

Mechanism of water inrush driven by grouting and control measures—a case study of Chensilou mine, China

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Abstract Water inrush into coal mines from aquifers underlying coal seams often causes serious casualties and economic losses. The key to preventing the disaster is to discover a water inrush mechanism suitable for specific geological and hydrogeological conditions and apply reasonable control measures. A case of the Chensilou mine is studied in this paper. Complex geological and hydrogeological conditions, such as 12 aquifers in the floor and small distance between coal seam and aquifer, make the mining face in the synclinal basin have a great risk of water inrush. In addition, as an important way to prevent the disaster, grouting will aggravate the risk of water inrush from the floor. The slurry will drive groundwater in the limestone aquifers L_8 , even L_7 and L_6 along the horizontal (fracture zone in L_{11} – L_8) and vertical (Fs1 ~Fd1) water flow channel into the mining face and synclinal basin. A new water inrush mechanism driven by grouting is formed. In order to prevent this disaster, based on statistical law of hole deviation, the relative error of vertical depth and the angle between the borehole and the rock formation are obtained. Finally, an improved grouting method is proposed, which is useful to ensure the safe production of coal mine and reduce the cost of grouting.

Keywords Water inrush mechanism · Grouting · Hole deviation · Synclinal basin · Coal mine

Introduction

Water inrush from confined aquifers underlying coal seams often causes serious accidents, especially in North China, coal mines have become more vulnerable to water inrush as mining depths increase. The key to preventing this disaster is to figure out the mechanism of water inrush and adopt reasonable management methods (Bai and Miao 2016). Many scholars believe that the evolution of water-conducting channel is closely related to the water inrush during mining. Zhu et al. (2014) obtained the stress analytical solution for complete floor by elastic mechanics method and studied the effect of ground pressure on the damage thickness of aquifuge. Zhu and Wei (2011) and Ma et al. (2016) believed that the geological structure was the main reason for the water inrush from floor. They got the stress, strain and plastic zone of the karst collapse column or fault by numerical simulation. Yin et al. (2015) argued that hydraulic fractures penetrated each other and formed a water-conductor under groundwater pressure. They also studied the generating conditions of fractures by fracture mechanics. Based on the data of water injection test, Zhang (2005) found that the damage thickness of the floor increased with the mining width in the form of power function. For the management methods, groundwater dewatering is one of the safest methods of coal mining (Pfaffenberger and Scheele al. 1992). However, groundwater is of critical importance as a source of drinking water in China. As a result, Chinese engineers often use grouting methods before mining practice. In the face of the small distance between the coal seam and the

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aquifer, Yang et al. (2013) and Chen et al. (2014) used the method of grouting into the broken limestone to increase the thickness of aquifuge. Wang et al. (2015) and Shi et al. (2017) injected cement slurry into a karst collapse column or a fault to prevent water inrush from floor.

As mentioned above, most scholars have studied the effects of ground pressure, geological structure, mining size, and water pressure on the damage thickness of aquifuge by mechanical methods. However, these mechanical models can only explain the formation of water-conducting channel under simple geological conditions, because the models are simplified from the engineering practice. Moreover, they did not pay more attention to another factor that caused water inrush disaster—mine water source. As a measure widely used to prevent mine flood, grouting is believed to be a simple technology, which only requires appropriate grouting materials (Wang et al. 2017), grouting pressure (Yang et al. 2013), and grouting capacity (Cao et al. 2010). However, if we concern only the safety of the grouting face, rather than the safety of the hydrogeological unit or the entire mine, it is possible to cause serious risk of water bursting in other mining faces, especially in coal mines with complex geological conditions.

In this paper, the south part of Chensilou mine has been chosen as the study area, where the floor contains 12 aquifers, a synclinal basin and faults. Instead of the mechanical methods, the in-site test method is utilized to record the water inflow of drillings in different mining faces with different production time. Based on the data of water inflow from aquifer, we established three criteria, and analyzed the characteristics of salinity and isotope in groundwater before and after the floor grouting near the synclinal basin. A new water inrush mechanism driven by grouting is proposed, and the root of this phenomenon lies in the tilted drillings. Based on statistical law of holes deviation, we put forward an improved grouting solution, which is useful to reduce the grouting cost and ensure the safety production. This study is of great significance for the prevention of water inrush from floor in coal mines with complicated geological conditions.

The study area

Overview of the Chensilou mine

Chensilou mine is located in northwest of Yongcheng City, Henan Province. It covers an area of 62 km², and has an annual production of 4.5 million tons. As of 2014, the north-east and southeast parts of the mine have been mined (Fig. 1). According to the mining plan, coal will be mined in the

southwest. Therefore, the southwest of the mine is selected as the study area.

Engineering situations

The geological and hydrogeological conditions of the Chensilou mine are quite complex. The stratigraphic succession consists of Ordovician (O), Carboniferous (C), Permian (P), Neogene (N), and Quaternary (Q) from bottom to top. The main minable seam is No.2 coal seam, which belongs to Permian formation. The coal seam floor consists of 11 layers of Taiyuan limestone (L₁~L₁₁), sandstone, mudstone, and Ordovician limestone. In the horizontal direction, there is a synclinal basin in the southwest of the mine, in which the mining depth is 892 m, the water pressure is 6~7 MPa, and the distance between the coal seam and the L₁₁ limestone is about 41 m. The faults may form water channels under the mining influence and water pressure.

