

## Research Article

# Evaluation of Water Retention Capacity of Bulkheads in Underground Coal Mines

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The mechanism of water flow in and around the bulkheads and the surrounding rock is studied for Panel No. 21102 in the Sanhejian coal mine in Xuzhou, China. Based on an analysis of the properties of the bulkheads and the surrounding rock, three types of water conducting pathways are identified: (1) a water conducting pathway at the interface between the bulkhead and the surrounding rock; (2) a water conducting pathway in the faults of the rock; and (3) a water conducting pathway in the fractures of the rock. The possibility of these three pathways for water flow at Panel No. 21102 is analyzed, and the connectivity coefficient of the water conducting pathway is determined. The expression for calculating the critical hydraulic gradient of the rock by using the connectivity coefficient in the water conducting pathways is presented which is based on the permeability and integrity of the rock. The ratios of the critical hydraulic gradient to the steady state hydraulic gradient are calculated for 13 mines in China. An acceptable safety factor in controlling the water flow for the bulkhead is found to be 1.68. When the safety factor is less than 1.68, water leakage has occurred in a number of cases. Finally, changes in the water pressure in the bulkheads with time and changes in the seepage flow with time in the surrounding rock are analyzed. It is found that there is a good correlation between the rate of water flow and water pressure which confirms that water pressure plays a decisive role in controlling seepage from the rock in and around the bulkheads.

## 1. Introduction

One of the main coal mining incidents in China deals with the problems of sudden inrush of water into the mine which often results in significant economic losses in coal production and seriously threatens the safety of underground miners [1, 2]. As underground coal mining in China gradually goes deeper with complex geological conditions and high ground stress, the activities result in more frequent accidents [3]. The hydrogeological conditions of underground mines become more complex with increase in the depth of the mines [4, 5]. Together with more damage and disturbances caused by coal mining to the original strata [6],

the risk of water inrush in coal mines is greatly increased. Therefore, effective prevention and prediction of water inrush in mines are very important tasks [7, 8].

The construction of water bulkheads is a common measure to prevent and control water inrush in coal mines. The purpose of a water bulkhead is to effectively isolate the flooded part of the mine due to water inrush from the normal production part to provide a safe working environment for the miners [9]. A well designed and constructed bulkhead can effectively prevent water from flowing into mines especially when the mine encounters large water aquifers under high pressure with abundant water resources and poor predictability. Therefore, the bulkhead must be able to withstand

sufficient hydrostatic pressure with structural integrity [10]. Garrett and Campbell [11] from South Africa proposed three basic designs of bulkheads in metal mines: recessed, tapering, and parallel (without recessing or tapering) plugs. The design curve for the bulkhead was developed based on the test results to withstand up to 46.9 MPa of water pressure [11]. Yuan et al. proposed that the mechanism of slurry infiltration and its influence on pore water pressure should be fully considered during the construction of tunnel [12]. Many researchers later used this design curve to calculate the hydraulic gradient of the bulkhead to determine its stability under seepage [13, 14]. Yuan et al. described a device used in hydraulic gradient tests [15]. Garrett and Campbell also emphasized that the leakage of the bulkhead should be considered as the main factor in the stability and suitability of the bulkhead under high water pressure [16]. Harteis and Dolinar pointed out that some of the important factors that should be taken into consideration in the designing of bulkheads are the behavior of the contact surface between the bulkhead and the surrounding rock, and the water pressure that acts on the bulkhead [17]. Some countries, such as the United States and Canada, have done comprehensive studies on the design and construction of underground bulkheads in coal mines with appropriate supervision and construction standards [18, 19]. China has adopted different design approaches for the structure and size of bulkheads but has not clearly stipulated the requirements for quality control in the construction of bulkheads and the monitoring requirements during their operation [20]. Yang et al. researched the notion that the geotechnical improvement materials can effectively reduce the deformation and collapse of subgrade [21, 22]. A 3D structural model of sluice wall was established by FLAC3D to analyze the distribution of stress and displacement of rock around the sluice wall and the range of plastic zone [23]. An improved three-dimensional displacement measuring system was developed to measure the displacement fields [24]. Therefore, in comparison to international standards, improvement is needed in the design, construction, regulations, and operations of water bulkheads in underground mines in China.

Experience in preventing water inrush in underground mines has shown that water bulk heads are relatively simple to build and provide a safe and reliable barrier against the threat of sudden water inrushes in comparison to other methods such as drainage and grouting. However, there are still many challenges associated with the wide selection of bulkhead designs, complex calculations required for the bulkhead walls, and difficulties in quality control during construction. Moreover, the integrity of bulkheads is affected by long-term high water pressure during their operation, thus resulting in seepage damage of the surrounding rock and walls. Therefore, in complex hydrogeological conditions and abundance of water resources, it is important to carry out in-depth and systematic studies on the water containment mechanism of the bulkhead and seepage in the surrounding rock for the safe and efficient operation of the mine to improve its productivity. At the same time, the protection and utilization of groundwater is also an important design consideration.

