Grouting for ensuring coal mining safety above limestone aquifers with high water pressure

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Abstract This paper presents a case study for ensuring coal mining safety under high confined water pressure using grouting. The Xinyi coal mine located in Henan Province, China, has been threatened by the Ordovician limestone aquifer with high confined water pressure beneath the coal seam. Based on geological investigation, characterization and evaluation of the Ordovician limestone aquifer, a grouting project was carried out. The geophysical transient electromagnetic technique was applied to inspect grouting quality. Coal seam No. 2–1 in panel 12011 was safely mined after grouting. Therefore, grouting was verified as a feasible method to ensure the coal mining safety under high confined water pressure.

Keywords water inrush, risk assessment, grouting, geophysical survey, limestone aquifers

Introduction

More than 150 mine inrush and inundation accidents occurred worldwide in coal mines during the last decade (Bringemeier 2012). China is the largest coal producing country with the production over 3,500 Mt in 2012. According to the incomplete official statistics, about 285 of 600 key coal mines in China are threatened by water inrushes during coal mining. Many coal mines in China encounter water inrush hazard from limestone aquifers which underlie coal seams with high confined water pressure (Peng 2007). Strata under coal seam would deform during mining, which increases hydraulic conductivity. Water with high confined pressure will be able to inrush from the fractures to coal mines, which always causes disastrous consequences (Sui 2011). Generally, drainage and grouting are two main methods to ensure mining safety above limestone aquifers. Drainage will decrease the water table by powerful pumping. However, this method not only increases the cost of production, but also results in environmental disasters such as shortage of water supply and subsidence of land surface (Wang 2003). Therefore, it is necessary to employ grouting project to ensure the coal mining safety. Grouting will enforce the strength of bed rock that underlie the coal seam and seal the inherent geological structures such as faults and fractures. Moreover, grouting project is more economical and environmentally friendly than drainage.

Coal mine grouting principles

Grouting is defined as filling open voids existing in rock or soil with slurry (Bruce 2005). Coal mining resulted *in situ* stress releasing and induced discontinuity surfaces which are described as water-conducting failure zone as shown in Fig. 1. The formation of this zone mainly depends on length and width of mining area. Borehole and geophysical methods are often used to investigate this zone. While goaf in Fig. 1 is defined as that part of a mine from which the mineral has been partially or wholly removed. The objectives of coal mine grouting project are reducing the permeability and deformability of rocks between water-conducting failure zones and aquifer. It is also used for increasing rock strength against shearing forces.

Grouting projects have three important components including the design, implemen-

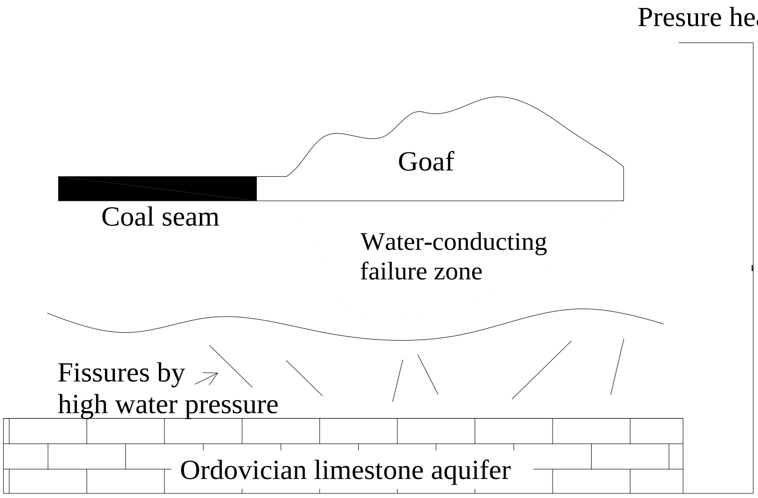

Fig. 1 *Sketch of water-conducting failure zone caused by coal mining*

tation and quality testing of the placed grout. Grouting design requires a good knowledge of geological conditions and grout flow theory. Therefore, the investigation should be carried out to gain a good understanding of geology. In addition, choosing one appropriate grout material and applying relative grout flow theory are necessary. Based on the assumption of Laminar flow, some theories were proposed to describe a Newtonian fluid and a Bingham fluid flow in fractures (Warner 2004). The feasibility, durability, costs and time consumption are most important aspects in grouting design (Giovanni 2004). Moreover, drilling and grouting equipments are needed to implement grouting design. At final stage, grouting quality should be tested to verify the effect.

