

Research Article

Prevention of Water Inrushes in Deep Coal Mining over the Ordovician Aquifer: A Case Study in the Wutongzhuang Coal Mine of China

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Through field observation and theoretical study, we found that the Hanxing mining area has a typical ternary structure in coal mining under high water pressure of the aquifer. This ternary structure is the Ordovician limestone aquifer-aquiclude including thin limestones-coal seam. Although the aquiclude is considerably thick, there is still a great risk of water burst during mining under water pressure in the deep burial environment. Multidimensional characteristics of floor water inrush in deep mining are summarized in the paper, including water migration upwardly driven by the Ordovician confined water, the planar dispersion of the water inrush channel, the stepped increase of the water inrush intensity, the hysteretic effluent of the water inrush time and the exchange, and adsorption of the water quality. The water inrush mechanism is clarified that the permeability, dilatancy, fracturing, and ascending of the water from the Ordovician limestone aquifer form a planar and divergent flow through the transfer, storage, and transportation of thin limestone aquifers. The corresponding water inrush risk evaluation equation is also proposed. Based on the thickness of the aquiclude, the thickness of the failure zones, and the water inrush coefficient, the floor aquiclude is classified into five categories. While water inrush cannot be completely controlled by the traditional underground floor reinforcement with ultra-thick aquiclude or even zonal grouting, a comprehensive prevention and control concept of the four-dimensional floor water hazard in full time-space domain are proposed. A tridimensional prevention and control model of three-dimensional reticulated exploration, treatment, verification, and supplementation is presented. A full time domain technological quality control process of condition assessment, exploration, remediation, inspection, evaluation, monitoring, and reassurance is formed, and a water disaster prevention method with full time-space tridimensional network in deep coal mining is established. Case study in the Hanxing mining area demonstrates that the proposed methods are highly effective.

1. Introduction and Background

The Ordovician limestone aquifer contains abundant water with very high water pressure. It is deposited in the bottom of coal measure formations and exists in many mining areas in Northern China (Figures 1 and 2). The Ordovician aquifer has caused numerous aquifer water inrush accidents during coal mining. Water inrush from the Ordovician aquifer is

one of the major hazards in mining safety [1]. Many studies have been conducted to investigate the mechanism and mitigation methods of water inrushes in this area [2–4]. However, coal mining in those cases was mainly at a shallower depth (<700 m), where the burial depth and water pressure were relatively low, and the water inrush accidents were not very serious. As the mining depth increases in recent years (depth>700 m), in situ stresses and water pressures increase