## 2. Geological Exploration of the Sanhejian Coal Mine

In order to examine the problem of water inrush and the containment mechanism of bulkheads in coal mines, a real case history is studied in detail here, which involves the Sanhejian coal mine. The Sanhejian coal mine is located southeast of the City of Xuzhou in the Jiangsu Province of China. Figure 1 shows the location of Sanhejian coal mine. Water inrush occurred in the Sanhejian coal mine at 8:40 am on October 26, 2002. The incident occurred in the Ordovician limestone aquifer on the floor of Panel No. 21102. During the water inrush, the maximum water flow rate reached 2170 m<sup>3</sup>/h for a short period of time. The water flow continued for several days and the rate of flow fluctuated during this time and became steady at 1020 m<sup>3</sup>/h at 10:00 am on October 31, 2002. To control the flow of water, a water bulkhead was constructed at the Panel to quickly and effectively control the inrush to ensure mine safety and continuing operation of the mine. The depth of Panel No. 21102 lies between approximately 770.8 and 831.2 m. The dip angles of the coal seam vary from 16° to 20° with a coal seam thickness of 1.3 m. The roof and floor of the coal seam are limestone and mudstone with thicknesses of 5.2 m and 1.1 m, respectively, as shown in Figure 2 [25].

Based on the water level measurements in the exploratory boreholes, the maximum water pressure used in the design of the bulkheads in the transportation and material roadways is 8.32 MPa and 8.0 MPa, respectively. The positions of the bulkheads are shown in Figure 3 [25].

The longitudinal profile and cross section of the water retention bulkhead in the roadway are shown in Figure 4 [25]. The bulkhead is divided into three parts. Construction joints are installed between two adjacent sections with a total of 21 uprights in the bulkhead. The length of the main wall of the bulkhead is 24 m. There are 30 m and 10 m reinforcement sections in front of and behind the bulkhead, respectively. The total length of the bulkhead is 64 m. The main design parameters of water retention bulkheads are listed in Table 1.

## 3. Evaluation of Hydraulic Connectivity and Permeability of Bulkheads

Many previous mining incidents show that failure of the sluice wall and water leakage of the bulkhead often occur at the interface between the wall and the surrounding rock or are caused by the fractures inside the surrounding rock where the bulkhead is located, or due to seepage in water conducting fractures thus forming a major flow channel with concentrated flow. According to the formation mechanism and spatial location of the seepage paths, the water flow pathway can be classified into three types: (1) the pathway at the interface between the bulkhead and the surrounding rock, (2) the pathway in the water conducting faults in the surrounding rock around the bulkhead, and (3) the pathway in the water conducting fractures in the surrounding rock around the bulkhead.

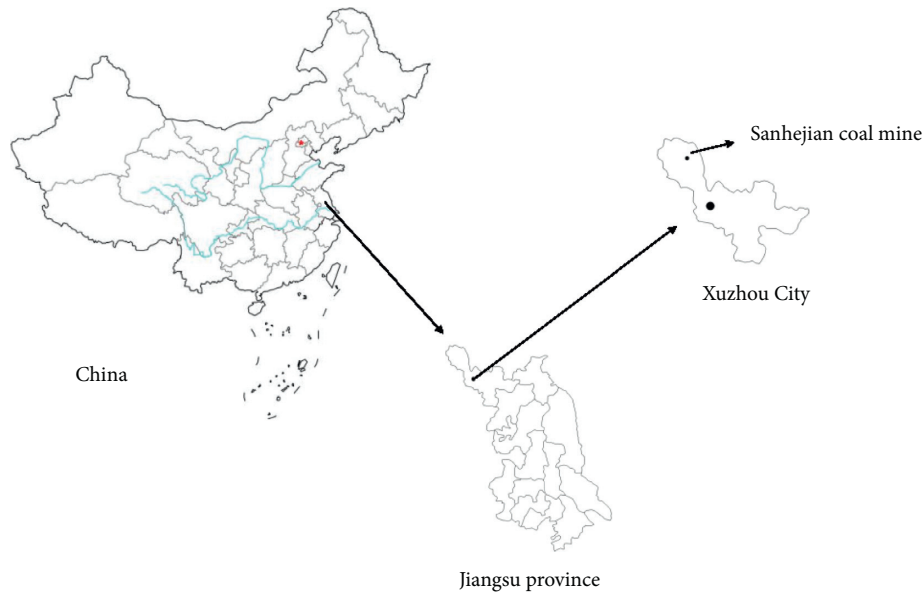


FIGURE 1: Location of Sanhejian coal mine.

