Water Disaster Control with Grouting in Bed Separation due to Deep Mining

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Abstract

This paper investigates the overburden bed separation evolution and grouting propagation in the Menkeqing coal mine, China, using laboratory test, numerical, and field monitoring methods. Bed separation develops vertically from low-order to high-order and aligns with the mined-out area horizontally, forming stable separations in the Zhidan Formation. A comprehensive evaluation of water inrush disaster risk was conducted for the panel 11-3101. Grouting with coal gangue slurry effectively mitigated groundwater inrush and surface subsidence. Results confirm grouting as a viable measure for controlling bed-separation water inrush hazards.

Keywords: Overburden bed separation; Water inrush disaster evaluation; Grouting

Introduction

With the increasing depth of coal resource mining in China, mine water hazards have become more prominent, posing important constraints on the safe extraction of coal. Bed separation water hazards, as a new type of water hazard, severely threaten coal mine safety due to their characteristics of high concealment, suddenness, and large instantaneous water inflow. It is generally believed that the occurrence of static water pressure-induced bed separation water inrush hazards requires three basic conditions: sufficient water sources, stable separation spaces, and unstable aquicludes (Bai *et al*, 2021; Gao *et al*, 2023).

Grouting is one of the effective measures for preventing and controlling bed separation water inrush hazards. By filling and reinforcing the separation space through grouting, the prevention and control of bed separation water hazards can be achieved, ensuring mining safety. To improve the precision of bed separation treatment, various comprehensive methods can be used to determine and monitor the separation location on-site. Using coal gangue as a component of the grout not only handles large amounts of coal gangue but also prevents bed separation water hazards in advance. This is a highly green and environmentally friendly filling mining method, achieving efficient utilization and harmless treatment of solid waste (Cao *et al*,2024; Qiao *et al*, 2021).

This paper takes the panel 11-3101 of the Menkeqing coal mine as the research background. Through multiple methods, including numerical simulations, and on-site monitoring, the development, localization, and characteristics of bed separation spaces in deep coal mines are analysed in depth. A risk assessment of bed separation water hazards and coal gangue grouting treatment is conducted, and the effectiveness of the treatment is evaluated. Ultimately, effective prevention and control of bed separation water hazards in complex strata and green treatment of coal gangue are achieved.

The strata of the Menkeqing coal mine mainly consist of conglomerate sandstone, sandstone, sandy mudstone, mudstone, and coal seams. The geological structure is a monocline inclined to the west. The faults are mainly NW-trending normal faults, which are neither water-bearing nor water-conductive. The panel 11-3101 of the Menkeqing coal mine is bounded by solid coal on both sides, with a tendency width of 260.4 m, a burial depth of 693–721 m, a coal seam dip angle of 1°–4°, and an average thickness of 4.92 m.

The water-filled aquifers affected by mining activities in the Menkeqing coal mine are the clastic rock confined aquifers of the Yan'an Formation and the Zhiluo Formation. These aquifers have limited hydraulic connection with the overlying phreatic aquifer and atmospheric precipitation, weak water abundance, and poor groundwater recharge conditions, posing minimal threat to mine exploitation. The maximum unit water inflow is 0.2068 L/s·m (The facility' s drainage capacity, expressed in liters per second per meter). The aquicludes include the Middle Jurassic Anding Formation, the aquiclude from the floor of the Anding Formation to the roof of the No. 2 coal seam, and the aquiclude from the base of the No. 2 coal seam to the roof of the No. 3 coal seam in the Yan'an Formation.

Materials and Methods

Laboratory Test

Coal gangue was used as the primary grouting material. It was initially crushed with a ball mill to achieve a particle size under 10 mm before being combined with cement to form the slurry.The slurry' s waterproofing capability was governed by its post-solidification physical properties, including water-solid ratio, density, viscosity, and mass concentration. The experimental results were summarized in Table 1. Based on field grouting tests, a slurry formulation with a water-solid ratio of 2:1 and an average density of 1.3 g/cm^3 was selected for production.