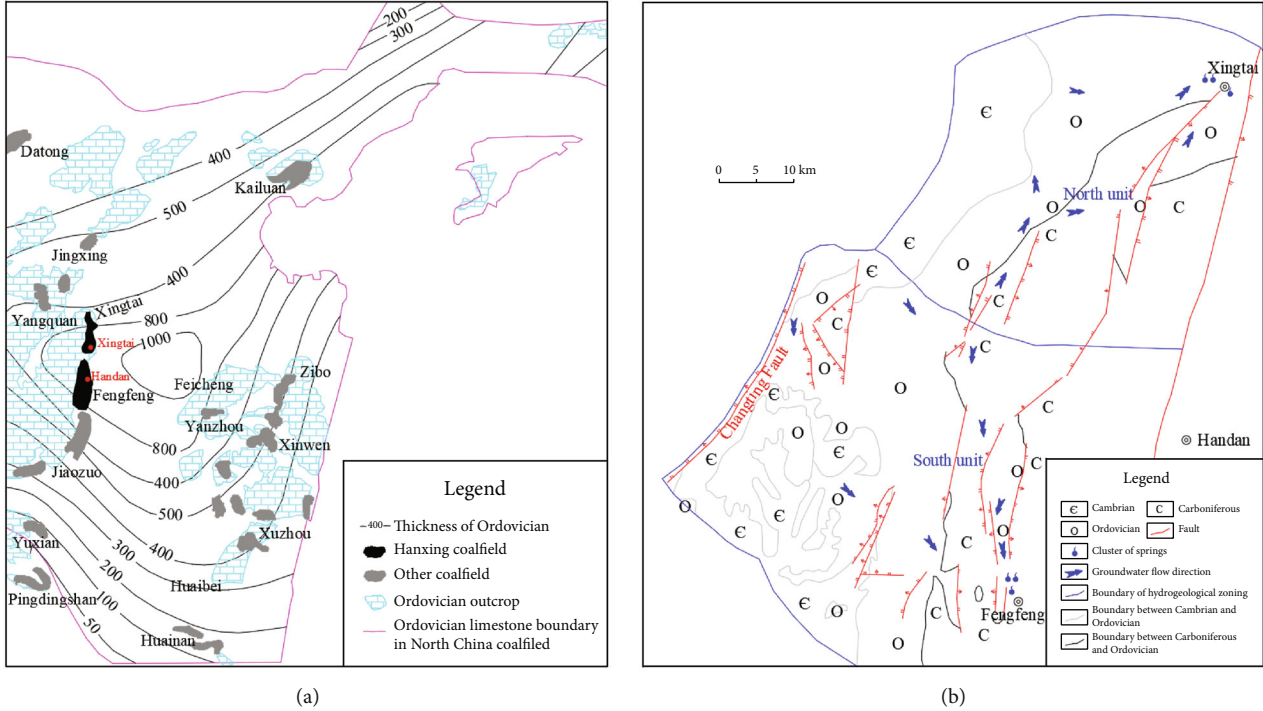


FIGURE 1: Map view of location of the Hanxing coalfield and other coalfields in North China coalfield: (a) The Ordovician hydrogeological system in North China and (b) north and south units of the Hanxing area.

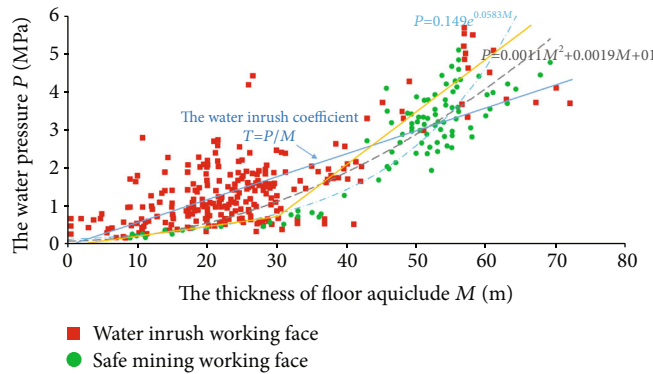


FIGURE 2: Theoretical and statistical analysis of water pressure and thickness of aquiclude for mining under water pressure.

greatly in the mining area, causing water inrush to become more serious and water disasters more devastated [3–5]. Furthermore, the existing theories and methods of water inrush prevention are not very suitable for this new situation [6–9]. Therefore, it is of critical importance to understand new mechanisms and prevention methods of water inrushes for coal mining at a great depth.

Safe mining under water pressure refers to coal mining over confined aquifers. Since the first water inrush from the Ordovician limestone aquifer occurred in the Kaiping coalfield in 1920 [10], different models for mining under water pressure and predicting water inrushes have been proposed [1]. To date, the development history of mining under water pressure is divided into three stages. The first stage was from the early 1950s to the mid-1980s, in which the system of technologies and theories had been basically formed