Lithology	Thickness (m)	Column 1 m	Hydrogeological property
Mudstone	1.1		Aquifuge
L <sub>12</sub> limestone	5.2		Aquifer
21-coal seam	1.3		
Mudstone	1.1		Aquifuge
Fine sandstone	2.7		Aquifuge
L <sub>13</sub> limestone	0.8		Aquifer
22-coal seam	0.68		
Mudstone	4.0		Aquifuge

FIGURE 2: Schematic diagram of Panel No. 21102 and surrounding rock in Sanhejian coal mine.

For the case of Panel No. 21102 in the Sanhejian coal mine, the hydraulic connectivity coefficient is calculated for all three potential water pathways.

(1) Calculation of the hydraulic connectivity coefficient of water conducting pathway at the interface between the sluice wall and the surrounding rock.

In order to control the flow of water from the surrounding rock into the bulkhead, the contact between the bulkhead and the rock is normally grouted. The effects of grouting reinforcement behind the bulkhead depends on a

variety of factors which include the grouting pressure, equipment, materials, and technology, spatial characteristics of the interface between the bulkhead and the surrounding rock, development of fractures in the surrounding rock, and dynamic characteristics of the groundwater [26]. Since it is difficult to quantify all of these factors in detail, only some indicators are selected to quantitatively evaluate the interface between the bulkhead and the surrounding rock in becoming a water conducting pathway and the possibility of developing a pathway. The connectivity coefficient and the

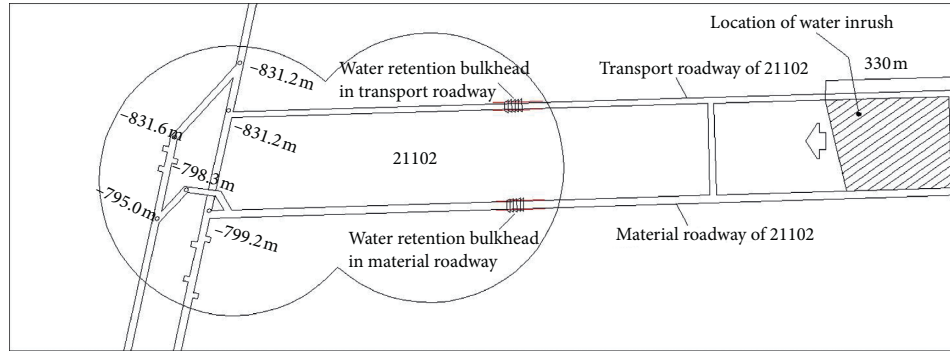


FIGURE 3: Schematic plan view of locations of water retention bulkheads in Sanhejian coal mine.

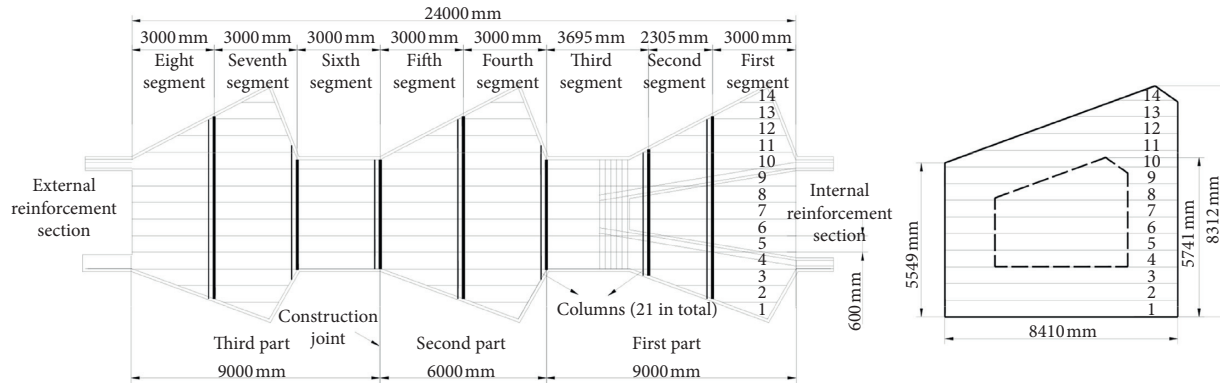


FIGURE 4: Longitudinal profile and cross section of water retention bulkhead in roadway.

TABLE 1: Design parameters of water retention bulkhead.

