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TECHNICAL ARTICLE

Using a Fluid–Solid Coupled Numerical Simulation to Determine a Suitable Size for Barrier Pillars When Mining Shallow Coal Seams Beneath an Unconsolidated, Confined Aquifer

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Abstract Barrier pillars are an effective and fundamental measure to prevent water inrush when mining shallow coal seams under an unconsolidated, confined aquifer. Based on the complex geological and hydrogeological conditions in the southern area of the Qidong coal mine, the no. 6_1 coal seam there was selected for a research demonstration. A fluid–solid coupled numerical simulation was carried out using the universal distinct element code. The hydraulic pressures and seepage rates in overlying strata were analyzed for two mining cases, near the aquifer and near the fault. The results showed that the degree of interconnection between the bed-separated and vertical fractures, and increases in hydraulic pressures and seepage rates in overlying strata were key factors in predicting potential water inrush when mining shallow coal seams under an unconsolidated, confined aquifer. Combining the numerical simulation results with China's coal mining requirements, the no. 6_1 coal seam can be mined up to 90 m beneath the unconsolidated, confined aquifer, which limits mining to an altitude of −509.36 m. The width of the barrier pillar should be 30.7 m near the fault.

Keywords Unconsolidated and confined aquifer · Fluid–solid coupled numerical simulation · Waterproof coal pillar · Shallow coal seam

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Introduction

Thousands of casualties have occurred in coal mine accidents in China since 2000 (Sui et al. 2011). Water inrush is the second leading cause of these casualties and is responsible for the greatest economic loss (Yao et al. 2012; Zhang et al. 2014). Nowadays, with more shallow coal seams being mined, water-inrush events under unconsolidated and confined aquifers are a serious mine safety issue (Wu et al. 2014, 2015; Zhang and Peng 2005; Zhang et al. 2012), and pose a major threat in some mines, such as the Panyi mine in the Huainan coalfield, the Baodian mine in the Yanzhou coalfield, and the Qidong mine in the Huaibei coalfield (Chen et al. 2014; LaMoreaux et al. 2014).

Barrier pillars are typically used to minimize the risks of water-inrush hazards associated with water-conducting fractures or faults. The height of the barrier pillar is defined as the shortest vertical distance between the aquifer and the working face (Miao et al. 2011; Zhang and Peng 2005), and the width of the barrier is defined as the shortest horizontal distance between the fault and the working face. In practice, there were no uniform rules on the amount of coal that must be left for protection; these decisions were usually based on mechanical analysis or field experience. Using the English design formula (Liu et al. 2010), the Pennsylvanian empirical formula (Koehler and Tadolini 1995; Rangasamy et al. 2001), or the Chinese regulation for mining under a waterbody (SAWS and SACMC 2009; Wu 2009) produce variably sized barrier pillars for the same geological and hydrogeological conditions. If the pillars were too small, water inrush can occur, with serious consequences, such as mine inundation, endangering the lives of miners, and surface collapse. If the pillars were too large, coal resources were lost.

A great amount of research has been conducted on this issue with some rich theoretical results, such as the stress analysis method (Gui 1997), the effective water-resisting thickness method (Xu 2005), and the water-inrush risk coefficient method (Meng et al. 2013). These methods have contributed to more effective barrier pillars and greater mine safety. However, existing theory and methods were unable to fully accommodate many real-world scenarios, so that the appropriate size of barrier pillars in shallow coal seams under an unconsolidated and confined aquifer is still a viable, multi-disciplinary, research topic.

Case Study

The Qidong coal mine is situated in the Huaibei coalfield, where shallow coal seams are directly covered by an unconsolidated, confined aquifer. Mining is complicated by the strong water yield and high hydraulic pressure in the aquifer, the special structure of overlying strata, and a complex fault distribution. The Qidong mine is divided into two areas by the Weimiao fault. In the northern mining area, most of the working faces have been mined and at least 18 water-inrush hazards have occurred (Wang et al. 2012b; Xu et al. 2011). Though coal production has just begun in the southern mining area, it was anticipated that the shallow coal seams in the southern area will face the same danger of water inrush.

Mining of the no. 6_1 coal seam in the southern area of the Qidong coal mine is regarded as a case study for the formation of water-conducting channels and fractured zones. In this study, a generalized fluid–solid coupled numerical simulation was established along the dip direction of the no. 6_1 coal seam using the universal distinct element code (UDEC; Itasca 2004). The results were combined with the empirical formulae in China's coal mining regulations.

Geological Settings

The Huaibei coalfield (Fig. 1), one of China's eastern mining areas is located in northern Anhui province and is bordered by the nearly EW Fengpei trend and Bengbu uplift. The main tectonic structure is controlled by the EW and NNE trend faults and the NNE or NE and NW trend folds (Tan et al. 2011). The EW trend faults mainly contain the north Suzhou fault and the Banqiao fault, and the NNE trend faults mainly contain the Fengguo fault and the Guzhen-Changfeng fault. The NNE or NE trend folds include the Huagou anticline, the Guoyang syncline, the Nanping syncline, and the south Suzhou syncline, while the NW trend folds include the Tongting anticline and the East Suzhou syncline. Most mines in the Huaibei coalfield face the risk of water inrush while mining shallow coal seams under an unconsolidated, confined aquifer.

The Qidong coal mine (Fig. 1), at 35 km^2 in area, is one of the largest mines in the Huaibei coalfield. The tectonic structure of the mine is a monoclinal structure with an EW trend and N10°–15° dip, following a series of secondary folds and faults (Wu et al. 2010). The unconsolidated formation, which is mainly made up of clay, sandy clay, clayey sand, silt, fine sand, medium sand, and gravel, can be divided into four aquifers and three aquifuges from top to bottom (Fig. 2). The fourth aquifer, directly overlying the shallow coal seams, is the main water-inrush aquifer to the working faces in the Qidong coal mine. During mining of the no. $3_2$22 working face, with a 63 m barrier pillar, and the no. $7_1$14 working face, with a 71 m barrier pillar, in the northern mining area of the Qidong mine, groundwater rushed from the aquifer into the working faces, causing serious hazards. The corresponding maximum values of water yield were 1520 and 169 m^3/h, respectively. Based on the drainage tests and previous water-inrush data in the northern mining area, it was clear that the aquifer presents high pressure and strong seepage, which is typical for many unconsolidated, confined aquifers. Although the no. $6_1$63 first working face has been safely mined in the southern area, it was decided that additional verification was needed to determine whether other working faces could be mined safely under this aquifer. In addition, strata near a fault have a much lower strength and are sometimes poorly consolidated, and thus more likely to cause water-inrush hazards during mining shallow coal seams near an unconsolidated, confined aquifer. Therefore, the safe mining of working faces near faults was also given attention in this study.