Numerical simulation

The development of roof bed separation in the panel 11-3101 was simulated using three-dimensional discrete element technology. The model dimensions were 800 m × 460 m × 685 m (Fig. 1). Given the stratum dip angle of only 1°–2° in this area, the dip angle was simplified to 0° for modelling purposes. To improve the computational efficiency of the model, the Quaternary system was equivalently treated as a uniformly distributed load of 0.44 MPa applied to the top of the model. Except for the top boundary, which was free, all other boundaries were fixed. The model included the following layers: a 10 m thick floor of the No. 3–1 coal seam in the Yan'an Formation, a 5 m thick No. 3–1 coal seam, a 40 m thick layer from the roof of the No. 3–1 coal seam to the top boundary of the Yan'an Formation, a 160 m thick Zhiluo Formation, a 60 m thick Anding Formation, and a 410 m thick Cretaceous system.

Field Monitoring

The development of bed separations was investigated using drilling mud loss, ultrasonic imaging, and borehole television. The phenomenon of complete mud loss indicated that rock layer movement led to the formation of overburden bed separation. After flushing with clean water and allowing it to settle, downhole colour television imaging logging and ultrasonic imaging were conducted to observe fractures. Prior to mining, drainage boreholes were drilled in the roof to dewater the aquifer, and continuous drainage was carried out for nearly three months. During this period, changes in water discharge were recorded, and water samples were collected for quality analysis.

***Table 1** Experimental results of coal gangue slurry ratio.*

Particle size 0.125 mm				Particle size 0.106 mm			
Water-solid ratio	Density /g/cm^3	Viscosity/s	Mass concentration	Water-solid ratio	Density /g/cm^3	Viscosity /s	Mass concentration
1.6:1	1.32	19.5	43.4%	1.6:1	1.33	20.0	43.4%
1.8:1	1.30	17.4	40.0%	1.8:1	1.31	18.0	40.0%
2.0:1	1.29	16.9	37.0%	2.0:1	1.30	18.0	37.0%
2.2:1	1.28	17.0	34.4%	2.2:1	1.28	17.5	34.4%
2.4:1	1.26	16.5	32.0%	2.4:1	1.26	16.9	32.0%

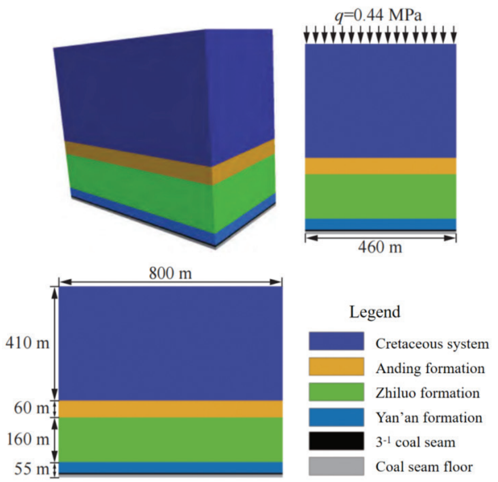

Figure 1 Numerical simulation model of the panel 11-3101.

Zoning Evaluation

The evaluation of bed separation water hazards is typically divided into five steps: ① Analysis of geological and hydrogeological conditions: understand the structural development of the panel and analyse the water inrush processes in adjacent mines within the mining area. ② Extraction of influencing factors: based on previous water inrush cases, analyse the necessary conditions for the formation of bed separation water. Combine this with the actual geological conditions of the mine to screen suitable influencing factors and normalize them. ③ Weight determination: use a combination of the Analytic Hierarchy Process (AHP) and the Entropy Weight Method to determine the weights. ④ Weight assignment: comprehensively calculate the weights obtained from each algorithm to determine the final weight values. ⑤ Risk zoning: utilize a Geographic Information System (GIS) to overlay different influencing factors according to their weights and create a risk zoning map for bed separation water hazards.