	Length of wall (m)				Design water pressure on walls (MPa)	Strength of concrete	
	Total length	Main wall	Internal reinforcement section	External reinforcement section		Design standard	Construction standard
Transport roadway	64	24	30	10	8.32	C25	C28
Material roadway	64	24	30	10	8.00	C25	C28

parameters at the interface between the bulkhead and the surrounding rock are shown in Table 2.

Two ratios are defined in the table: (1)  $L_D/L$  is the ratio of the total length of the interface to the length of the main section of the bulkhead, and (2)  $P_g/P_d$  is the ratio of the actual grouting pressure to the design grouting pressure. These two parameters are important in characterizing the water connectivity at the interface.

In the Sanhejian coal mine, the thickness of the main part of the transport and material roadways of the bulkhead at Panel No. 21102 is 24 m, internal reinforcement section is 30 m, external reinforcement section is 10 m, and total length of the reinforcement section on both sides is 40 m. The length of the interface between the main section of the bulkhead and the surrounding rock is about 28.5 m, and  $L_D/L$  is about 1.19. The design water pressure of the bulkheads in the transport and material roadways is 8.32 MPa and 8.0 MPa, respectively. The final grouting

pressure behind the main section of the bulkhead is 9.32 MPa, so that  $P_g/P_d$  for the transport and material roadways is 1.12 and 1.25, respectively. The bulkheads at Panel No. 21102 adopt a six-stage approach on water release and pressure control. The increase in grout pressure is divided into six stages which allow 24 to 72 h for the pressure to stabilize in each stage. The flow rate of the seepage of water from the surrounding rock is measured. When the water flow rate is less than  $2 \text{ m}^3/\text{h}$ , the increase in grout pressure then proceeds to the next stage. The above quantitative indicators are substituted into Table 2 to produce the results in Table 3. The final values of the connectivity coefficient of the water conducting pathway at the interface between the bulkhead and the surrounding rock are high with values between 8 and 10.

(2) Calculation of the connectivity coefficient of water conducting pathway in the fault in the surrounding rock of the bulkhead.

TABLE 2: Connectivity coefficients of water conducting pathway of interface between bulkhead and surrounding rock.

Connectivity coefficient of water conducting pathway $m$	Type of bulkhead	Length of bulkhead $L$ (m)		$L_D/L$	Water pressure $P$ (MPa)	$P_g/P_d$	Pressure test stabilization time $t$ (h)
		Main section	Reinforcement section on both sides				
8–10	Rectangular/flat	$\leq 2$	$\leq 10$	$< 1$	$\geq 5$	$\leq 1$	$\leq 24$
5–7	Cylindrical	2–4	10–15	1–1.1	3–5	1.0–1.5	24–28
3–4	Tapered	4–6	15–20	1.1–1.2	2–3	1.5–2	28–32
1–2	Inverted pyramid	$\geq 6$	$\geq 20$	$\geq 1.2$	$\leq 2$	$\geq 2$	$\geq 32$

Whether water will flow through the faults in rock depends on the hydraulic conductivity of the rock, the size and type of faults, and the relative position or distance of the faults and the bulkheads. In the case of the Sanhejian coal mine, the connectivity coefficients of the water conducting pathway,  $m$ , in the fault are determined based on the actual fault information at the bulkheads as shown in Table 4.

After analyzing the data from Chen et al., the main reason for the water inrush at Panel No. 21102 is that three faults with a drop less than 2 m are exposed during the mining process [27]. In addition, the effects of normal faults, the Zhangzhuang fault, F1/-1 in the south, and F0 in the northeast, Zhangzhuang syncline in the northwest, and Sunshidian fault with a drop of 100 m, reduce the thickness of the effective water resistance layer in the floor of the Panel. The Ordovician limestone basement with good hydrodynamic conditions is connected to Panel No. 21102 and water inrush was triggered under the combined effect of the ground stresses and water pressure. Based on this information and the data in Table 4, the connectivity coefficients for the water conducting pathway in the faults in the surrounding rock are calculated and shown in Table 5. The connectivity coefficients are high with values that lie between 8 and 10.

(3) Calculation of the connectivity coefficient of water conducting pathway in the water conducting fracture in the surrounding rock at the bulkhead.

The transport and material roadways of Panel No. 21102 are interbedded coal and rock roadways as shown in Figure 2. The rocks that surround the roadways are limestone, mudstone, fine sandstone, and coal. The surrounding rocks range from soft to hard and the floor of the coal seam is very argillaceous after it comes into contact with water [27]. Once the fractures in the surrounding rock are connected to the roadway, a continuous water conducting pathway is formed which will cause water leakage in the bulkheads. Therefore, multiple factors such as the roadway, surrounding rock, bulkheads, and water sources should be considered in order to calculate the connectivity coefficient of the water conducting pathway. Table 6 shows the calculated connectivity coefficients of the water conducting pathway in a fractured zone around the mine opening in the surrounding rock. The thickness of the fractured zone around the mine opening is determined based on borehole data from geophysical exploration.