Numerical Model

As a two-dimensional discrete element software, Universal Distinct Element Code (UDEC) can be used to analyze the static and dynamic problems of a discontinuous medium during mining (Itasca 2004). Through fluid–solid coupled simulation of fractured rocks around extensional faults using UDEC, Zhang and Sanderson (1996) indicated that the deformation of the fault zone caused significant variations in fracture dilation (porosity), stress distribution, fluid pressure, and fluid flow. Combining UDEC with physical

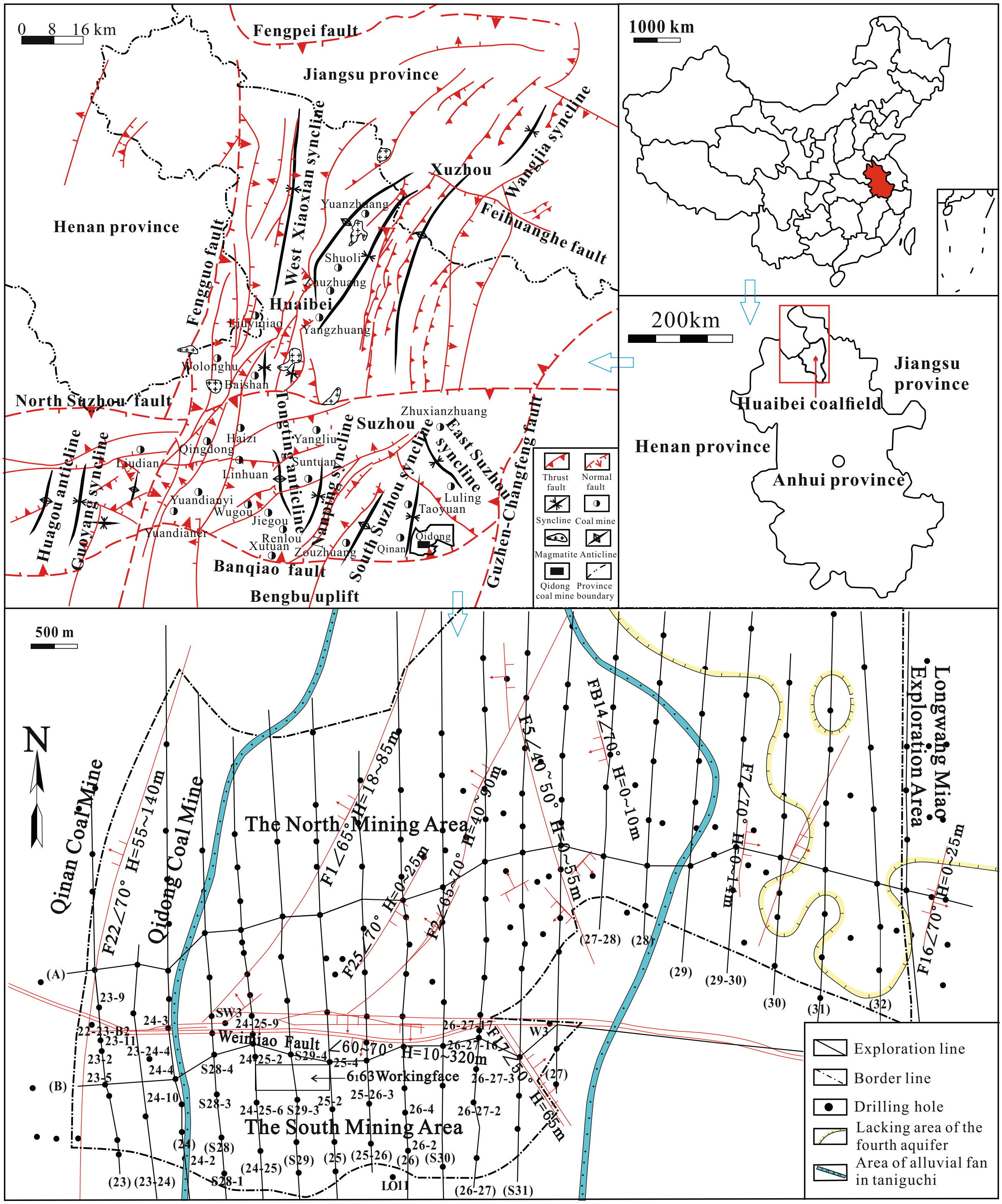

Fig. 1 Diagram of regional geology in the Qidong coal mine of the Huaibei coalfield (Wang et al. 2013; Guo et al. 2014)

simulation, Chen et al. (2007) simulated the possibility of water inrush during the mining of shallow coal seams under a thick, unconsolidated formation and thin overlying strata and confirmed the optimal caving ratios for preventing water inrush. Wang et al. (2012a) used the fluid–solid coupled module of UDEC to analyze the