Case study

The Xinyi coal mine is located at Luoyang City, Henan Province, China, as shown in Fig. 2. The construction of this coal mine was finished on November 2005. The coal seam No. 2–1 is the main coal resource with a dip angle of 6° to 14°.

Panel 12011 was chosen as research area as shown in Fig. 3. Geology and hydrogeology of this panel are summarized in Table 1. The depth of this panel ranges from -213 m to -296 m below sea level, the length and width of this panel are, 800 m and 130 m, respectively. The coal reserves of this panel are around 800 kt.

A number of criteria have been proposed to evaluate the water inrush hazard. Water inrush index method was recommended by State Administration of Work Safety and State Administration of Coal Mine Safety of China (2009). This index is defined by water pressure bearing capacity per unit thickness of waterproof floor strata.

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

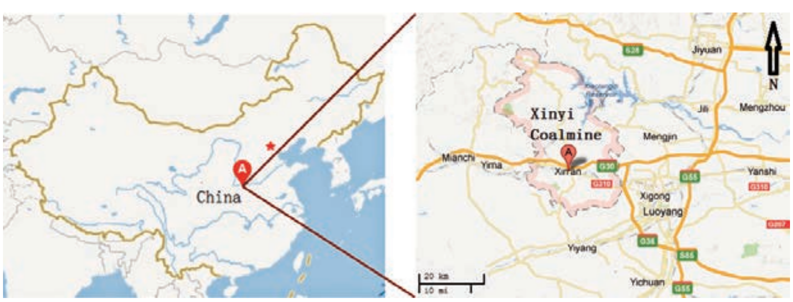

Fig. 2 *Location of the Xinyi Coal mine*

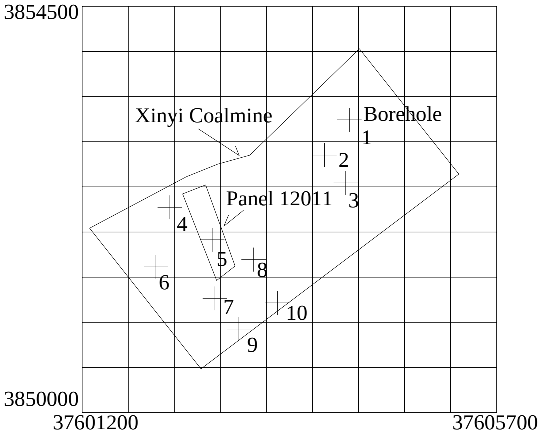

***Fig. 3** Location of Panel 12011 and ten boreholes*

where T is water inrush index, MPa/m; P is water pressure, MPa; M is the thickness of waterproof strata in floor, m.

It is considered as high risk in regards to safety when the water inrush index T exceeds critical 0.1 MPa/m according to the statistics around Chinese coal mines.

Ten boreholes reached the Ordovician limestone in the whole coal mine as shown in Fig. 3. Water inrush indexes of these ten boreholes calculated from equation 1 are summarized in Table 2. No. 5 borehole is the only one in the research panel 12011 and its water inrush index is 0.092 close to critical 0.1. Therefore, a detailed geological investigation should be carried out in this panel to make the grouting design more effective.

A geophysical transient electromagnetic technique was used to investigate the strata below the coal seam. The principle of this method is that electric and magnetic fields are induced by transient pulses of electric current

Stratum	Thickness (m)	Distance (m)	Hydrogeology
Coal Seam No. 2-1	0.5—12 Avg. 4.9	Coal seam floor=0	Depth of coal seam: -213m to -296 masl
Sandy mudstone and mudstone	5.8—21	Avg. 10	Aquitard
L_7 limestone	6.3—19	6—21 Avg. 12	Aquifer Pressure head:+330.22 m — +336.13 masl Hydrochemistry type: HCO_3-Ca·Mg Specific capacity: q=0.048 L/s·m Hydraulic conductivity: K=0.1—0.551 m/d
Bauxitic mudstone	6.5—26.12 Avg. 13.36	Avg. 43.39	Aquitard
The Ordovician limestone	273	44.3—79.68 Avg. 55	Aquifer Pressure head:+291.14 m — +375.75 masl Hydrochemistry type: HCO_3-Ca·Mg Specific capacity: q=0.006—4.03 L/s·m Hydraulic conductivity: K=0.000451—9.2 m/d

***Table 1** Stratum and hydrogeology that underlie the coal seam No. 2-1*

Borehole No.	1	2	3	4	5	6	7	8	9	10
P(MPa)	5.14	5.16	5.06	5.17	5.16	5.13	5.14	5.18	5.15	5.20
M(m)	56.64	56.39	46.19	47.53	56.39	53.26	53.85	57.61	54.99	59.65
$T=P/M$ (MPa/m)	0.091	0.092	0.110	0.109	0.092	0.096	0.095	0.090	0.094	0.087