For the hydrogeology, in the vertical direction, limestone, sandstone, and fine sandstone are aquifers due to fissures development. The L₁₁~L₆ have significant influence on safety production, and the salinity of L₁₁~L₈ (upper Taiyuan formation) is different from that of L₇~L₆ (middle Taiyuan formation) (Fig. 2). The mudstone with large thickness and low permeability is mixed between the upper and middle formations, so the hydraulic connection is weak in the vertical direction. In the horizontal direction, the faults at the north, west, and south boundaries of the southern part of the mine have water-insulating capability, and the eastern boundary is granite dike (Fig. 1). Meanwhile, the upper part of strata is covered with thick clay layers. Such geological environment makes the south part become a relatively independent water circulation system, and the water in the aquifers flows slowly in the horizontal and vertical directions in natural conditions.

Problems

The accidents of water inrush from L₁₁~L₆ have occurred more than 20 times since 1997. As the mining faces advance towards to the syncline basin, the risk of water inrush continues to increase and the hydrogeological conditions are more complicated.

Complex natural conditions

In the east of the south part, the mining depth is 390 m, the water pressure is 3 MPa, and the distance between the coal seam and L₁₁ is 60 m. However, in the synclinal basin, the mining depth increases to 892 m, the water pressure increases to 7 MPa, and the distance between the coal seam and L₁₁ reduces to 41 m. Meanwhile the sandstone in floor is broken,

Fig. 1 Chensilou coal mine location and the study area

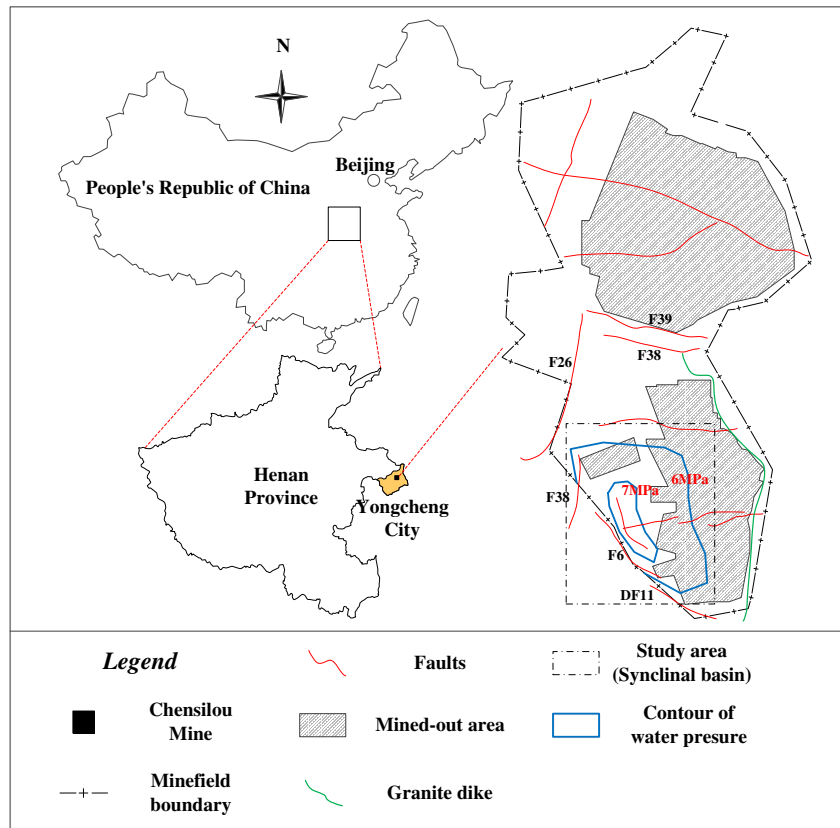


Fig. 2 Histogram of the floor strata

Formation		Column	Average thickness /m	Salinity / (g/L)	Description	Distance /m
System	Stage					
Permian (P)	Shanxi	No.2 coal	2.4 m			41.0 m 48.6 m 60.3 m 86.2 m
		Sandstone	14.2 m		Aquifer	
		Fine sandstone	10.1 m			
		Mudstone	6.3 m		Aquifuge	
		Sandstone	10.4 m			
Carboniferous (C)	upper	L11	1.5 m	2.96 ~ 3.60	Aquifer	
		Fine sandstone	6.1 m			
		L10	4.8 m			
		Sandstone	6.9 m			
		L9 (L8)	4.8 m			
	middle	Mudstone	0.4 m		Aquifuge	
		L8	14.4 m		Aquifer	
		Mudstone	6.3 m		Aquifuge	
		L7	5.8 m	3.31 ~ 4.14	Aquifer	
		Mudstone	2.9 m		Aquifuge	
L6	7.2 m	Aquifer				
Fine sandstone	17.1 m		Aquifuge			
Sandstone	18.8 m		Aquifer			
L5	4.2 m					

the number of faults increases, and the thickness of the natural aquifuge is only 6.3 m (Fig. 2).

In addition, engineers drilled 24 hydrologic boreholes in the southern part of the mine near the syncline basin. According to the drilling data from 6601~6605 shown in Fig. 4a, the coring rate is only 66, 52, and 23% in L₁₁, L₁₀, and L₈, respectively (Fig. 3). However, the coring rate outside the 6601~6605 is as highly as 87, 75, and 71%, respectively. The data indicates that a distinct natural fracture zone exists in the upper Taiyuan formation, and points to the syncline basin (purple line in Fig. 4a). As mentioned above, the water circulation in natural conditions is very weak in south part of the mine. However, if the unreasonable grouting method continues to be used, the water inflow will increase in the study area.