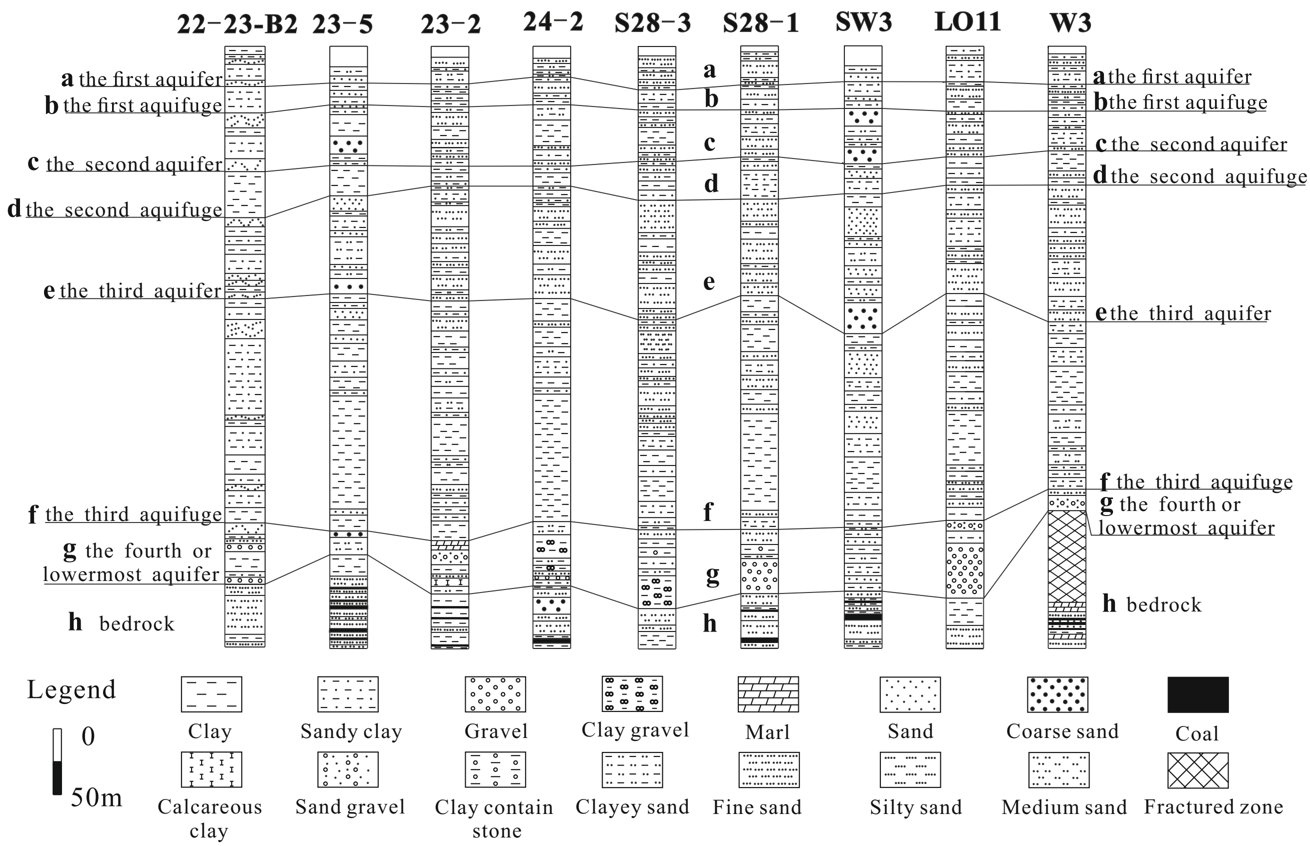

Fig. 2 Stratigraphic column and aquifer division

characteristics of stress and seepage in the floor of a coal seam during mining above a confined aquifer. Due to its flexibility and high efficiency, UDEC can be used to solve many groundwater problems induced by mining in complex geological conditions (Jaiswal and Shrivastva 2009; Zhu and Wei 2011).

Generalized Numerical Model and its Parameters

The no. $6_1$63 first working face in the southern area of the Qidong coal mine is about −527 to −610 m in elevation, 1100 m in the trend direction, and 180 m in the dip direction, where the dip angle and thickness of the no. 6_1 coal seam average 17° and 2.0 m, respectively. The first working face was passed through by three exploration lines along the dip direction (Fig. 1), from which the S29 exploration line was selected to establish the generalized mining model (Fig. 3b). Figure 3a shows the original geological section of the S29 exploration line along the dip direction.

The generalized numerical model (Fig. 4), which was 1156 m wide and 350 m high, consisted of the 60 m of unconsolidated formation and 40 m of confined aquifer, the 250 m of coal measure strata, and the 35 m fault zone. The constitutive model for rocks was the Mohr–Coulomb model and for joints was the Coulomb slipping model. Horizontal displacement was restrained on the lateral boundaries, and vertical displacement was fixed in the base. A vertical stress of 5 MPa was applied on the top boundary to simulate the additional load of the upper unconsolidated formation. Based on mining experience in the Huaibei coalfield and related research results by Chen et al. (2007), the lateral pressure coefficient, which is the ratio of the horizontal and the vertical rock natural stress, was set to be 0.5. In addition, the hydraulic pressure on the lateral boundaries of the unconsolidated, confined aquifer was defined to be 4.4 MPa. The mechanical parameters of the corresponding strata were listed in Table 1 and the mechanical and hydraulic parameters of the joints were shown in Table 2.

Mining Cases

According to the China's regulations for mining coal beneath water bodies (SAWS and SACMC 2009), the vertical height of the barrier (H_{sh}) should be greater or equal to the sum of the maximum height of the water-conducting fracture zone (H_{li}) and the thickness of the protective bedrock cover (H_b):