The surrounding rock around the transport and material roadways at Panel No. 21102 ranges from soft to hard which provides a generally stable condition around the mine opening. Based on a stability analysis of the surrounding rock, the thickness of the fractured zone around the mine opening is estimated to be about 100 to 150 cm. There is no obvious visual abnormality at Panel No. 21102 with the highly stressed zones. By combining this information and the data in Table 5, the calculated connectivity coefficients of the water conducting pathway of the fractures in the fractured zone of loose material of the surrounding rock are shown in Table 7. The connectivity coefficients are the highest of these three cases with values that lie between 9 and 10.

Based on the results in Tables 3, 5 and 7, the connectivity coefficients of the water conducting pathway of the bulkheads at Panel No. 21102 are at the highest level, 8 to 10 or 9 to 10; therefore, a value of 9 or 10 is selected. The results show that the possibility of forming a water conducting pathway at the interface between the bulkhead and the surrounding rock, water conducting fault in the surrounding rock of the bulkhead, and water conducting fracture in the surrounding rock of the bulkhead are very high. The most important reason is that the design water pressure of 8.00 MPa and 8.32 MPa of the bulkheads is presently not commonly used in China, which plays a decisive role in the calculated values of the connectivity coefficients. Besides, the bulkheads are located in the interbedded coal and rock roadways, and the lithology, strength, and stability of the surrounding rock are more complex with hidden structures which adversely affect the stability of the foundation of the bulkheads and the seepage and water retaining characteristics of the surrounding rock.

#### 4. Calculating Hydraulic Gradient and Water Retaining Characteristics of Bulkheads at Panel No. 21102

4.1. Hydraulic Gradient Calculation of Bulkheads at Panel No. 21102. The hydraulic gradient of seepage in the surrounding rock is related to the groundwater pressure, geometry and size of the roadways and bulkheads, and permeability of the rock. Based on a seepage analysis of the water bulkhead in coal mines including the seepage of the surrounding rock, the critical hydraulic gradient,  $I_{cr}$ , to prevent the disintegration of the surrounding rock

TABLE 3: Connectivity coefficients of water conducting pathway at the interface between bulkhead and surrounding rock of Panel No. 21102.

Connectivity coefficient of water conducting pathway $m$	Type of bulkhead	Length of main wall (m)	Length of reinforcement section on both sides (m)	$L_D/L$	$P_g/P_d$	Stability time of pressure test
8-10	Inverted pyramid	24	40	1.19	1.12 (TR)	24-72
8-10	Inverted pyramid	24	40	1.19	1.25 (MR)	24-72

TR represents transport roadway and MR represents material roadway.

TABLE 4: Connectivity coefficients of water conducting pathway of faults in surrounding rock.

Connectivity coefficient of water conducting pathway $m$	Properties of surrounding rock	Water pressure (MPa)	Fault scale			Properties of fault	
			Type	Drop (m)	$L_D/L$	Shape	Dynamics
8-10	Hard	$\geq 5$	Extra large	$\geq 50$	$\leq 1$	Normal fault	Tensile
5-7	Medium hard	3-5	Large	20-50	1-10	Normal fault	Tensile
3-4	Soft	2-3	Medium	5-20	10-50	Translational fault	Shear
1-2	Extremely soft	$\leq 2$	Small	$\leq 5$	$\geq 50$	Reverse fault	Compressional

TABLE 5: Connectivity coefficients of water conducting pathway of faults in surrounding rock of Panel No. 21102.

Connectivity coefficient of water conducting pathway $m$	Properties of surrounding rock	Water pressure $P$ (MPa)	Fault scale			Properties of fault	Dynamics property of fault
			Type	Drop (m)	$L_D/L$		
8-10	Soft-hard	8.32 (TR)	Small	2	-	Normal	Tensile
8-10	Soft-hard	8.00 (MR)	Small	2	-	Normal	Tensile

TABLE 6: Connectivity coefficients of water conducting pathway in fractured zone around mine opening in surrounding rock.