Huge grouting costs

The grouting costs in Chensilou mine are enormous, because the grouting thickness needs to meet the requirements of “Coal mine water control regulations” (Wu et al. 2017). The concept of “water bursting coefficient” is as follows.

$$T = P/M \quad (1)$$

Where P is the water pressure acts on the floor, MPa. M is the thickness of aquifuge, m. T is the water bursting coefficient, MPa/m. According to the statistics (Wu et al. 2017), the mining practice is safe if $T \leq 0.1$ MPa/m. From Eq. 1, it can be seen that the grouting thickness increases with the increase of water pressure.

More than 60 mining faces in Chensilou mine have been excavated safely based on Eq. 1. However, the water inrush accidents occurred frequently (Fig. 4a) when the water pressure exceeds 6 MPa and the grouting thickness is 60 m according to Eq. 1 (the grouting layers are L₁₁ and L₁₀). In order to ensure the mining safety, engineers have to carry out grouting practice again, and the grouting thickness has reached 120 m, the grouting capacity is about 6280 t in a

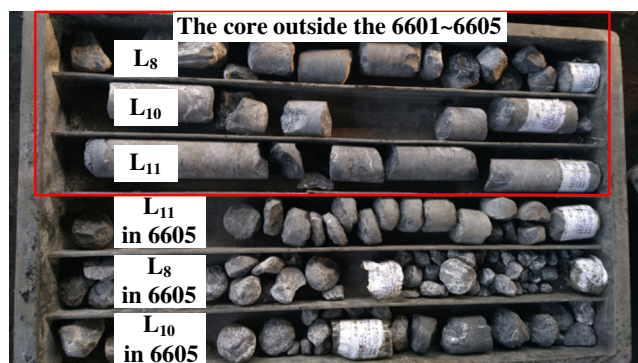


Fig. 3 Cores at 6605 borehole and outside the boreholes of 6601~6605

mining area, and the grouting cost is as high as 24.78 million dollars per year.

Water inrush driven by grouting

The mine water source and the water-conducting channel are two necessary factors to cause water inrush, and the results of the two can be expressed by “water inflow.” We no longer follow the majority of scholars to study water source or channel by numerical simulation or similar simulation methods, but directly study the changes of water inflow during mining advance according to the hydrogeological theory. In mining practice, water inflow from boreholes is affected by a variety of factors, including ground pressure, mining size, water pressure, mining depth, rock mechanics, and hydrodynamic parameters and so on. In the adjacent mining area, the above factors are roughly the same (such as mining faces 2513, 2517 and 21701, 21503 in Fig. 4a and Table 1); however, there is a big difference in water inflow, which is mainly caused by the floor grouting operation. The irrational grouting operation in the synclinal basin will not only lead to the insecurity of the mining face itself, but also will increase the risk of water bursting in other mining faces. In order to describe the amount of water inflow in different mining areas, some simple and practical criteria are established.

Average thickness of karst water in unit area

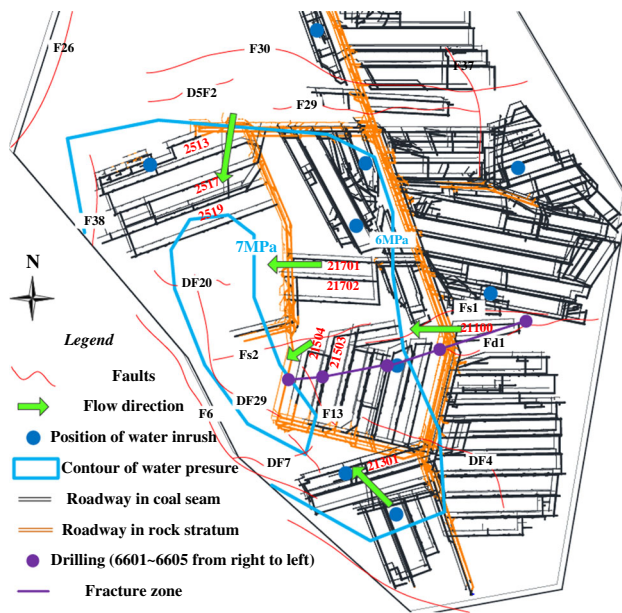
$$H_i = \sum_{n=1}^m Q_i / A \quad (2)$$

Where, H_i is the average thickness of karst water in unit area, m. It represents the average amount of water that can flood in the mining face. $\sum_{n=1}^m Q_i$ is the sum of water inflow in an hour when the hole is exposed limestone L_i , m³/h. $i = 8, 10, 11$, representing limestone of L₈, L₁₀, L₁₁, respectively (the mudstone thickness between L₈ and L₉ is almost 0 m in the south of the mine, so there is no need to distinguish L₈ and L₉). m is the number of effluent holes when limestone L_i has been exposed. A is the area of mining area, m².

Average water flow in a borehole

$$q_i = \sum_{n=1}^m Q_i / m \quad (3)$$

Where, q_i is the average water flow in a borehole, m³/h, and it represents the amount of karst water that flows to the mining face from a borehole. If karst is



(a) Positions of water inrush, broken zones, mining faces and groundwater flow directions

Fig. 4 Mechanism of water inrush driven by grouting

developed in some parts of mining face floor, there will be a large q_i and small H_i .