Results

Positioning of Bed Separation

Fig. 2 shows the numerical simulation results. When the panel advanced to 100 m, the immediate roof of the No. 3–1 coal seam caved, along with the No. 25 fine sandstone and No. 24 sandy mudstone of the Yan'an Formation. Transverse and vertical fractures developed, extending to the top of the Yan'an Formation. At 200 m of advancement, the fractures propagated upward to the No. 21 fine sandstone. By 300 m, the interconnected fractures reached the No. 20 sandy mudstone, and the water-conducting fractured zone reached its maximum extent. At this stage, uneven settlement occurred between the No. 16 sandy mudstone and No. 17 fine sandstone at the base of the Anding Formation, forming temporary transverse fractures. At 400 m of advancement, the overburden subsidence range expanded, the caved zone compacted, and the temporary transverse fractures closed. At 500 m, two bed separation spaces formed: the first separation between the No. 16 sandy mudstone and No. 17 fine sandstone at the base of the Anding Formation, and the second separation between the No. 13 medium sandstone and No. 14 sandy mudstone at the base of the Zhidan Formation. Numerous small fracture sets developed within the Anding Formation, likely due to the interbedded sandstone and mudstone structure. At 600 m of advancement, the bed separation further propagated upward, forming the third separation between the No. 8 fine sandstone and No. 9 medium sandstone in the middle of the Zhidan Formation.

Before conducting bed separation grouting, observation boreholes were drilled in Panel 11-3101 to validate the results of numerical simulations, thereby obtaining the actual development of bed separation on-site (sequence of treatment: mining and simulations, on-site verification, and grouting). It was found that the theoretical calculations were in good agreement with the measured results, except for the Class II (Jia *et al*, 2023) bed separation at the base of the Anding Formation (burial depth of 450–500 m), where the drilling fluid consumption was not large. This is because the Anding Formation consists of interbedded sandstone and mudstone, lacking thick sandstone layers, resulting in minimal grout leakage. Most small bed separations were also observed in the borehole color television imaging (Fig. 3).

Water Inrush Zoning

Three main factors influencing bed separation water hazards were identified: aquifer water

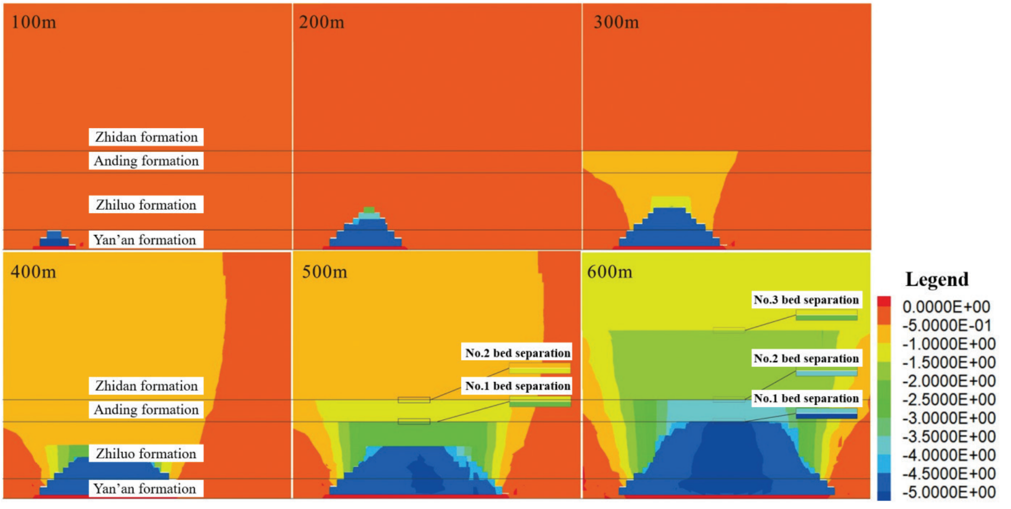

Figure 2 Vertical displacement of overburden rock of the panel.

pressure (weighting of 0.4), aquiclude thickness (weighting of 0.2), and height of the water-conducting fractured zone (weighting of 0.4). Based on borehole data around panel 11-3101, the computational datasets for each influencing factor were statistically analysed. The greater the aquifer water pressure, the stronger the recharge capacity to the bed separation space, and the higher the risk of water inrush. The water pressure distribution ranges from 3.33 to 3.97 MPa, with an average of 3.73 MPa (danger threshold of 3.95 MPa).