***Table 2** Results of water inrush index from ten boreholes*

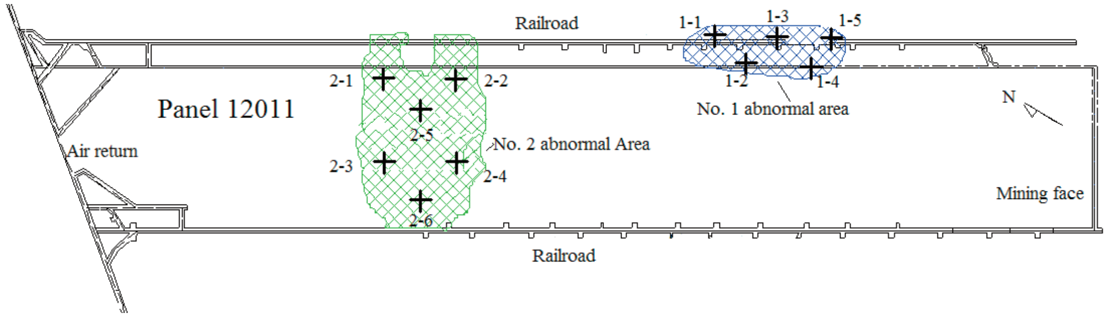

Fig. 4 *Location of two abnormal water areas and grouting boreholes*

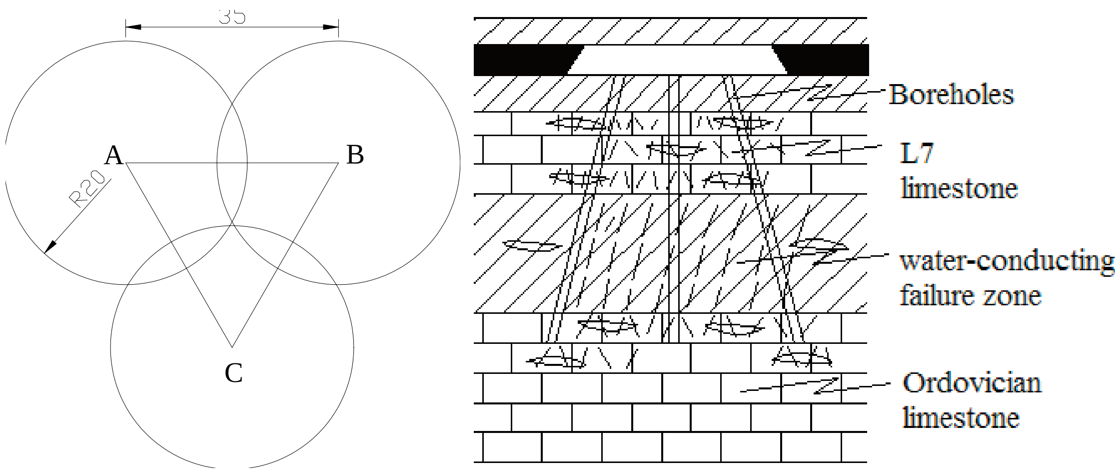

Fig. 5 *Grouting borehole design. (a, left) plane view; (b, right) cross section view*

and the subsequent signal attenuation response is measured. This method is suitable to detect water because of its low resistivity. Two abnormal water areas were detected as shown in Fig. 4. No.1 abnormal water area with 40 m length and 20 m width was located at railroad. No. 2 abnormal area with 130 m length and 80 m width was located near the vent tunnel.

Grouting project

Design

The grouting target is to prevent water inrush from two abnormal water areas, as well as reduce costs. Therefore, the grouting boreholes should be arranged at abnormal water areas with different depth so that the grouting slurry can form a thick barrier. Karstic rock shows the some features including large caverns extending up to several hundreds of meters and small caverns extending up to several meters. However, caverns are partly or completely filled with gravel, sand, clay or mud.

Cement was chosen as grout material because the abnormal water areas are full of Karstic fissures. Water pressure test was carried out to identify the degree of karsticity. According to hydraulic conductivity of the Ordovician limestone, the grouting radius of cement slurry in Karst stratum can be ranged from 20 to 40 m. In order to ensure safety, the grouting radius is assumed as 20 m for conservative design. Considering the effect of group boreholes grouting, three neighbor boreholes should be arranged at corner of triangle with distance no more than 35 m. Fig. 5 illustrates principle of boreholes arrangement.