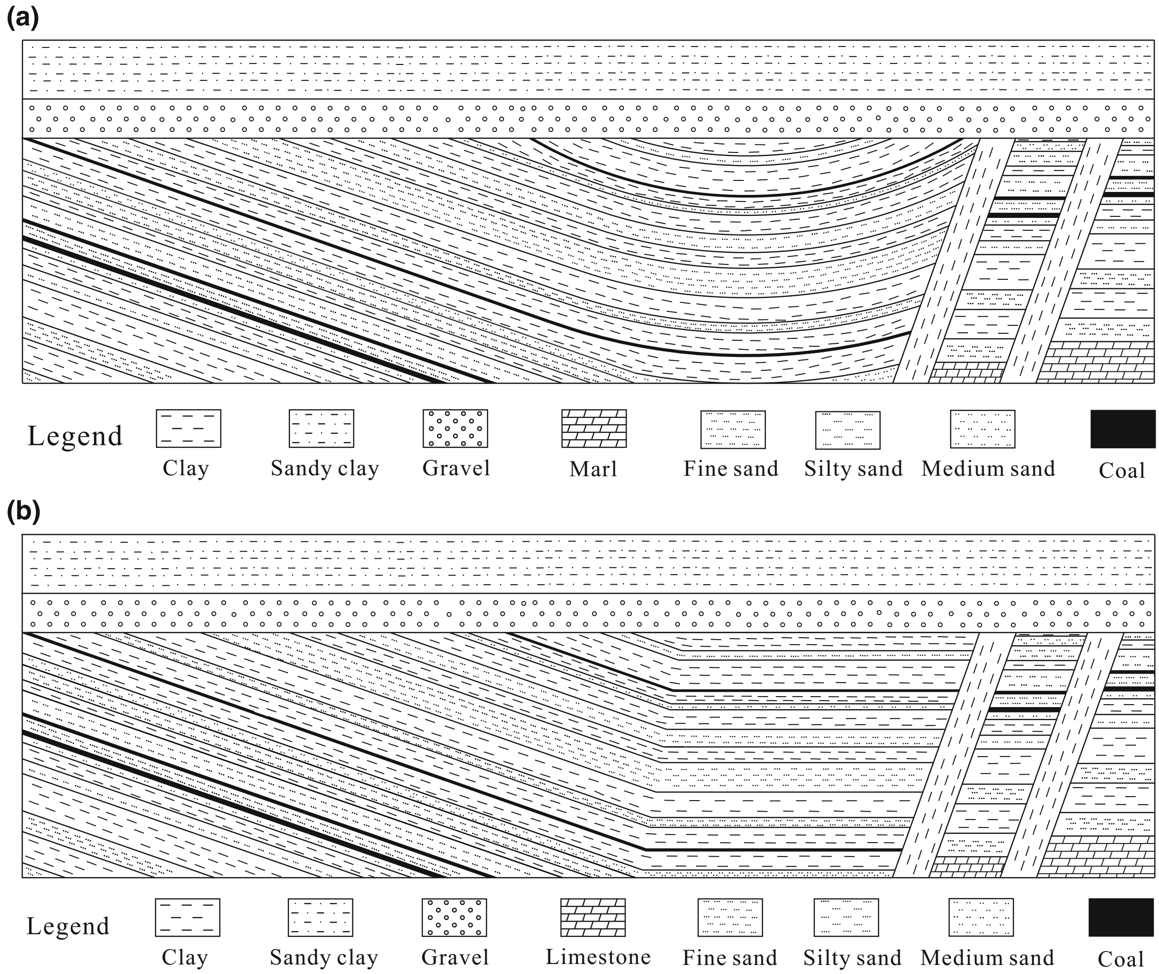

Fig. 3 Geological section of the S29 exploration line along the dip direction. **a** Original geological section, **b** generalized geological section

$$H_{sh} \geq H_{li} + H_b \qquad (1)$$

Based on the geological and hydrogeological conditions in the southern area of the Qidong coal mine, the computational formula for the maximum height of the water-conducting fracture zone (H_{li}) is:

$$H_{li} = \frac{100\sum M}{1.2\sum M + 2.0} \pm 8.9 \qquad (2)$$

where M is the mining height of coal seam.

According to the regulations, when the mining height of the coal seam doesn't exceed 3 m, the thickness of the protective bedrock cover should be eight times the mining height. The mining height of the no. 6_1 coal seam in the southern area of the Qidong mine was defined as the average thickness of 2 m (see Supplemental Table 1), so the required thickness of protective bedrock cover was 16 m. For the sake of safety, the plus sign was used in Formula 2. Therefore, the maximum height of the water-conducting fracture zone was calculated to be 54.35 m. From Formula 1, the required vertical height of the barrier was determined to be 70.35 m.

Two different mining cases were tested for the no. $6_1$63 first working face. In Case 1, the C working face was established to be 180 m on the left side of the no. $6_1$63 first working face. In Case 2, the A and B working faces were established to be 120 m on the right side of the no. $6_1$63 first working face, near the fault. These working faces were laid out at a separation of about 15 m, while the B working face and the fault plane were set at a separation of about 20 m, as shown in Fig. 4.

Monitoring Lines and Points

Due to the distance of the first no. $6_1$63 working face from the unconsolidated, confined aquifer, the water-conducting fracture zone in the overlying strata didn't contact the aquifer, so no water inrush occurred, so there was no need to set monitoring lines and points above the working face. Therefore, in Case 1, eight monitoring lines (Fig. 4) were