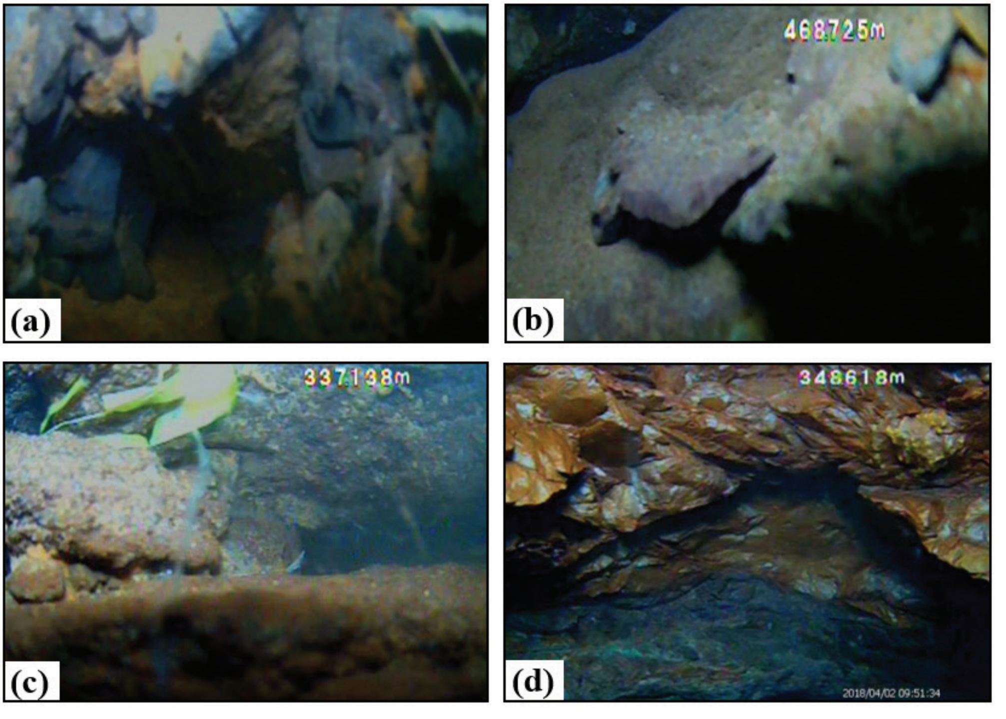

Figure 3 Borehole TV and ultrasonic imaging reveal bed separation and fracture development.

(a) (b) Multiple small bed separations at the bottom of the Anding Formation, (c) (d) bed separations at the junction of the Zhidan and Anding Formation.

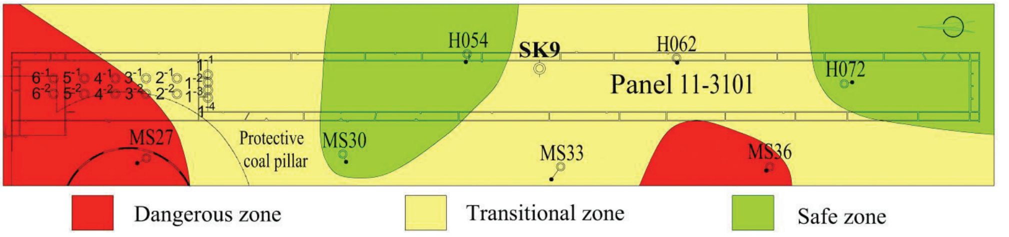

Figure 4 Water inrush risk zoning.