Connectivity coefficient of water conducting pathway $m$	Stability of surrounding rock	Thickness of fractured zone $L_p$ (cm)	Water pressure (MPa)	Roadway depth $B$ (m)	Type of bulkhead	Properties of surrounding rock
9-10	Extremely unstable	$\geq 300$	$\geq 7$	$\geq 5.0$	Rectangular	Hard
7-8	Unstable	200-300	5-7	4.0-5.0	Flat	Hard
5-6	Generally unstable	150-200	3-5	3.5-4.0	Cylindrical	Medium hard
3-4	Fair	100-150	2-3	3.0-3.5	Tapered	Soft
2	Somewhat stable	40-100	1-2	2.5-3.0	Inverted pyramid	Very soft
1	Stable	0-40	$\leq 1$	2.0-2.5	Inverted pyramid	Very soft

The thickness of the fractured zone is determined by geophysical prospecting or drilling methods.

along a seepage path, Path- $m$ , in the bulkhead can be expressed as follows:

$$I_{cr} = \frac{H}{L + 2E} \frac{m\sqrt{k}}{LK_V}, \quad (1)$$

where  $I_{cr}$  is the critical hydraulic gradient;  $H$  is the pressure head of the groundwater along the seepage path, Path- $m$ ;  $L$  is the length or thickness of bulkhead along the roadway axis in Path- $m$ ;  $E$  is the depth of the bulkhead embedded into the

surrounding rock along the radius of the roadway in Path- $m$ ;  $m$  is the connectivity coefficient of the water conducting pathway;  $K$  is the permeability of the surrounding rock,  $\text{um}^2$ ; and  $K_V$  is the integrity coefficient of the surrounding rock mass which is generally determined by measuring the elastic wave propagation in the rock. The values of  $K_V$  for different rock mass integrities are given in Table 8.

When the flow field in the rock reaches a stable state after continuous seepage for a period of time, the hydraulic gradient can be expressed as follows:

TABLE 7: Connectivity coefficients of water conducting pathways of fractures in fractured zone of surrounding rocks of Panel No. 21102.

Connectivity coefficient of water conducting pathway $m$	Stability level of surrounding rock	Thickness of fractured zone $L_p$ (cm)	Water pressure $P$ (MPa)	Span length $B$ (m)	Types of bulkhead	Properties of surrounding rock
9–10	Fair	100–150	8.32 (TR)	8.4	Inverted pyramid	Semi-coal and semi-rock
9–10	Fair	100–150	8.00 (MR)	8.4	Inverted pyramid	Semi-coal and semi-rock

TABLE 8: Values of  $K_V$  for different rock mass integrities.

$K_V$	>0.75	0.75–0.55	0.55–0.35	0.35–0.15	<0.15
Degree of integrity	High	Good	Medium	Low	Extremely low

$$I_s = \frac{H}{L + 2E} \quad (2)$$

When the ratio of the critical hydraulic gradient to the steady state hydraulic gradient is greater than the safety factor for the safe operation of the bulkhead, this means that the bulkhead is able to control the flow of water from the surrounding rock. The safety criterion can be expressed as follows:

$$\frac{I_{cr}}{I_s} \geq F_S, \quad (3)$$

where  $F_S$  is the safety factor against the disintegration of the rock due to water flow.

Based on the analysis of cases where the bulkhead is used to control water flow in a number of coal mines in China, the relationship between the observed water flow rate due to leakage around the bulkhead and  $I_{cr}/I_s$  is shown in Table 9. As can be seen in the table, the bulkhead is effective in controlling water from its surroundings. For the cases with no water leakage, the  $I_{cr}/I_s$  ratio is greater than 1.68. Therefore, a safety factor,  $F_S$ , of at least 1.68 should be used to control water flow with the use of a bulkhead.

The parameters in (1) and (2) can be determined as follows. The water pressure, head  $H$ , in the rock around the bulkhead can be directly obtained from a hydrogeological investigation such as from water pressure measurements in observation well bores. The length,  $L$ , of the bulkhead along the roadway and the depth,  $E$ , of the bulkhead embedded radially into the surrounding rock along the roadway can be found based on the design specification of the bulkhead. The coefficient of permeability,  $k$ , that is, the permeability of the surrounding rock, can be measured or determined based on local experience. The rock in the roof of the roadway at Panel No. 21102 is a hard rock that is part of the twelve layers of limestone in the Taiyuan Formation. However, the two sides and floor of the roadway are part of Coal Seam No. 21 with interbedded soft and easily broken siltstone and sandy mudstone. Based on the lithology and permeability of the surrounding rocks at Panel No. 21102, the intrinsic coefficient of permeability of the rock mass is estimated to be  $0.30 \text{ um}^2$ . Taking into consideration that the connectivity coefficient value of the water conducting pathway of the

surrounding rock at Panel No. 21102 is around 9 or 10, the higher value of 10 is chosen to be on the safe side. From (1) and (2), the critical hydraulic gradient  $I_{cr}$  and steady state hydraulic gradient  $I_s$  and ratio  $I_{cr}/I_s$  of the bulkheads in the transport and material roadways are calculated and shown in Table 10. The  $I_{cr}/I_s$  values of the transport and material roadways are both found to be 0.65, which is less than the safety factor  $F_S$  ( $F_S = 1.68$ ) on water control, thus indicating possible leakage of the two bulkheads.