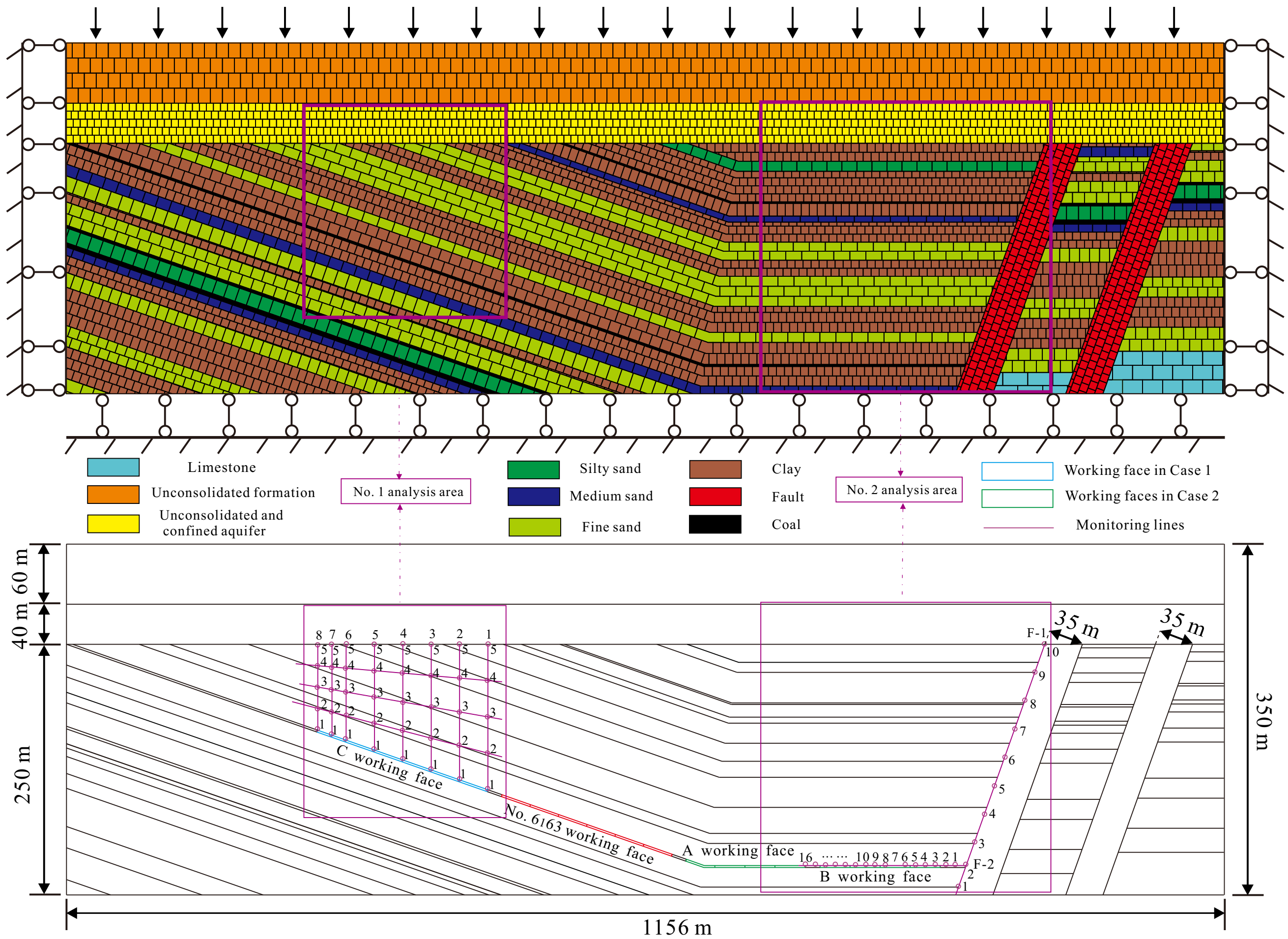

Fig. 4 Boundary conditions, working faces and monitoring lines in the generalized numerical model

Table 1 Mechanical parameters of strata

Strata and lithology	Density (kg/m^3)	Bulk modulus (GPa)	Shear modulus (GPa)	Cohesion (MPa)	Friction angle (°)
Unconsolidated formation	1600	4.77	3.28	3.00	25
Unconsolidated and confined aquifer	2000	8.33	2.85	4.00	25
Clay	2760	5.12	1.58	1.50	30
Silty sand	2720	8.11	6.08	2.75	36
Coal	1350	1.67	1.25	1.25	40
Medium sand	2550	8.10	5.57	2.92	36
Fine sand	2700	7.74	5.219	3.20	35
Limestone	2300	25.00	11.50	12.00	40
Fault	2760	5.12	1.58	1.50	30

set above each mining section of the C working face. The length between two adjacent monitoring lines among no. 1–6 was 30 m, while among no. 6–8 it was 15 m. For each monitoring line, five monitoring points were evenly distributed between the no. 6_1 coal seam and the aquifer to monitor the hydraulic pressures and the seepage rates in overlying strata. In Case 2, the no. F-2 and F-1 monitoring lines (Fig. 4) were set on the roof of the no. 6_1 coal seam and the fault plane, respectively. There were 16 monitoring points in the no. F-2 monitoring line at a 10 m distance,

Table 2 Mechanical and hydraulic parameters of the joints

Strata and lithology	Normal stiffness (GPa)	Shear stiffness (GPa)	Cohesion (MPa)	Friction angle (°)	Permeability factor (Pa^{-1} s^{-1})	Zero stress aperture (mm)	Residual aperture (mm)
Unconsolidated formation	4.00	4.00	0.020	15	8.30	0.10	0.01
Unconsolidated and confined aquifer	4.00	3.00	0.020	10	300.00	5.00	1.00
Clay	3.50	1.46	0.375	26	8.30	0.10	0.01
Silty sand	5.40	2.23	0.688	32	12.50	0.15	0.15
Coal	1.50	2.00	0.010	5	200.00	1.00	1.00
Medium sand	6.80	2.80	0.730	32	167.00	2.00	0.20
Fine sand	3.32	1.39	0.800	31	167.00	2.00	0.20
Limestone	12.00	12.00	0.100	15	5.00	0.01	0.01
Fault	3.50	1.46	0.375	26	8.30	0.10	0.01

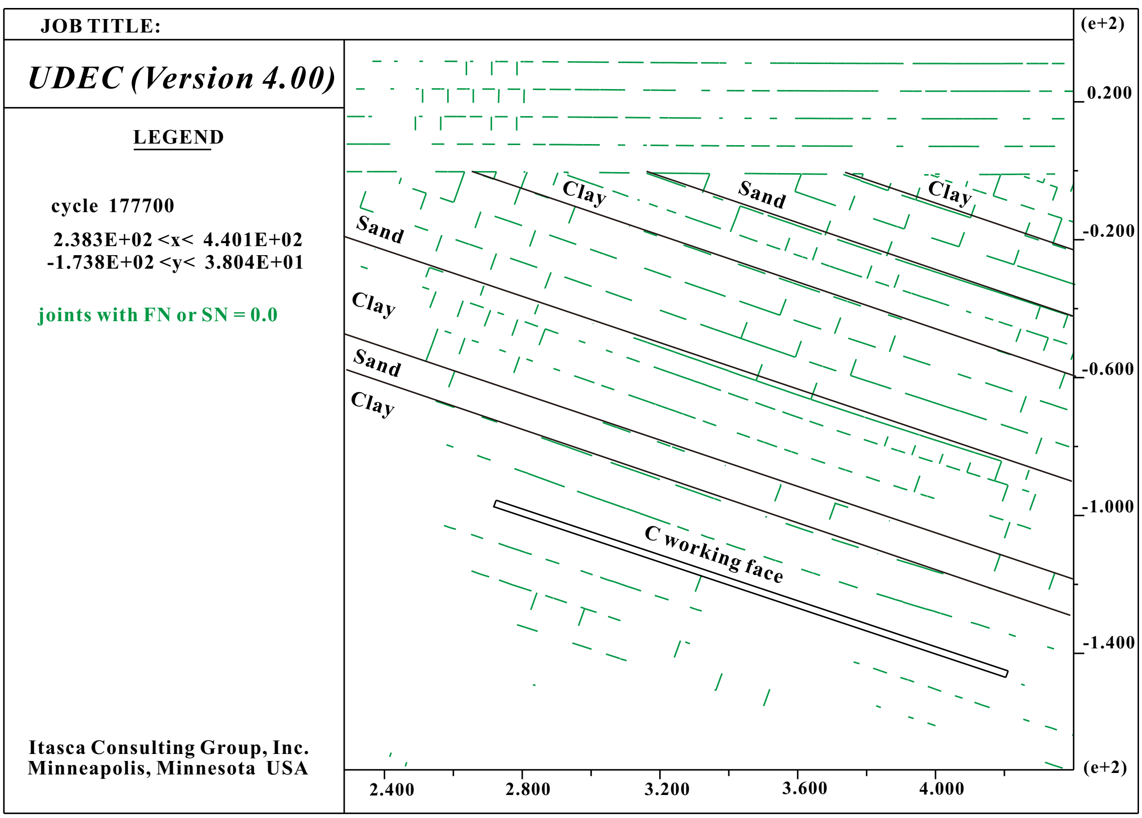

Fig. 5 Fractures in overlying strata when the mining length is 165 m in the C working face in the no. 1 analysis area

and 10 monitoring points in the no. F-1 monitoring line at a 30 m distance, which were used to monitor the hydraulic pressures and the seepage rates through the roof of the no. 6_1 coal seam and the fault plane. In addition, fracture evolution in overlying strata during mining near the aquifer and near the fault were clearly analyzed through the no. 1 and no. 2 analysis areas, respectively (Fig. 4).