[11]. Some systematic researches on the main technical measures of drainage and depressurization for confined water or grouting for aquicludes were carried out [12], and the concept of mining under water pressure and the risk evaluation method of water inrush coefficient were put forward. The system of mining under pressure technologies [13], including mining methods and the water control technologies, such as exploration, prevention, and guarantee, had been basically formed, and the theories [14], including water inrush mechanism, safety evaluation, and water inrush prediction, had also been preliminarily constructed. The second stage, from the late 1980s to 2009, was the popularization and application stage of the theory and technology. With the acceleration of mining depth, the mining under water pressure for lower coal seam formations faced the dangerous condition of water inrush coefficient $T > 0.06$ MPa/m, with

the frequency of water inrushes increased, the underground treatment of grouting reinforcement of floor aquicludes or thin limestone transformation had been widely applied, and a large number of coal resources had been safely mined [15]. The third stage refers to recent 10 years, in which the regional preact grouting technology for deep mining was developed. The shallow coal resources were exhausted and had to turn to deep mining, facing a more dangerous situation of water inrush coefficient $T > 0.1$ MPa/m, the frequency of floor water inrushes was high, the water influxes were large, and the treatment technology for shallow mining was obviously not suitable for deep mining. With the help of horizontal drilling technology, the regional preact grouting technology tends to mature [6, 7, 9].

With the increasing depth of the coal seam mining, northern China coal fields face various safety issues that are different with those in the shallow mining. In situ stresses, tectonic stresses, water pressure, and temperature continuously increase. Exploitation of deeper coal formations, especially safe mining under water pressure in the deep coal formations, faces new challenges, which is due to the fact that aquifer containment characteristics, water filling regularities of the deep Ordovician limestone karst cavities, main control factors of coal floor water inrush, and water inrush mechanism change fundamentally. The theories and techniques of safe mining under water pressure are also changed profoundly.

The Hanxing mining area consisted of three parts: Fengfeng, Handan, and Xingtai mining areas and is a typical northern China coalfield (Figure 1). It is the main coal production zone in China, with an annual coal production of 7930 tons. The coal and rock formations in this area have a typical ternary tactic model, i.e., the coal seams are above the Ordovician limestone but separated by aquicludes and thin limestones (see Figure 3). The Ordovician limestone aquifer with rich water and high water pressure is a regional main water supply source [16]. However, it also threatens the mining of coal seams by recharging the thin limestone aquifers in the coal measures, i.e., the Benxizu, Daqing, Shanfuqing, and Yeqing limestones from bottom to top. Coal mining may not only cause the water inrush and coal mine flooding but also induce the aquifer water level to drop sharply, affecting water resources and ecological environment [2]. Mines within the area mostly have shifted to deep mining. In this situation, water pressure of the Ordovician limestone can be as high as 10 MPa and water inrush coefficient exceeds 0.1 MPa/m. Based on the national regulations, coal seam cannot be exploited without adopting additional measures. In order to exploit the deep or the lower group of coal formations, zonal preact grouting method is developed on the basis of traditional shallow mine floor reinforcement. Although greatly reducing the risks of water inrushes, it still cannot eliminate the hazard of water inrushes. The main reason is that deep safe mining under water pressure theory has not yet been established nor is the technical system.

2. Water Inrush Prevention Theory of Deep Mining under Water Pressure

Safe mining under water pressure originally means mining safely by taking advantage of natural capability of floor aquic-

lude for resisting confined aquifer. Because of its simple concept and easy application, the water inrush coefficient method is still widely used in China, and it can be used in either shallow or deep mining, regardless of the conditions of aquicludes. According to related research, this method is only applicable in the condition that the thickness of aquiclude is less than 60-80 m, and the water pressure is less than 4 MPa. In addition, with the great variations in the deep mining environment, the theory and technology of mining under water pressure also need to improve.

2.1. Distinguishing Deep and Shallow Mining for Water Inrush Prediction. According to the current situation of mining, the mining depth in China is set to be 700 to 1500 m. Most of shallow rock masses are in the state of elastic stress, while at the deep depth, rock masses may show large deformation under high crustal stress and mining disturbance. Practice shows that the prediction and evaluation theories, detection method, monitoring tools, and treatment technology used for shallow mining are difficult to achieve effective control of deep water inrush disaster. The risk evaluation method of water inrush, i.e., water inrush coefficient, based on thin plate theory [17], may not be valid in the deep depth. Therefore, the concept of deep mining is proposed from the perspective of mine water inrush prevention and treatment. The surface formed by Eq. (1) in space is defined as the interface between shallow depth and deep depth, with shallow depth above it and deep depth below it. Equation (1) is derived from the formation breakdown pressure in hydraulic fracturing (e.g., [18]):

$$P_0 = 3\sigma_3 - \sigma_1 - P_p + R_m, \quad (1)$$

where σ_3 and σ_1 are the minimum and maximum in situ stresses, P_p is the water pressure of the Ordovician aquifer, and R_m is the tensile strength of the rock.