On August 5, 2003, a pressure test of the bulkheads at Panel No. 21102 revealed a water leakage rate of less than  $2 \text{ m}^3/\text{h}$ . The water pressure at the material roadway was measured and found to be 7.35 MPa on August 26, 2003, with a water leakage rate of  $1.1 \text{ m}^3/\text{h}$ . For the transport roadway, the water pressure at the bulkhead was measured and found to be 7.6 MPa with a water leakage rate of  $3.5 \text{ m}^3/\text{h}$ . These measurements and observations show that water leakage occurred during the operation of the bulkheads at Panel No. 21102 by forming a water conducting pathway through the surrounding rock of the bulkhead. This is consistent with the evaluation results based on the calculation of the critical and steady state hydraulic gradients at the bulkhead. The amount of water leaked from the rock is small compared to the total volume of water, thus indicating that the bulkhead is effective; that is, the bulkhead can almost entirely control the water flow.

## 5. Discussion of Water Inrush in the Sanhejian Coal Mine

Based on field measurements in the Sanhejian coal mine from August 26, 2003, to December 20, 2008, the changes in the water seepage and water pressure with time in the rock that surrounds the bulkhead are shown in Figures 5 and 6, respectively.

In general, the pressure tests show that the overall trend in the variations of water flow from the surrounding rock is consistent with the trend in the variations of water pressure at the bulkheads for both the material and transport roadways at Panel No. 21102. At the beginning of the test, the water pressure and flow rate fluctuate with an overall upward trend. On June 22, 2005, the flow rate and water pressure reach their peak values on the same day followed by

TABLE 9: Calculated  $I_{cr}/I_s$  ratio and observed water flow rate (leakage) around bulkheads in different mines in China.

Trial no.	Mine site	Critical hydraulic gradient $I_{cr}$	Steady state hydraulic gradient $I_s$	$I_{cr}/I_s$	Water flow (leakage) rate
1	Yangzhuang mine ②③④	26.88	7.51	3.58	0 m <sup>3</sup> /h
2	Xiazhuang	31.64	9.94	3.18	0 m <sup>3</sup> /h
3	Qixi mine ②③④	16.67	6.84	2.44	0 m <sup>3</sup> /h
4	Gequan mine	30.13	13.61	2.21	0 m <sup>3</sup> /h
5	Hemei 10 mine	26.32	13.58	1.94	0 m <sup>3</sup> /h
6	Qixi mine ①	20.00	10.62	1.88	0 m <sup>3</sup> /h
7	Taoyuan mine	50.77	28.09	1.81	0 m <sup>3</sup> /h
8	Yangzhuang mine ①	25.91	15.45	1.68	0 m <sup>3</sup> /h
9	Quanshang mine	33.33	21.16	1.58	5.0 m <sup>3</sup> /h
10	Qidong mine conveyor roadway	49.44	43.73	1.13	2.0 m <sup>3</sup> /h
11	Qidong mine caved roadway	53.35	57.34	0.93	2.6 m <sup>3</sup> /h
12	Dongjiahe mine	9.08	13.16	0.69	1.5 m <sup>3</sup> /h
13	Dongzhuang mine	38.61	63.59	0.61	2.0 m <sup>3</sup> /h

TABLE 10: Parameters to calculate hydraulic gradient of the surrounding rocks in Sanhejian coal mine.

Location of bulkhead	Transport roadway	Material roadway
Length of wall $L$ (m)	24	24
Height $H$ (m)	760	735
Embedded depth $E$ (m)	2	2
Permeability $k$ (um <sup>2</sup> )	0.30	0.30
Rock mass integrity coefficient $K_V$	0.35	0.35
Penetration coefficient of water diversion channel in surrounding rock $m$	10	10
Critical hydraulic gradient $I_{cr}$	17.70	17.12
Stable hydraulic gradient $I_s$	27.14	26.25
$I_{cr}/I_s$	0.65	0.65