Results and Discussion

Case 1: Mining Near the Unconsolidated and Confined Aquifer

In Case 1, the cumulative mining lengths of the no. 6_1 coal seam were set at 30, 90, 120, 150, 165, and 180 m in the C working face. At mining lengths up to 165 m, the bed-separated fractures (parallel with the strata direction) and vertical fractures in the overlying strata were mutually independent (no water-conducting channels formed between the bed-separated and vertical fractures), and the water-conducting fracture zone didn't reach the aquifer. At a length of 165 m, with at least 90 m between the working face and the aquifer, the bed-separated fractures extended to the aquifer (Fig. 5), but the vertical fractures were undeveloped in clay, so no water-conducting channels formed between the working face and the aquifer, and again, the water-conducting fracture zone didn't reach the aquifer. At a mining length of 180 m (Fig. 6), vertical fractures developed in the clay and connected with the bed-separated fractures, forming water-conducting channels, especially over the head and tail gates of the working face. As a result, the water-conducting fracture zone was well formed and reached the aquifer easily.

When the mining length of the C working face was 165 m (Supplemental Fig. 1 and 2), the fluid flow mainly occurred along fractures in the overlying strata in the region controlled by the no. 7–3, 7–5, 6–5, and 6–3 monitoring points, where the hydraulic pressures and seepage rates varied as the fractures repeatedly opened and closed, and stabilized if the fractures closed again. The hydraulic pressures and seepage rates at other monitoring points approached 0 because no water-conducting channels were formed between the working face and the aquifer. According to fracture development in the overlying strata and changes in the hydraulic pressures and seepage rates at the monitoring points (Fig. 5 and Supplemental Fig. 1 and 2), it was concluded that a water-inrush event was very unlikely when the mining length of the C working face was 165 m.

When the mining length of the C working face was 180 m, the hydraulic pressures of a few monitoring points in the no. 8 monitoring line increased (Supplemental Fig. 3a), while the seepage rate reached 10^{-4} m^3/s in the no. 7 monitoring line (Supplemental Fig. 4b). Between the no. 7 and 8 monitoring lines, the bed-separated fractures and the vertical fractures connected and water-conducting channels formed, resulting in a water-conducting fractured zone beneath the aquifer. Based on fracture development in the overlying strata and changes in the hydraulic pressures and seepage rates of these monitoring points (Fig. 6 and Supplemental Fig. 3 and 4), it was concluded that groundwater from the aquifer had recharged the working face circuitously via the water-conducting channels.

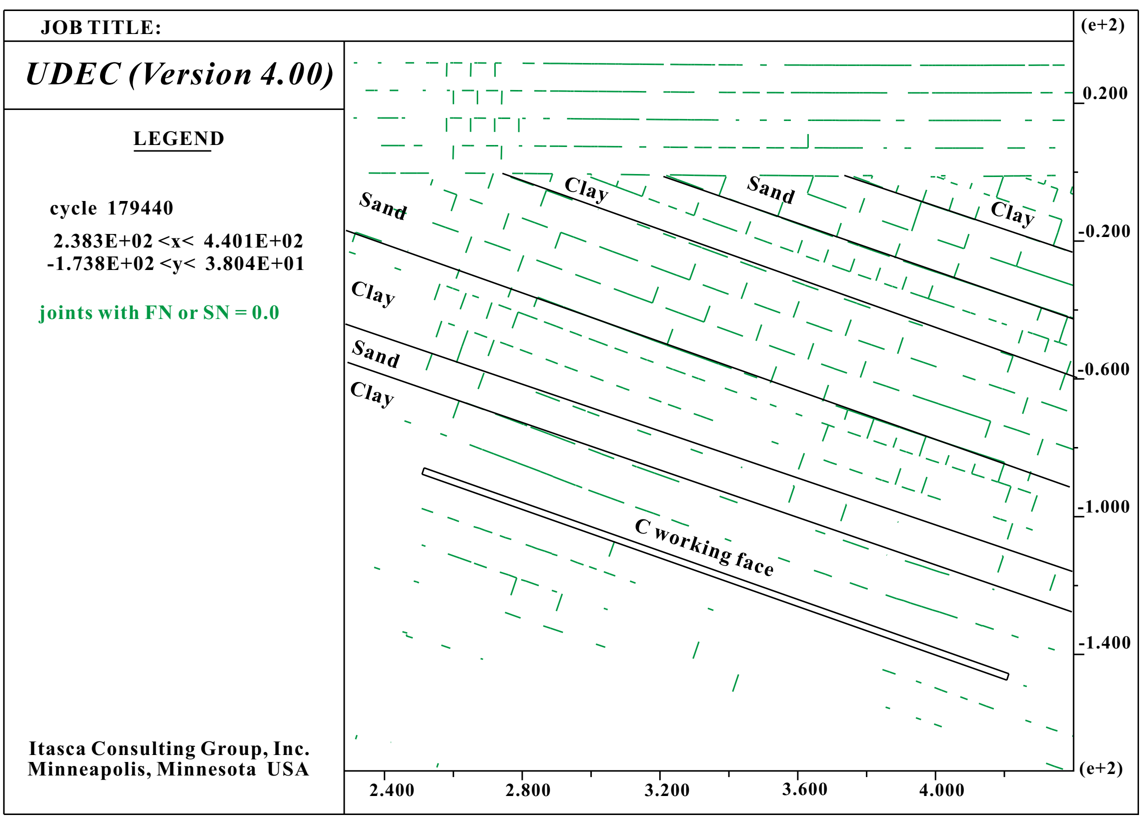

Fig. 6 Fractures in overlying strata when the mining length is 180 m in the C working face in the no. 1 analysis area

Case 2: Mining Near the Fault

When mining the A working face near the fault, the fractures in the overlying strata were far from the aquifer and the fault, so the working face was unaffected. When mining of the B working face was completed, only bed-separated fractures had developed in the overlying strata with a maximum height of 112 m (Fig. 7) and no water-conducting channels had formed between the working face and the aquifer. In addition, although the horizontal distance between the B working face and the fault was only 20 m, the bed-separated and vertical fractures were all undeveloped and mutually independent, so water inrush will not occur along the fault (Fig. 7).