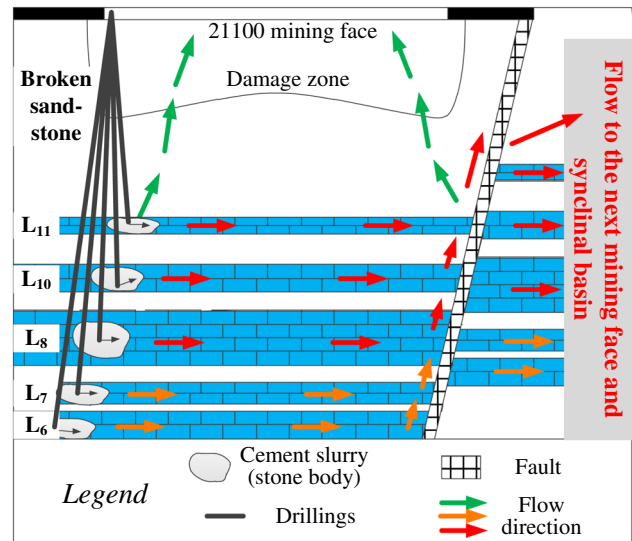
Probability of water inflow from borehole

$$P_i = m/s \tag{4}$$

Where, P_i is the probability of water inflow from borehole. s is the total number of boreholes exposed the L_i limestone. If P_i is large, there could be geological structures near the boreholes.

Statistical data are obtained from 1152 drillings in six mining faces with similar altitude and different time of excavation, as shown in Table 1.

As shown in Table 1, (1) the positions of the vertical water flow channel can be determined. For P_{11} , the maximum



(b) Groundwater flow caused by grouting and mining practice (Take 21100 mining face as an example)

probability of water inflow is the 21100 face, which is located between the faults $Fs1$ and $Fd1$ (Fig. 4a). As the mining faces advance towards the synclinal basin, the P_{11} is reduced to 12% (21301 face). And then the P_{11} increases to 20~25% in the inclined basin (2517, 21701, 21503 faces). The data of P_{10} and P_8 have similar change laws. Although the water inflow of L_{11} is much lower than that of L_{10} and L_8 in 21,100 face, P_{11} is still close to P_{10} and P_8 , indicating that faults $Fs1$ and $Fd1$ are vertical water channels and link three aquifers of L_{11} , L_{10} , and L_8 . (2) Drilling data show that the grouting practice has caused the water inrush from floor in the synclinal basin. During the excavation of the 21100, 21301, and 2513 faces (from 2010 to 2012), H_{11} is 0.003~0.010 m, and q_{11} is 23~30 m^3/h . However, during the excavation of the 2517, 21701, and 21503 faces (from 2014 to 2016), H_{11} increases to 0.013~0.035 m, and q_{11} increases to 36~52 m^3/h . H_{10} and H_8 , q_{10} and q_8 have similar change laws. It means that, as the grouting advances towards the synclinal basin, the water

Table 1 Drilling statistics

Mining face	Altitude/m	Year	$P_{11}/\%$	$P_{10}/\%$	$P_8/\%$	H_{11}/m	H_{10}/m	H_8/m	$q_{11}/(m^3/h)$	$q_{10}/(m^3/h)$	$q_8/(m^3/h)$
21100	-400	2010	62	66	73	0.007	0.016	0.019	30	28	26
21301	-520~-580	2012	12	23	40	0.003	0.007	0.001	23	23	20
2513	-680~-700	2011	23	37	42	0.010	0.020	0.016	28	26	28
2517	-700~-720	2014	25	51	50	0.022	0.069	0.030	52	50	30
21701	-560~-680	2015	22	51	50	0.035	0.052	0.033	47	48	33
21503	-600~-680	2016	20	49	48	0.013	0.039	0.020	36	40	28

inflow of $L_{11}\sim L_8$ increases gradually from the north (2517 face), the east (21701 face), and the southeast (21503 face) (Fig. 4a). In addition, three large-scale hydrogeological explorations also proved the water inrush mechanism driven by grouting in the synclinal basin. The pumping test method was used for hydrological exploration in 1986, the units-inflow in the upper Taiyuan formation ($L_{11}\sim L_8$) was 0.461~4.132 L/(s·m) in the vicinity of the synclinal basin. In 1994, the units-inflow in this area is 0.510~4.025 L/(s·m). With the increase of the water inrushes, the engineers carried out floor grouting operation at the Chensilan mine from 2003. In the supplementary exploration in 2010, the units-inflow increased to 0.483~6.801 L/(s·m). However, in 2014~2016, the units-inflow of L_8 and L_{11} which was converted from water inflow of grouting borehole is 0.434 L/(s·m) and 9.629 L/(s·m), respectively. Obviously, the above hydrological and grouting boreholes are in the same study area, and have similar geological factors, including in situ stress, water pressure, strata distribution, strata thickness, rock mechanics, and hydrodynamic parameters. Therefore, the variation of the water inflow is mainly caused by the floor grouting.

More seriously, groundwater from the L_6 and L_7 aquifers is also involved in the water cycle due to floor grouting. In natural conditions, the change range of salinity in each aquifer is small. However, in 2016, the salinity of karst water in L_{11} , L_{10} , and L_8 increases from 2.96~3.60 g/L to 3.20~3.89 g/L, and the values are close to that of L_7 and L_6 (3.31~4.14 g/L). Isotope test results can also reflect the fact that the karst water in the middle Taiyuan formation (L_7 and L_6) has become a mine water source. The hydraulic connection between the limestone formations in the south part of the Chensilou mine is very weak, and there is a big difference of isotope between D and ^{18}O in 2002 and 2016. The results (Table 2) show that the D and ^{18}O of the first five water samples from different depths of the synclinal basin are almost the same. The data indicates that the karst water in L_7 and L_6 is also involved in the water cycle and exacerbates the risk of water inrush in the synclinal basin.