Due to the relief of the vertical stress after mining, the evaluation criterion by Eq. (1) varies to $P_0 \geq \sigma_3 + R_m$. According to water filling characteristics, the treatment to the floor in deep mining then shifts to large scale grouting from centralized channel treatment, so that the deep water inrush prevention and control method of zonal preact grouting are formed.

2.2. Water Inrush Prediction of the Ordovician Limestone in Shallow Mining. In traditional shallow mining, the thickness of floor aquiclude is generally within 60~80 m, and the confined water pressure is below 3.0~4.0 MPa. In this condition, the water inrush coefficient method is suitable for evaluating the risk of safe mining under water pressure. According to regulations issued by the Chinese government, the conditions for normal mining under water pressure are that the water inrush coefficient for the floor in the area with geologic structures is generally not greater than 0.06 MPa/m and for the floor in the normal area is not greater than 0.1 MPa/m. The water inrush coefficient can be expressed in the following [2]:

$$T = P/M, \quad (2)$$

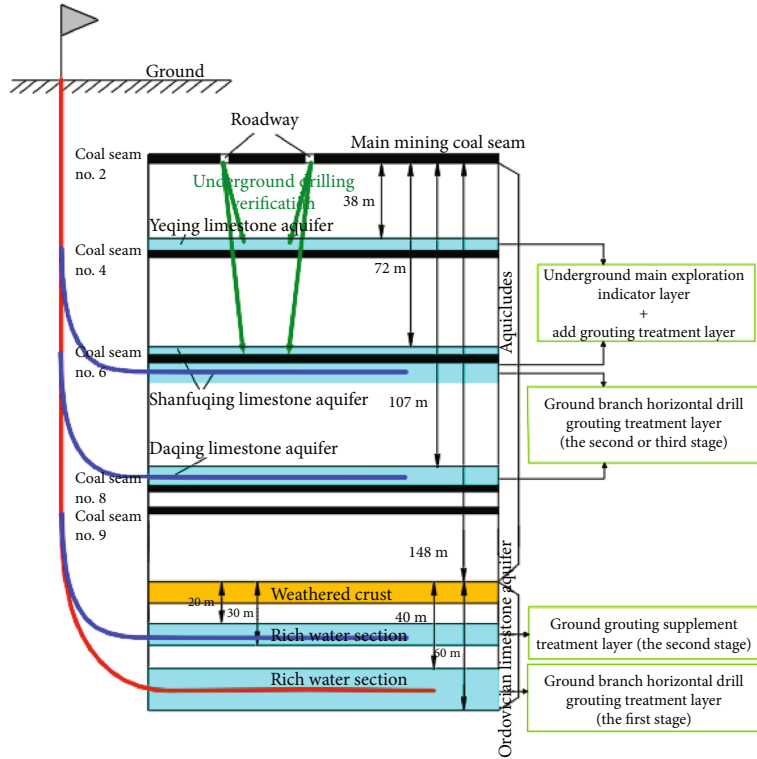


FIGURE 3: Stratum structural model of the Ordovician limestone and thin limestones under coal seams and grouting treatment of coal seam floor strata for preventing water inrush.

where T is the water inrush coefficient, P is the water pressure, and M is the thickness of the aquicludes.