In this situation, based on the hydraulic pressures of the 10 monitoring points in the no. F-1 monitoring line, the closer the aquifer, the greater the hydraulic pressure (Supplemental Fig. 5a). The seepage rates at the monitoring points were small and approached 0, with only the point closest to the aquifer showing instability, with downward seepage that eventually disappeared (Supplemental Fig. 5b). In addition, the hydraulic pressures and seepage rates of the 16 monitoring points in the no. F-2 monitoring line all approached 0. Therefore, no water-inrush hazards will occur after the B working face is mined even though the terminal mining line is 20 m from the fault plane.

Retaining Barrier Pillars

Applying Formula 1 of the Chinese coal mining regulation to Case 1, the minimum vertical height of the barrier pillar of the no. 6_1 coal seam near the unconsolidated, confined aquifer is 70.35 m. According to the fluid–solid coupled simulation result by UDEC, the minimum vertical height is 90 m. For safety's sake, the results of the numerical simulation was adopted. Based on geological information from the drilling holes (Supplemental Table 1), the upper mining limit near the aquifer is −509.36 m in the southern area of the Qidong coal mine.

In Case 2, according to the UDEC fluid–solid coupled simulation result, no water-inrush hazard will occur when the horizontal distance between the terminal mining line and the fault plane is at least 20 m. Applying the appropriate Chinese regulation for mining near a fault, the empirical formula is:

$$L = 0.5\,KM\sqrt{\frac{3p}{K_p}} \tag{3}$$

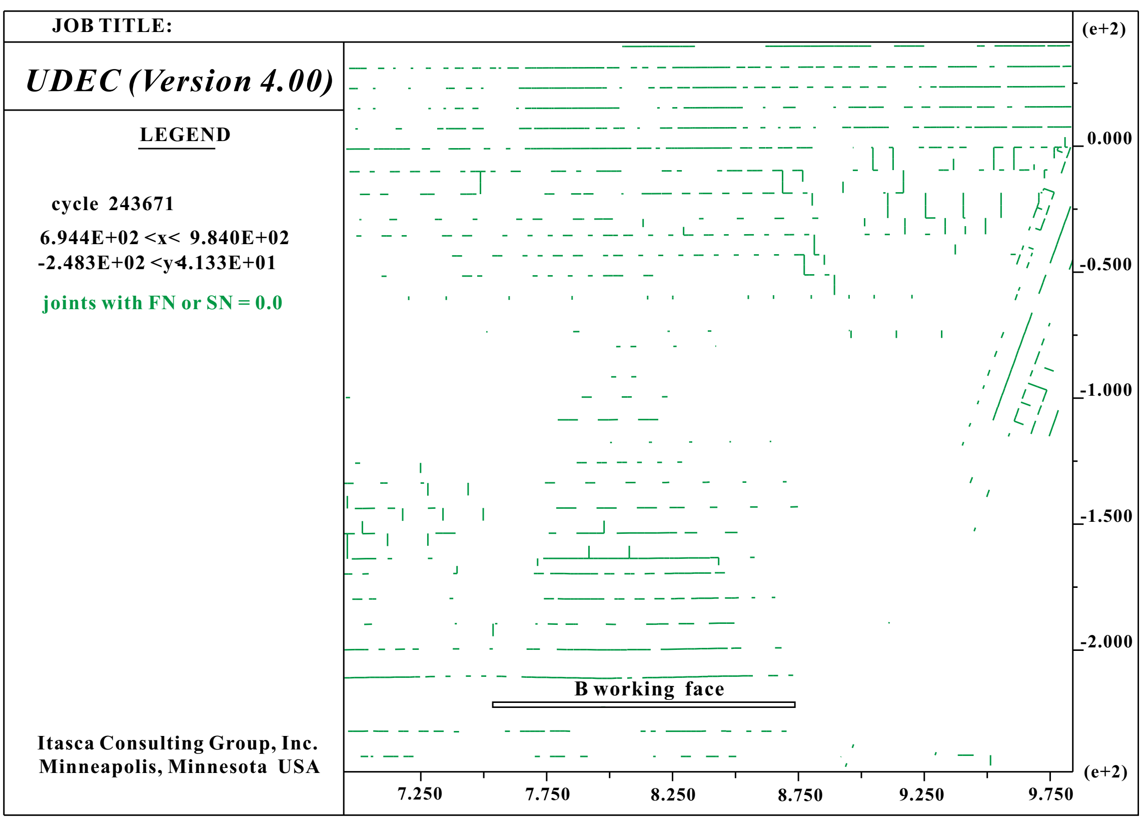

Fig. 7 Fractures in overlying strata when mining of the B working face is completed in the no. 2 analysis area

where L is the width of waterproof coal pillar, m; K is the safety coefficient, which is generally defined as from 2 to 5; M is the thickness or the mining height of coal seam, m; P is the hydraulic pressure of the unconsolidated and confined aquifer, MPa; and K_P is the tensile strength of coal seam, MPa.

In the southern area of the Qidong mine, the mining height of the no. 6_1 coal seam is 2 m, and the hydraulic pressure of the unconsolidated and confined aquifer is 4.4 MPa. The safety coefficient is defined as 5, and the tensile strength of coal is 0.35 MPa. Therefore, the minimum barrier pillar width near the fault is 30.7 m by Formula 3. Based on the numerical simulation and China's mining regulations, the safe barrier pillar width near the fault was set at 30.7 m.

Conclusions

A generalized numerical model of the no. 6_1 coal seam in the southern area of the Qidong coal mine was established based on the UDEC fluid–solid coupled numerical simulation. Through two mining cases near the aquifer and near the fault, fracture evolution, hydraulic pressures, and seepage rates in overlying strata were analyzed to distinguish the water-inrush hazard. When mining near the unconsolidated, confined aquifer, the main fractures in the overlying strata were the bed-separated fractures, supplemented by vertical fractures, which were primarily located over the headgate and tailgate of the working face. When the minimum distance between the working face and aquifer was 90 m, a water-conducting fracture zone developed as the bed-separated and vertical fractures connected and reached the aquifer, water began flowing into the mine at 10^{-4} m^3/s.