Eventually, the groundwater flows in both the horizontal and vertical directions to the synclinal basin, forming water inrush disaster driven by floor grouting (Fig. 4b).

Other problems

There are other problems in the mining process.

- (1) According to grouting design, L_{11} is the main grouting layer of floor. The core indicates that there is no cement slurry or stone body in L_{11} but in L_7 and L_6 .
- (2) After grouting, the floor water inrush still occurs occasionally. In order to ensure the safety of mining, engineers often re-grout in the sandstone, resulting in low production efficiency.

Reasons and methods

The main reason for the grouting-driven water inrush is that the grouting layer moves down as a whole. The cement slurry occupied the fissures in the L_6 and L_7 aquifers, and drove groundwater into the L_8 , L_{10} , and L_{11} aquifer, which exacerbated the risk of floor water inrush. The prediction was verified by in-site test.

Hole deviation and statistical law

From June to October in 2016, the borehole inclinometer was used to test the 14 grouting holes. The results are shown in Fig. 5 and Table 3.

As shown in Fig. 5, the borehole z-1 has a significant deviation during drilling, and the actual vertical depth at the bottom of the hole is 20 m larger than the design value. There are two reasons for this phenomenon: First, the fine sandstone and sandstone at the bottom of the Shanxi formation are broken, and the mudstone itself has lower modulus and strength. Second, the engineers use a drill bit with a

Table 2 Results of isotope test

Sampling sites	Water source	Sampling time	Testing item	
			$\delta\text{D}_{\text{v}}$ - SMOW(‰)	$\delta^{18}\text{O}_{\text{v}}$ - SMOW(‰)
21503 mining area	L_{10}	16.03.13	-73	-9.9
21503 mining area	L_8	16.03.27	-73	-9.9
Hydrological borehole near 21701 area	L_6	16.04.11	-73	-9.9
21701 mining area	L_{11}	16.04.11	-73	-9.9
The sump in fifth panel near 21301 area	Mixed water	16.04.13	-72	-9.8
Hydrological borehole near 2513 area	L_6	2002.06	-76	-9.6
Hydrological borehole near 2513 area	L_{10}	2002.06	-73	-9.9

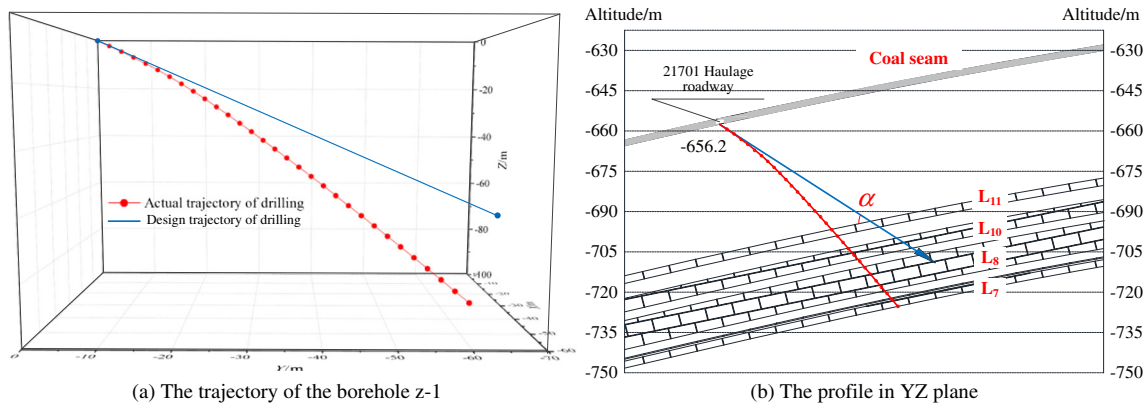


Fig. 5 Hole deviation (Take drilling z-1 as an example)

diameter of 133 mm for drilling operations. The bit is heavy, under the influence of gravity, the dip angle of the drilling hole increases when the vertical depth is no more than 20~41 m. Under the combined action of above two factors, the phenomenon of hole deviation has come into being. Once the drilling enters into Taiyuan formation, the increase of borehole inclination decreases because of the large elastic modulus of limestone. The actual trajectories of the drillings in Table 3 are similar to those in Fig. 5, but the vertical depth is different in different holes. The data in Table 3 shows that the average value of the azimuth relative error is only 6.1%. However, the average value of relative error in vertical depth reaches 60.8%. Accordingly, it is not the azimuth, but the stratigraphic dip and the drilling angle have a significant effect on the vertical depth of drillings. There is a common characteristic between the formation dip and the

drilling angle, that is, the same dimensions. Therefore, the combined effects of the formation dip and the drilling angle on the drilling depth can be simplified as the effects of angle α (Fig. 4) between drilling and strata on the drilling depth. The statistic results are shown in Fig. 6.