Based on classical thin plate theory in elastic mechanics, critical water pressure of water inrush (Figure 2, black line) can be expressed as

$$P = 0.0011M^2 + 0.0019M + 0.1. \quad (3)$$

The empirical equation for the critical water pressure of water inrush (Figure 2, light blue line) obtained from the measured data can be written in the following:

$$P = 0.1409e^{0.0583M}. \quad (4)$$

The water inrush coefficient method is also shown in Figure 2 (blue line). Compared with these water inrush prediction methods to the actual water inrush statistical data, each prediction has its limitation. Therefore, a combined method is needed for a good prediction.

In the working faces at shallow and middepth, the characteristics of water inrush from Figure 2 can be summarized as follows:

- (1) The working faces could be safely extracted under conditions of confined water pressure less than 2.0 MPa and the thickness of the floor aquiclude more than 35 m, or the pressure less than 1.2 MPa and the thickness more than 20 m

- (2) The most prominent feature is that most floor water inrushes occur when the thickness of aquiclude is less than 30 m and the confined water pressure is less than 3.0 MPa

- (3) The water inrushes in shallow mining are mostly from the present karst runoff zones or water rich zones, with abundant and low salinity water mainly composed of $\text{Ca}\cdot\text{HCO}_3$ or $\text{Ca}\cdot\text{Mg}\cdot\text{HCO}_3$, and their channels are mainly concentrated water passage in large and medium-sized geologic structures such as paleosinkholes and faults, with huge water quantity

2.3. Water Inrush Characteristics of the Ordovician Limestone in Deep Mining. With the increase of mining depth, the water inrush threat of the confined aquifer in the Ordovician limestone under coal seams becomes increasingly prominent [19–21]. According to statistics, since 1995, 13 cases of water inrush incidents (Table 1) occurred in the Hanxing deep mining area, and they were all caused by water conducting geologic structures and mining-induced fractures.

Large numbers of water inrush cases in deep mining show that there are several characteristics of water inrushes. Water influx increases gradually while the peak values far less than those in the shallow mining, the channels of the influx scattered, and the delayed occurrence of the influx. The water quality of the influx has high salinity with the cations mainly Na^+ or Na^+ and Ca^{2+} . The detailed behaviors of

TABLE 1: Statistics of water intrushes from coal floor in the Hanxing deep mining area.

No.	Mine	Occurred time (year.month.day)	Occurred sites	Influxes ($\text{m}^3 \cdot \text{h}^{-1}$)	Pathway types
1	Wutongzhuang mine	1995.12.3	Main and auxiliary shaft connecting roadway	34000	Shaft submergence caused by the Ordovician limestone water intrush through water conducting fault
2	Wutongzhuang mine	2000.5.14	Tunneling of north main return air roadway	160.2	Ordovician limestone water outflow from the floor of fractured zone connected to water conducting paleosinkhole
3	Xingdong mine	2003.4.12	Tunneling of 2903 working face	7000	Driving outflow from the water conducting paleosinkhole
4	Wutongzhuang mine	2004.8.10	Mining of 2101 working face	180	Ordovician limestone water outflow from the floor of fractured zone connected to water conducting fault
5	Lincheng mine	2006.12.16	Mining of 0915 working face	4200	Coal mine submergence by small water conducting fault
6	Jiulong mine	2009.1.8	Mining of 15423 N working face	7200	Ordovician limestone water outflow from the floor of fractured zone connected to paleosinkhole
7	Huangsha mine	2010.1.19	Tunneling of 2124 working face	7200	Ordovician limestone water outflow through small faults connected to large water conducting fault
8	North well of Xingdong mine	2010.11.15	Mining of 92081 working face	1500	Ordovician limestone water outflow from the floor of fractured zone
9	Xingdong mine	2011.4.13	Mining of 2127 working face	125	Ordovician limestone water outflow from fractured zone connected by hidden microfaults
10	Huangsha mine	2011.12.11	Mining of 2106 working face	24000	Ordovician limestone water outflow from the floor of fractured zone connected to a hidden paleosinkhole
11	Wutongzhuang mine	2014.7.25	Mining of 2306 working face	11250	Ordovician limestone water outflow through small faults connected to a hidden paleosinkhole
12	Jiulong mine	2017.1.17	Mining of 15252 N working face	300	Ordovician limestone water outflow from a hidden paleosinkhole
13	Xingdong mine	2018.3.5	Mining of 2228 working face	2649	Ordovician limestone water outflow from a group of faults

the water intrushes in the deep mining are listed in the following:

- (1) Water intrush source. The Ordovician limestone is the general source, and the water pressure in the confined aquifer is the driving force. Thin limestones store and accumulate water from the Ordovician aquifer and act as a connecting path. The water with high pressure moves upward from the Ordovician aquifer through fractures to pass the bottom layer of the thin limestone and move to upper layer of the thin limestone till breaking through the coal seam floor and forming water intrush in the mining area
- (2) Water intrush channels. The dispersed fracturing zones in the floor, which may connect to the hidden geologic structures, are the main water-conducting channels. For instance, on July 25 of 2014, the mine flooding accident occurred in 2306 working face of the Wutongzhuang mine. The mining depth reached 700 m, the water pressure was as high as 6.5 MPa, and the distance of the mining area to the Ordovician limestone aquifer was 160 m. Water intrush influx in this accident reached as high as 11264 m^3/h . Although the inflow channels were the floor fractured zones, it connected to the Ordovician limestone by a hidden paleosinkhole
- (3) Water intrush intensity. As confined water of the Ordovician limestone flows to the floor and continuously fractures the floor rocks, the water-conducting channels increase and more water flows into the channels, and the water inflow presents a step growth trend, eventually forms a water intrush disaster. The water influx generally reaches the peak value through several or even dozens of step growths from a small to a large value (Figure 4) and then stabilizes or decreases depending on the water supply situation of the Ordovician aquifer
- (4) Water intrush time. With the initial or periodic mining-induced pressure caused by the collapses of the coal seam roof, the floor deformation and heave appear in the goaf area, and this may cause water intrush. Due to the delay of the floor fracturing process, the water inflow has an obvious delay phenomenon [22, 23]

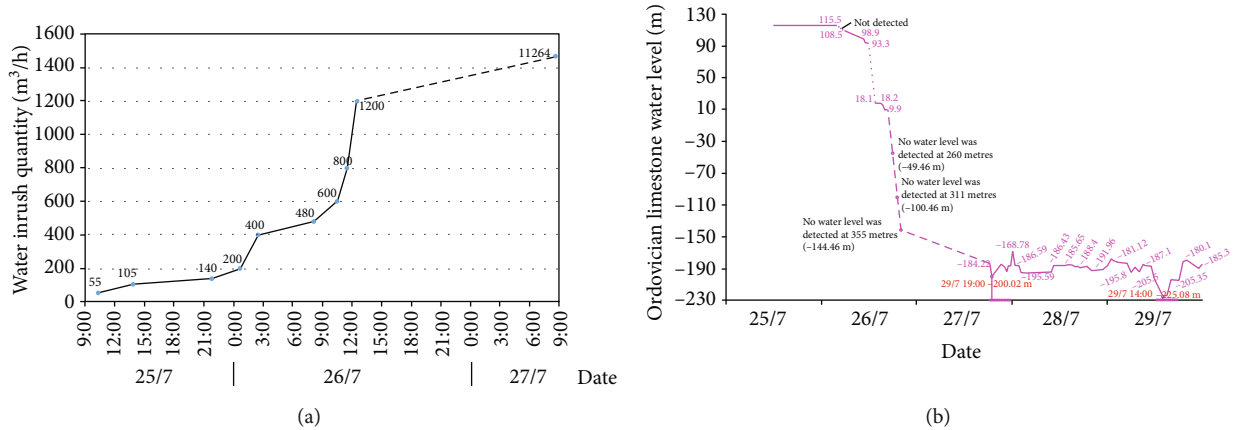


FIGURE 4: Dynamic variations of water inrush influx (a) and water pressure (water level) (b) in the accident described in the Wutongzhuang mine.