Aquiclude thickness refers to the distance between the bottom of the bed separation and the top boundary of the water-conducting fractured zone. The thinner the aquiclude, the weaker its resistance to deformation and failure, increasing the likelihood of bed separation water hazards. The thickness distribution ranges from 179.14 to 238.06 m, with an average of 204.6 m (danger threshold of 234 m). When the bed separation layer is fixed, the higher the water-conducting fractured zone, the thinner the aquiclude, and the greater the risk of water hazards. The height distribution ranges from 112.1 to 129.16 m, with an average of 124.5 m (danger threshold of 127 m). The panel was divided into five zones (two dangerous, two safe and one transitional zone) based on the risk intensity of water inrush from bed separation (Fig. 4). At the MS27 borehole located near the stopping line of the panel, there is a high risk of bed separation water hazards due to the high aquifer water pressure (3.96 MPa), thin aquiclude thickness (210 m), and development height of the water-conducting fractured zone (128 m). To ensure the safe mining of the panel, it is necessary to implement bed separation grouting in this area in advance.

Water Inflow and Quality

Fig. 5 shows that water from the Yan'an Formation-Zhiluo Formation aquifer flowed into the panel space as the water-conducting fractured zone gradually developed upward after grouting and during mining. When the panel advanced to 263 m, the water inflow was 187 m³/h. At an advancement distance of 430 m, the water inflow reached 296 m³/h, followed by a slight continuous increase. When the panel advanced to 3,300 m, the water inflow increased to 686 m³/h. As the panel continued to advance, the water inflow gradually decreased. By the end of grouting and during mining, the water inflow in the goaf was 480 m³/h, after which it continued to decline. Except for fluctuations in water inflow at 263 m and 2,800 m of advancement, the water inflow showed a relatively steady increase during other periods, followed by a gradual decreasing trend. No large water inrush from bed separation was observed.

Water quality analysis of samples from the goaf and roof drip water in the panel showed that the salinity of the water samples ranged from 1,990.68 to 2,814.8 mg/L, which differs from the salinity of the Cretaceous aquifer (252.84–761.48 mg/L). This indicates that the water inflow primarily originated from the Zhiluo Formation to the Yan'an Formation aquifers, with no infiltration from bed separation water. The grouting project effectively prevented and controlled bed separation water hazards, ensuring the safe mining of the panel.

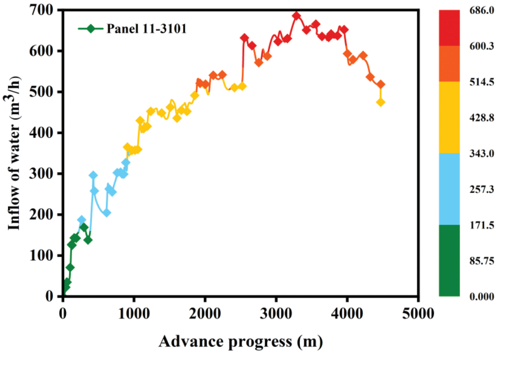

Figure 5 Water inflow curve in the panel.

Conclusions

(1) A three-dimensional numerical simulation model of overburden bed separation was constructed, simulating and revealing the distribution characteristics and development patterns of the bed separation space. As the panel advanced continuously, the separation space exhibited a phased development from low-order to high-order in the vertical direction and moved closely along the centre of the coal seam in the horizontal direction. Field verification demonstrated the accuracy of the model.

(2) The risk of water hazards from overburden bed separation in the panel was evaluated and zoned using a comprehensive weighting method. Based on the mechanism of water inrush from bed separation, the main controlling factors of water hazards were analysed, enabling precise identification and pre-grouting treatment of high-risk areas with high water pressure, thin aquicludes, and highly developed fracture zones.

(3) Through on-site monitoring of changes in water inflow, water quality analysis, it was confirmed that no sudden water hazards from bed separation occurred during the mining process, demonstrating effective prevention and control of bed separation water hazards.

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