As shown in Fig. 6, the data of 14 holes are fitted into a straight line, and the relative error of vertical depth is negatively correlated with the angle α , and the expression is as follows:

$$y = 158.34 - 2.57\alpha \tag{5}$$

Where, y is the relative error of vertical depth, %. Thus, the expression of actual depth of the drilling is as follows:

$$H_a = H_p \times (1 + y/100) \tag{6}$$

Table 3 Statistics of hole deviation

Drilling	Formation dip/ $^{\circ}$	Drilling angle/ $^{\circ}$			Vertical depth/m			Azimuth/ $^{\circ}$		
		Orifice	Hole bottom	Relative error/%	Design value	Actual value	Relative error/%	Orifice	Hole bottom	Relative error (absolute value)/%
z-1	0	23	48.3	110	-41	-76.7	87	110	-108.7	1.1
z-2	12	16	55.7	248	-45	-86.4	92	89	78.0	12.3
z-3	10	18	48	162	-46	-89.2	94	46	42.1	9.4
z-4	6	26	49.9	92	-63	-119.1	89	260	253.1	2.7
z-5	6	28	54.1	93	-53	-84.8	60	142	148.0	4.2
z-6	5	31	60.3	94	-66	-114.2	73	87	96.0	10.3
z-7	2	34	79.9	135	-72	-118.1	64	225	211.9	5.7
z-8	11	29	48.6	67	-70	-102.2	46	127	130.8	2.9
z-9	5	37	70.7	91	-80	-123.2	54	94	90.8	3.4
z-10	8	34	59.8	76	-81	-119.1	47	311	323.1	3.8
z-11	10	34	61.9	82	-87	-131.4	51	219	183.3	16.3
z-12	16	32	58.3	82	-112	-153.4	37	328	333.1	1.5
z-13	10	38	76.4	101	-108	-140.4	30	101	94.5	6
z-14	14	36	62	72	-116	-148.5	28	26	28.7	8.2

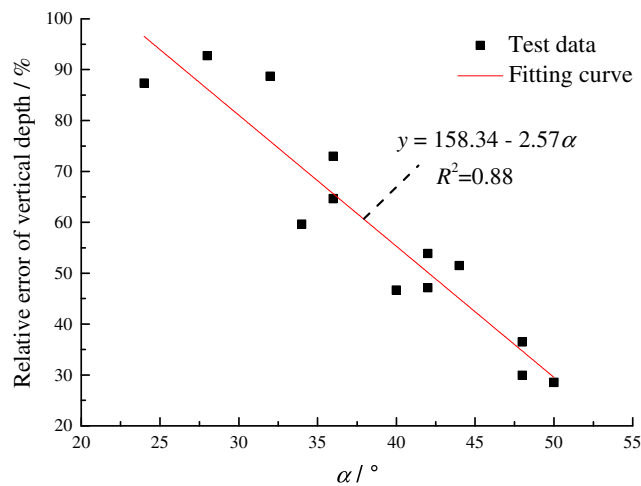


Fig. 6 Statistic results and fitting curves of hole deviation

Where, H_a is the actual depth, m. H_p is the designed depth, m. In engineering practice, the grouting layer (i.e., H_a) is determined by geological conditions. Thus the H_p could be obtained.

The constraints should be noted before using the above equations: (1) The stratigraphic dip in south part of the mine is in the range of $0^\circ\sim 16^\circ$. (2) The drilling angle at orifice is in the range of $16^\circ\sim 38^\circ$. (3) The same equipment and technique are utilized during drilling. (4) The distribution and thickness of floor strata are close to drillings in Table 3.

Improved grouting methods

The deviation of grouting layer caused by holes deviation is the root cause of frequent water inrush and high grouting cost during mining production.

Grouting layer

We have identified four grouting layers: (1) “Reinforcement layer” between the coal seam and L_{11} . (2) “Main remodeling layer” between L_{11} and L_{10} . (3) “Extension of the remodeling layer” between L_{10} floor and L_8 roof. (4) “Disturbance isolation layer” in the upper part of L_8 , as shown in Fig. 7.

The reasons are as follows: (1) The water abundance of sandstone between coal seam floor and L_{11} is a little. The sandstone formation has a large thickness, and has good mechanical properties of tension and compression after grouting. Therefore, the formation should be fully utilized. (2) According to hydrological exploration results, the water abundance of L_{11} and L_{10} is less than L_8 , the thickness between coal seam and L_{10} is about 60 m. When the water pressure is less than 6 MPa, this grouting thickness can meet the requirement of minimum thickness of aquifuge (Eq. 1). (3) The sandstone above L_8 is broken. When the water pressure exceeds 6 MPa, the grouting layer should extend to this stratum. (4)

Controlling groundwater in L_8 can effectively control the trend of further complication of hydrogeological conditions in the syncline basin.

Controlling hole deviation

Before drilling, the dip of borehole should be corrected and the drilling rig should be stabilized to prevent deflection. The drill pressure and the speed should be uniform. It is necessary to accurately measure the formation dip and the drilling angle at the orifice of the borehole. At the same time, we should pay attention to the application conditions before using Eq. 6 so as to determine the designed depth of drillings.

Drainage

The drainage method should be used in conjunction with the grouting method. The hydrogeological conditions are quite complicated due to the long-term and large-scale grouting in Chensilou mine. In order to reduce the groundwater flow into synclinal basin, the groundwater in the sandstone fissures, and karst water in the L_{11} and L_{10} should be drained from grouting holes before grouting in complete floor (blue arrow in Fig. 7). However, for the floor containing large faults, grouting operations near the faults are performed (i.e., waterproof curtain) before the floor grouting, so as to prevent groundwater from other aquifers consistently entering the grouting layer (Fig. 7).