- (5) Water inrush source and quality. The water quality of high mineralized water in the deep Ordovician limestone is different from that in the normal limestone, the water gradually changes from Na^+ or Na^+ and Ca^{2+} to Ca^{2+} or Ca^{2+} and Na^+ and from $\text{SO}_4^{2-} \cdot \text{Cl}^-$ or $\text{Cl}^- \cdot \text{SO}_4^{2-}$ to HCO_3^- in the initial stage of influx (Figure 5)

2.4. Water Inrush Mechanism for Deep Mining. The water inrush from the Ordovician aquifer can be assumed as a typical ternary structure model of the Ordovician limestone-thick aquiclude- (or with thin limestone-) coal seam. Due to the equilibrium of stresses of the surrounding rocks and water pressure prior to mining, the confined water in the aquifer ascends to a certain height inside fissures in the floor strata and maintains a static state. Once mining starts in the working face, the vertical stress of the overlying strata is removed in the mined area, causing the floor strata to be almost in a state of two-dimensional stresses. Under the high water pressure, the confined water in the Ordovician limestone seepages, expands, and fractures along fissures in the floor strata and continuously moves upward. After the water intruding into the first layer of thin limestone, the thin limestone is filled by the Ordovician limestone water (Figure 6). The water continues to flow up to the second and then the third layer of thin limestone, till it reaches the mining disturbed zone and failure zone of the coal seam floor and forms water inrush in the mining area (Figure 6).

The water inrush coefficient expressed in Eq. (2) and other equations such as Eqs. (3) and (4) presented in Figure 2 can be applied to estimate water inrush potentials. However, the water inrushes and the coal seam floor failures in deep mining have different behaviors from the shallow mining. Therefore, only using Eqs. (2)–(4) are not sufficient, and different prevention models are needed to be considered, as described in the following sections. In addition, numerical analyses need to be applied to analyze rock failures and water inrush possibilities based on the water inrush mechanism shown in Figure 6.

2.5. The Method of Risk Evaluation in Deep Mining under Water Pressure. Safe mining under water pressure refers to coal mining over aquifers with confined water pressure. Generally speaking, it refers to the mining to achieve the safety goal under natural conditions, i.e., only using the floor aquiclude to resist the aquifer water pressure rather than taking prevention measures to decrease water level by drainage and pressure reduction or local grouting reinforcement. At present, most of coal mines in North China coalfields adopt this method but taking appropriate measures. In deep mining, this method is no longer applicable.

Water inrush from the floor can be divided into two basic mechanisms [24, 25]: microfracturing of thick plate and failure of thin plate (key layer). The thin plate criterion is the ultimate bending moment theory: $M_p \geq M_s$ (M_p stands for actual bending moment, and M_s stands for critical bending moment). The microfracturing of thick plate criterion is a mechanical criterion: $P_0 > 3\sigma_3 - \sigma_1 - P_p + R_m$ (similar to Eq. (1)). According to water inrush mechanism and the statistical data of water inrush cases, the water inrush coefficient method is suitable for the thin plate theory. For the typical ternary structure model of the Ordovician limestone-thick aquiclude coal seam, the thickness of aquiclude is far more than 80 m, and water coefficient is no longer suitable for the risk evaluation of this rock structure model. For thick and ultra-thick aquicludes, theoretically, the holistic breaking the thick plate is impossible to occur. Under the presumption of no straight through structural channel exists, the only way that the Ordovician limestone water can transfer upwards is to ascend through fissured water-conducting fractures. Therefore, $P_0 > 3\sigma_3 - \sigma_1 - P_p + R_m$ can be used to evaluate the water inrush risk of deep Ordovician limestone and thin limestones under the coal floor.