Implementation

Drilling fields with the dimension of 4.5 × 3.5 ×3.5 m (length × width × height) were constructed to implement drilling. The borehole was drilled in three stages because the high confined water pressure. The first stage was drilled for borehole orifice-pipe with diameter of 133 mm. When the depth of this borehole exceed the coal seam floor 5 m, casing pipe with diameter of 127 mm was applied to prevent coal collapsing. The second stage was drilled for protecting pipe with diameter of 113 mm. This borehole penetrated L7 limestone with length no less than 35 m. Borehole wall in this stage was grouted to prevent water inrush from L7 Limestone. The third stage was drilled using the diamond bit with diameter of 73 mm. Borehole length in this stage was 20 m deep in the Ordovician limestone. The grouting was implemented at the pressure of 12 MPa with the volume ranges from 1 to 2 t.

Quality control

Quality control in this project includes grout material test and permeability test. Tests on grout material were conducted on water and suspension. Water's pH was 7.6 to 7.8, and hardness was 10.01 to 23.02. Suspension's Unit weight was 1.65 g/cm, viscosity was 19.6 s, setting time ranged from 16 to 35 min, compressive strength was 8 MPa.

Transient electromagnetic technique was employed to test permeability and verify the quality of this grouting project. Fig. 6 shows the resistivity of stratum after grouting. The contours of 0.2 or lower resistivity were deeper than before grouting, which means the abnormal water area was smaller than before.

Results

The water inflow rate was less than 5 m^3/h during mining of this panel from December 2011 to June 2012 and around 800 kt of coals were safely excavated. This grouting project was considered as a successful case.

Conclusions

A successful grouting project was presented in this paper to illustrate the steps of grouting design, implementation and quality verification. An effective and economical grouting design should be based on comprehensive understanding of geological and hydrogeological conditions.

Drilling and Water inrush index method were employed to evaluate the risk of water in-

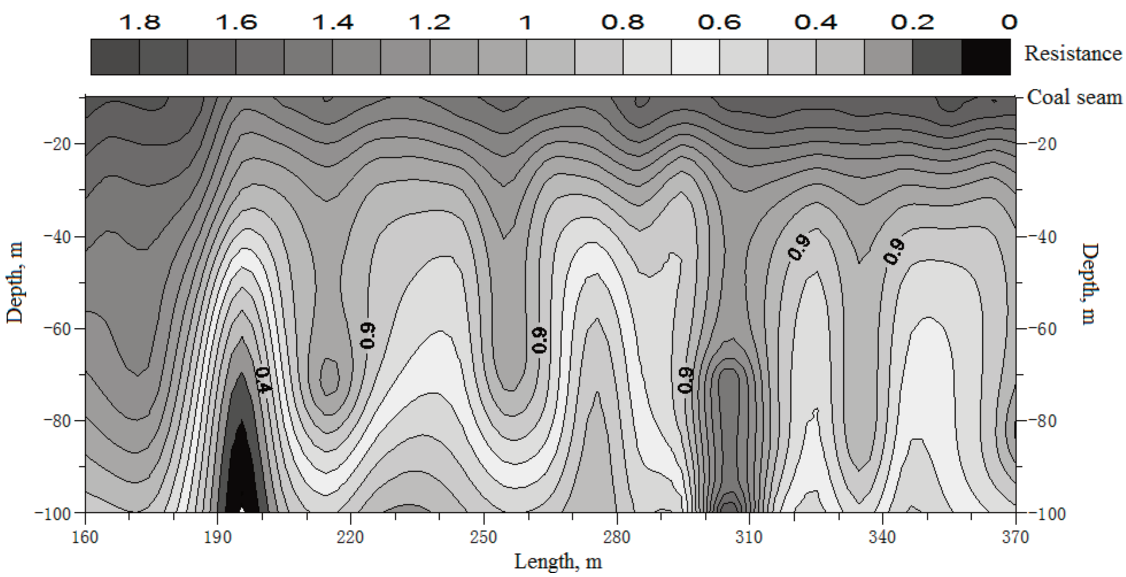

Fig. 6 *Apparent resistivity of vertical detection of No. 1 abnormal water area*

rush from the Ordovician limestone in the entire coal mine area. The geophysical transient electromagnetic technique was applied to detect the abnormal water area pre- and post-grouting in research panel. Grouting design was proposed based on the geological and hydrogeological analysis results. The quality was verified based on the reduction of the abnormal water area. Therefore, grouting can be considered as a feasible method to ensure the coal mining safety under high confined water pressure.

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