Results and discussion

Results

The improved grouting methods have been applied to the 2519 and 21504 mining areas (Fig. 3), in which the water pressure exceeds 7 MPa. Cement slurry was pressed into boreholes by a grouting machine, and entered the target layer to form a strong aquifuge with a thickness of about 80–90 m. From December 2016 to April 2017, the two faces have been mined in lengths of 580 and 610 m, respectively. So far, there has been no floor water inrush accident. As the grouting thickness decreased from 120 to 80 m, the grouting capacity reduced to 3760 tons in a mining face, and grouting costs reduced to 3.67 dollars when the company produced one ton of coal (according to this trend, the grouting cost in 2017 will be reduced by 8.28 to 16.50 million dollars).

Discussion

This paper investigates the reasons for the frequent water inrush from the floor in the Chensilou mine by using in-situ tests, carries on the statistical analysis to the data of water flow from drillings in different production time and different

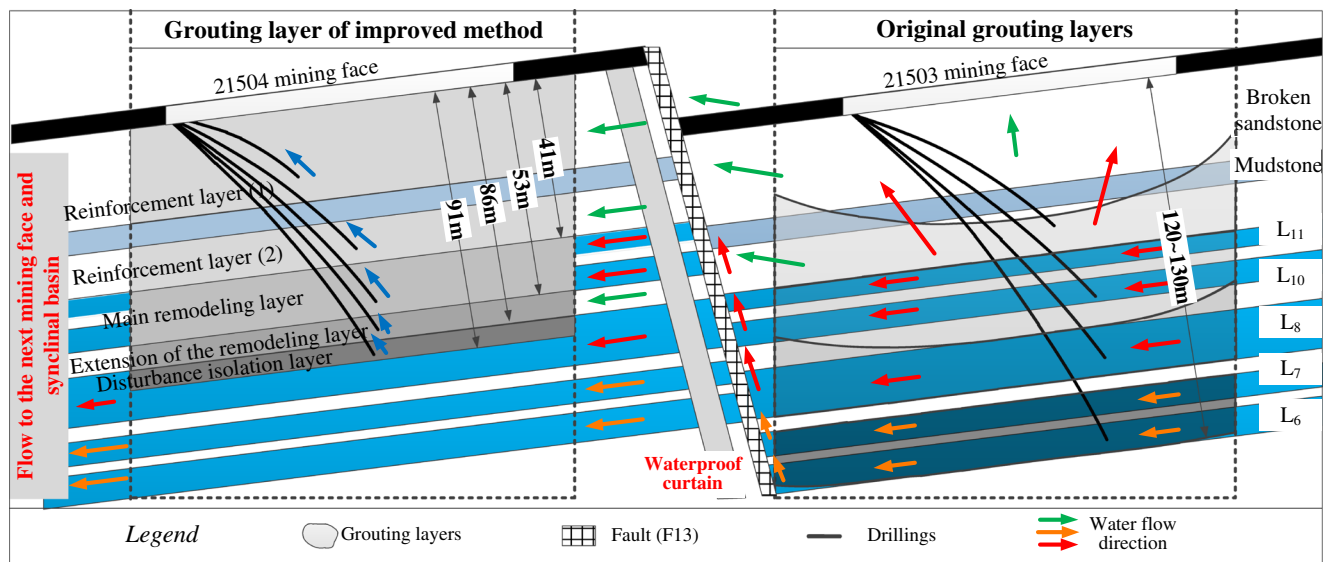


Fig. 7 Comparison of grouting layer between the original method and the improved method

mining faces, as well as deviation test of grouting drillings. The results demonstrate that the overall downward deviation of the grouting layer caused by holes deviation is the root cause of the water inrush disaster. This finding is significant because it offers a new mechanism of water inrush driven by grouting. Based on the mechanism, an improved grouting method is proposed. The engineering practices at 2519 and 21504 mining faces show that the improved method could not only prevent floor water inrush, but also reduce grouting costs by about a third. To our knowledge, the water inrush mechanism is proposed for the first time based on water inflow as well as the statistical methods.

Most scholars believe that the water-conducting channel resulting from mining activities is the root cause of water inrush. They used mechanical methods to study the effect of ground pressure (Zhu et al. 2014), faults or karst collapse columns (Zhu and Wei 2011; Ma et al. 2016), mining size (Zhang 2005), water pressure (Yin et al. 2016), and mining depth (Zhu et al. 2014) on the channel. However, the reasons of flood in Chensilou mine cannot be concluded from those studies because they were conducted by simplifying the geological conditions, mechanical parameters of rock mass, and the initial stress. In the present study, the probability of water inflow is calculated from 1152 boreholes, and Fs1 and Fd1 are the main water flow channels in the south part. This result from the in-situ test is very meaningful for the enterprise.

To date, most of the engineers are not aware that the unreasonable grouting layer will increase water inflow, and may cause serious water inrush due to deep groundwater involved in the water cycle. On the contrary, they believe that grouting is an effective way to control coal mine water in China (Kang et al. 2014; Wang et al. 2015). In the production practice, they focus on grouting

materials (Shimada et al. 2014), grouting capacity (Chen et al. 2014), and the diffusion radius (Feng et al. 2015). These factors could partially prevent the floor water inrush under simple geological conditions. Although hole deviation, which has great influence on grouting layer, was reported in a previous study (Li et al. 2013), the application of directional borehole to correct grouting layers and prevent water inrush caused by grouting was not noted. The exact mechanism of water inrush in south part of Chensilou mine is still not clear by above methods. The holes deviation has a unique characteristic in the study area. According to Eq. 6, the vertical depth of drillings is inversely proportional to the angle α , therefore, the grouting layer in the middle of face will be lower than that on both sides. This means that the pre-grouting mining face itself has the risk of water inrush, that is, groundwater flow into the middle of the coal mining area from sandstone aquifer, and flow two sides of mining face from limestone aquifer (Fig. 7). More seriously, the deviation of the grouting layer caused by holes deviation will drive the groundwater in the L₁₁~L₈ and the L₇~L₆ flow into the synclinal basin, thus exacerbating the risk of floor water inrush (Fig. 4a).