When mining near the fault, with a maximum height of 112 m, the fractures in the overlying strata were mostly bed-separation fractures, and no fractures developed near the fault. As a result, there was no water-inrush hazard.

Considering both the fluid–solid coupled simulation and the Chinese regulations, the appropriate vertical height of the barrier pillar was 90 m with an upper mining limit at an altitude of −509.36 m. The appropriate barrier width near the fault was 30.7 m.

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References

Chen LW, Gui HR, Li YF (2007) UDEC simulation of the water-pouring probability in exploiting waterproof coal pillars under the conditions of thick loose bed and ultrathin overlying strata. Hydrogeol Eng Geol 34(1):53–56 **(in Chinese)**

Chen LW, Zhang SL, Gui HR (2014) Prevention of water and quicksand inrush during extracting contiguous coal seams under the lowermost aquifer in the unconsolidated Cenozoic alluvium—a case study. Arab J Geosci 7(6):2139–2149

Gui HR (1997) Stress analysis and calculation method in waterproof coal (rock) pillar reasonable design. China Coal Industry Publ House, Beijing **(in Chinese)**

Guo PK, Cheng YP, Jin K, Liu YP (2014) The impact of faults on the occurrence of coal bed methane in Renlou coal mine, Huaibei coalfield, China. J Nat Gas Sci Eng 17:151–158

Itasca (2004) UDEC version 4.0 user's manual. Itasca Consulting Group Inc, Minneapolis

Jaiswal A, Shrivastva BK (2009) Numerical simulation of coal pillar strength. Int J Rock Mech Min 46(4):779–788

Koehler JR, Tadolini SC (1995) Practical design methods for barrier pillars. US Bureau of Mines, US Dept of the Interior, Washington, DC

LaMoreaux JW, Wu Q, Zhou WF (2014) New development in theory and practice in mine water control in China. Carbonate Evaporite 29(2):141–145

Liu CY, Liu YJ, Huang BX, Li YM, Li XM (2010) Instability characteristic and reasonable design of water-preventive coal-rock pillars in mining steep coal seam. J Min Safe Eng 27(3):330–334 **(in Chinese)**

Meng ZP, Gao YF, Lu AH, Wang R, Qiao X, Huang CY (2013) Water inrush risk evaluation of coal mining under Quaternary alluvial water and reasonable design method of waterproof coal pillar. J Min Safe Eng 30(1):23–29 **(in Chinese)**

Miao XX, Cui XM, Wang JA, Xu JL (2011) The height of fractured water-conducting zone in undermined rock strata. Eng Geol 120:32–39

Rangasamy T, Leach AR, Van Vuuren JJ, Cook AP, Brummer R (2001) Current practice and guidelines for the safe design of water barrier pillars. Durban, Itasca Africa (Pty) Ltd, SIMRAC

State Administration of Work Safety (SAWS), State Administration of Coal Mine Safety (SACMC) (2009) Chinese regulations for prevention and control of coal mine water. Publ House for Coal Industry, Beijing **(in Chinese)**

Sui WH, Liu JY, Yang SG, Chen ZS, Hu YS (2011) Hydrogeological analysis and salvage of a deep coalmine after a groundwater inrush. Envrion Earh Sci 62:735–749

Tan JQ, Ju YW, Yuan WM, Hou QL, Pan JN, Fan JJ (2011) Thermochronological and structural evolution of the Huaibei coalfield in eastern China: Constrains from zircon fission-track data. Radiat Meas 46(2):183–189

Wang JA, Wei XH, Chen SJ (2012a) Fissure and seepage characteristics in the floor strata when mining above a confined aquifer. J China Univ Min Technol 41(4):536–542 **(in Chinese)**

Wang XZ, Xu JL, Zhu WB, Li YC (2012b) Roof pre-blasting to prevent support crushing and water inrush accidents. Int J Min Sci Technol 22(3):379–384

Wang HF, Wang L, Cheng YP, Zhou HX (2013) Characteristics and dominant controlling factors of gas outburst in Huaibei coalfeld and its countermeasures. Int J Min Sci Technol 23:591–596

Wu Q (2009) Paraphrases of coalmine water control stipulations. China University of Mining and Technology Press, Xuzhou **(in Chinese)**

Wu SY, Hu BL, Yao DX, Zhang DS (2010) Analysis on geological structures influencing gas occurrence at Qidong coalmine. J Coal Sci Eng 16(3):292–295
Wu Q, Fan ZL, Zhang ZW, Zhou WF (2014) Evaluation and zoning of groundwater hazards in Pingshuo No. 1 underground coal mine, Shanxi Province, China. Hydrogeol J 22(7):1693–1705
Wu Q, Liu YZ, Zhou WF, Li BY, Zhao B, Liu SQ, Sun WJ, Zeng YF (2015) Evaluation of water inrush vulnerability from aquifers overlying coal seams in the Menkeqing coal mine, China. Mine Water Environ 34(3):258–269
Xu YC (2005) Design methods of the effective water-resisting thickness for the protective seam of the water barrier in fully-caving mechanized coalmining. J China Coal Soc 30(3):305–308
Xu JL, Zhu WB, Wang XZ (2011) Study on water-inrush mechanism and prevention during coal mining under unconsolidated confined aquifer. J Min Saf Eng 28(3):333–339
Yao BH, Bai HB, Zhang BY (2012) Numerical simulation on the risk of roof water in Wuyang coal mine. Int J Min Sci Technol 22(2):273–277
Zhang JC, Peng SP (2005) Water inrush and environmental impact of shallow seam mining. Environ Geol 48(8):1068–1076
Zhang X, Sanderson DJ (1996) Numerical modelling of the effects of fault slip on fluid flow around extensional faults. J Struct Geol 18(1):109–119
Zhang YX, Tu SH, Bai QS, Li JJ (2012) Overburden fissure evolution laws and water-controlling technologies in mining very thick coal seam under water-rich roof. Int J Min Sci Technol 23:693–700
Zhang JX, Jiang HQ, Deng XJ, Ju F (2014) Prediction of the height of the water-conducting zone above the mined panel in solid backfill mining. Mine Water Environ 33(4):317–326
Zhu WC, Wei CH (2011) Numerical simulation on mining-induced water inrushes related to geologic structures using a damage-based hydromechanical model. Environ Earth Sci 62(1):43–54