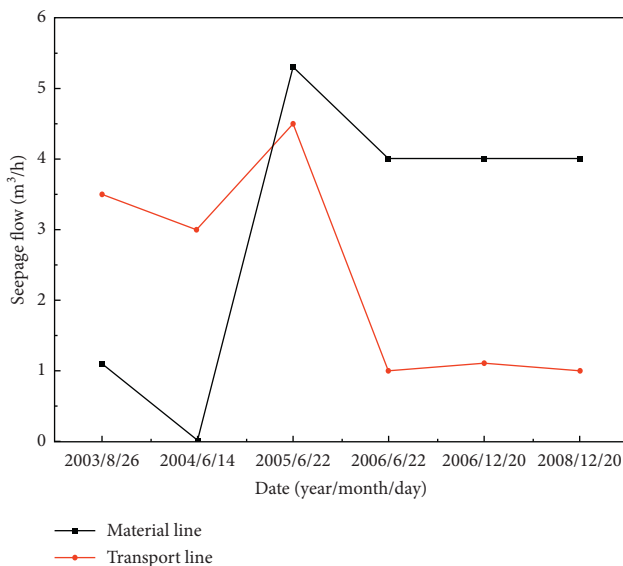


FIGURE 5: Changes in seepage flow with time of rock mass at Panel No. 21102.

a drop in both until reaching a stable state on June 22, 2006. After that, both the flow rate and water pressure remain constant until the end of the observation period on December 20, 2008.

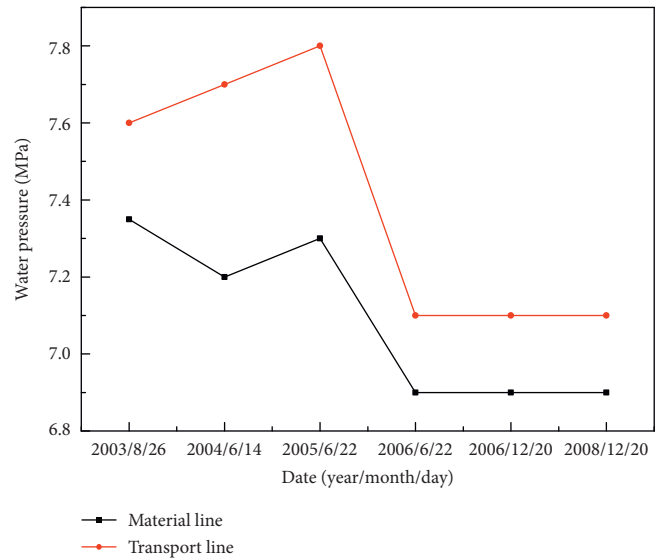


FIGURE 6: Changes in water pressure with time of bulkheads at Panel No. 21102.

The water pressure in the bulkheads at Panel No. 21102 was changing during the observation period and had a direct influence on the leakage of water from the surrounding rock. The measurements show that the water pressure and water flow rate are synchronized and rise and fall together. This



confirms that the water pressure was controlling the water seepage in the rock that surrounded the bulkheads.

Overall, only a small amount of water flow leaked through the bulkheads at Panel No. 21102 and the bulkheads provide a stabilizing effect of the water pressure. The design water pressure of the bulkheads at Panel 21102 is 8.0 and 8.32 MPa, and the actual observed water pressure is 7.35 and 7.60 MPa, for the material and transport roadways, respectively. The rock around the roadways consists of layers of coal with interbedded siltstone and sandy mudstone. The control of water in this case is more than 99% effective. The experience in the design, construction, grouting reinforcement, and pressure test of the bulkheads in the case of the Sanhejian coal mine is valuable for the application of underground bulkheads in China. This case is a success story on the use of bulkheads to control high pressure water flow in coal mines in China.

## 6. Conclusion

Based on the findings in this study, the following conclusions are made:

- (1) Three types of water conducting pathways in the bulkhead and its surrounding rock are identified. A concept is proposed to evaluate the connectivity coefficients for water conducting pathways. A quantitative analysis of the connectivity coefficients of the water conducting pathways is presented with the selection of representative indicators to evaluate the geology and hydrogeology that can be used in bulkhead design and construction considerations.
- (2) Based on the calculation of the steady state hydraulic gradient in the rock around the bulkhead, an expression to calculate the critical hydraulic gradient to initiate seepage in the surrounding rock is presented. The critical hydraulic gradient considers the permeability and integrity of the rock mass. A relationship between the ratio of the critical and steady state hydraulic gradients and the water flow rate from the bulkhead is established based on an analysis of a number of coal mines in China.
- (3) The relationships between the seepage flow rate and time and between the variation of water pressure and time of the bulkheads in the Sanhejian coal mine are analyzed. It is found that there is a good correlation between the change in water pressure and leakage flow rate which shows that water pressure plays a decisive role in controlling the seepage flow in bulkheads.

## Data Availability

The datasets generated during the current study are available from the corresponding author on reasonable request.

## Conflicts of Interest

The author declares that they have no conflicts of interest.

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