This study demonstrates the grouting-driven water inrush mechanism caused by the holes deviation. This prompts us that irrational floor grouting layers not only cause the risk of water bursting in the grouting face itself, but also lead to deterioration of the hydrogeological conditions in adjacent mining faces. Evaluation criteria for water inflow (Eqs.2~4), statistical methods of hole deviation, especially the new water inrush mechanism would be valuable tools in coal mines (Cao et al. 2010), tunnels (Kang et al. 2014), or underground engineering with complex geological conditions.

Conclusions

The following conclusions can be drawn based on the above analysis:

- (1) The water inflow of 1152 drillings was recorded during the in-site test process. By means of hydrogeology theory, three evaluation criteria were established to determine the locations of the water-conducting channel and water inflow in the whole and local senses. Compared with the mechanics methods, this method is of great significance to coal mines with complex geological and hydrogeological conditions.
- (2) In the south part of Chensilou mine, the $L_{11}\sim L_8$ aquifers have a broken zone pointing to the synclinal basin in the horizontal direction. Fs_1 and Fs_2 faults are water flow channels in the vertical direction. The groundwater is driven into the synclinal basin in both horizontal and vertical directions, and the risk of water inrush from the floor is increased sharply under the unreasonable grouting layers. A new water inrush mechanism driven by grouting is formed.
- (3) The holes deviation is the root cause of this new water inrush mechanism. According to the statistical law of holes deviation, an improved grouting method is proposed, which includes the control of grouting layer and holes deviation during drilling. The improved method can not only achieve the purpose of preventing water inrush disasters, but also can reduce the grouting cost by about a third.

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References

Bai HB, Miao XX (2016) Hydrogeological characteristics and mine water inrush prevention of late Paleozoic coalfields. *J China U Min Technol* 45:1–10

- Cao GS, Yao QL, Wang FH, Jiang HJ (2010) Analysis of water inrush risk from coal seam floor over a confined water body. *J Min Saf Eng* 27:346–350
- Chen MZ, Guan ET, Tao WP (2014) The application of floor grouting consolidation in Zhengzhou mining area. China University of Mining and Technology Press, Xuzhou
- Feng YL, Liang L, Duan LH, Li L (2015) Researching on grouting material in Chensilou coal mine. *Mater Res Innov* 19:454–457
- Kang YS, Liu QS, Gong GQ, Wang HC (2014) Application of a combined support system to the weak floor reinforcement in deep underground coal mine. *Int J Rock Mech Mining Sci* 71:143–150
- Li Q, Shi Z, Fang J (2013) Drilling technology of pre-grouting reinforcement with directional borehole in coal floor. *Trenchless Technol* 1: 803–811
- Ma D, Miao X, Bai H (2016) Effect of mining on shear sidewall groundwater inrush hazard caused by seepage instability of the penetrated karst collapse pillar. *Nat Hazards* 82:73–93
- Pfaffenberger W, Scheele U (1992) Environmental aspects of water price formation. An empirical investigation of the cost of ground water protection. *Environ Resour Econ* 2:323–339
- Shimada H, Hamanaka A, Sasaoka T (2014) Behaviour of grouting material used for floor reinforcement in underground mines. *Int J Min R Environ* 28:133–148
- Shi WH, Yang TH, Yu QL, Li Y, Liu HL, Zhao YC (2017) A study of water-inrush mechanisms based on geo-mechanical analysis and an in-situ groundwater investigation in the Zhongguan iron mine, China. *Mine Water Environ* 36:409–417
- Wang H, Dong SN, Chai R, Liu QS (2015) Technical status of mine water control in china and its development strategy. Springer International Publishing, Cham
- Wang SJ, Chen T, Li T, Feng J (2017) Grouting material and technique in water protection mining above confined water. *J China Coal Soc* 42: 134–139
- Wu Q, Guo XM, Shen JJ, Xu S, Liu SQ, Zeng YF (2017) Risk assessment of water inrush from aquifers underlying the Gushuyuan coal mine, China. *Mine Water Environ* 36:96–103
- Yang C, Bai HB, Jiao Y, Li HL (2013) An establishment about the floor strata strengthened by grouting system. *Electron J of Geotech Eng* 18:1247–1254
- Yin HY, Wei JC, Lefticariu L, Guo JB, Xie DL, Li ZL, Zhao P (2016) Numerical simulation of water flow from the coal seam floor in a deep longwall mine in China. *Mine Water Environ* 35:243–252
- Yin SX, Zhang JC, Liu DM (2015) A study of mine water inrushes by measurements of in situ stress and rock failures. *Nat Hazards* 79: 1961–1979
- Zhang JC (2005) Investigations of water inrushes from aquifers under coal seams. *Int J Rock Mech Mining Sci* 42:350–360
- Zhu SY, Jiang ZQ, Zhou KJ, Peng GP, Yang CW (2014) The characteristics of deformation and failure of coal seam floor due to mining in Xinmi coal field in China. *Bull Eng Geol Environ* 73:1151–1163
- Zhu WC, Wei CH (2011) Numerical simulation on mining-induced water inrushes related to geologic structures using a damage-based hydro-mechanical model. *Environ Earth Sci* 62(1):43–54