tests were conducted in two geological media – shalestone and fine sandstone, and bauxite. The test holes were drilled into the test rock from the working faces. The diameter of the test holes is 100 mm, except for the last 1 m where the diameter was changed to 58 mm. Packers were used to isolate the last 1 m. Water injection rate was 0.1 m³/min, which led to the gradual built-up of pressure. The occurrence of hydrofracturing was observed in the working face, as shown in Fig. 10. Table 2 shows the test results. In the shalestone and fine sandstone, two sets of joints developed in the rock with densities of 14 and 8 fractures/m, respectively. Similar joint sets develop in the bauxite. Their densities are 5 and

3.7 fractures/m, respectively. The in-situ hydrofracturing tests indicated that:

1. the water inrush (seepage) occurred preferentially through joints or fractures;
2. the hydrofracturing pressure of the shalestone and fine sandstone was larger than that of the bauxite;
3. the water pressure remained at a certain level after the water inrush occurred, which is a typical property of hard rocks;
4. the hydrofracturing pressure increases with depth.

Figure 11 shows the linear relationships established at shallow depths for both barriers, from which the hydrofracturing pressure at one particular point could be approximately calculated. The calculated pressure is then used to compare it with the local potentiometric pressure in the Ordovician limestone to determine the risk of water inrush during mining activities. However, caution must be taken when the equations are extrapolated to deep areas.

Conclusions

A geological barrier is a natural rock stratum that prevents groundwater from flowing into active mines. It can also be used to contain contaminants when similar geological conditions exist. The effectiveness of a geological barrier can be quantitatively evaluated by measuring its hydrofracturing pressure. The hydrofracturing pressure varies with depth because of the impact of mining activities. The initial conductive zone provides fractures for the wedging effect to take place. Water inrush occurs when the water pressure exceeds the hydrofracturing pressure in the initial conductive zone, otherwise minerals can be mined or shaft excavated safely without dewatering or depressurizing the underlain karst aquifer.

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