2.6. Prevention Models of Safe Mining under Water Pressure. According to the thickness of aquiclude (M), the failure depth of floor (h_d), height of the water conducting zone from the Ordovician limestone (h_r), and water inrush

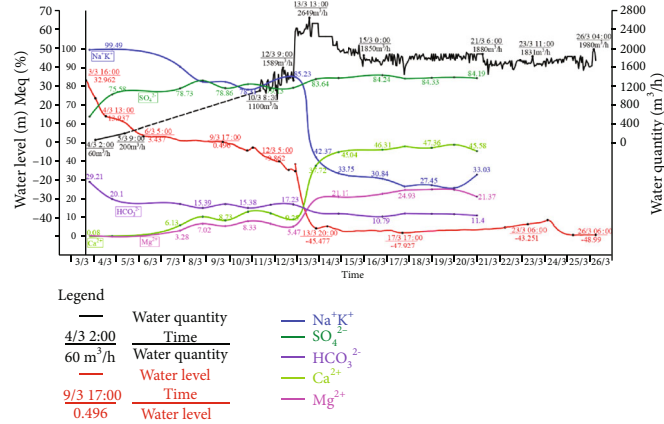


FIGURE 5: Water quantities and water levels variations before and after water inrush in observation boreholes of 2228 working face in the Kingdong Mine.

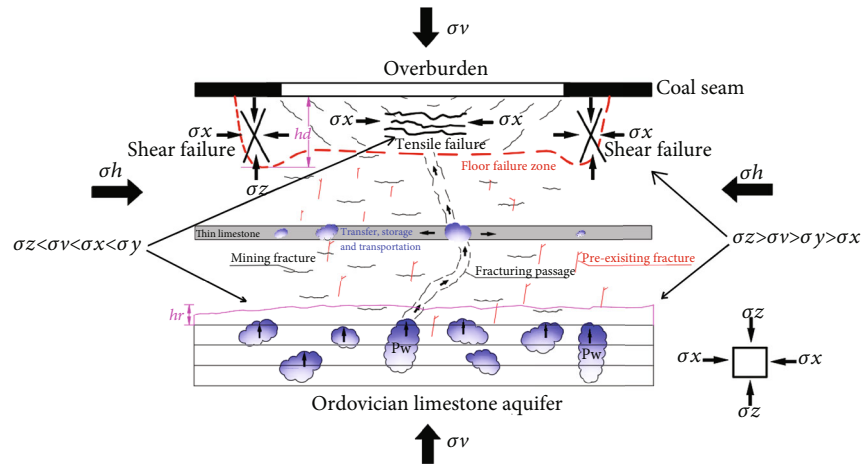


FIGURE 6: Mechanism of water inrush from the Ordovician limestone and thin limestones in deep mining.

coefficient (T), five categories for the floor aquiclude are classified [26, 27]. They are ultra-thin, thin, medium thick, thick, and ultra-thick aquiclude formations, and five prevention models of safe mining under water pressure are proposed correspondingly (Figure 6).

- (1) While $0 < M \leq h_d + h_r < 30$ m and $T > 0$, the aquiclude is classified as the ultra-thin aquiclude. For this category, as long as mining is under pressure, that is, confined water pressure exists, and water inrush from floor will happen

For this case, grouting should be carried out in the Ordovician limestone aquifer, and the grouting rock selection should mainly meet the condition of $T \leq 0.1$ MPa/m and taking into account the water rich property of the Ordovician limestone.

- (2) While $h_d + h_r < M \leq 80$ m, and $T > 0.06$ MPa/m, it is a thin aquiclude case. According to thin plate theory and statistics of water inrush cases, when the thickness of aquiclude is within 60-80 m, the water inrush coefficient method is suitable for the risk assessment

of water inrushes, and the thickness of aquiclude of 80 m is the critical value. In this category, water inrush risk is high

In this category, grouting at the top of the Ordovician limestone aquifer as well as grouting reinforcement in the floor aquiclude should be carried out. The grouting rock layer selection should mainly meet the condition of $T \leq 0.1$ MPa/m and also need to consider the water rich property of the Ordovician limestone. The reinforcement of the floor should be selected in the rocks below the floor failure zone.

- (3) While $h_d + h_r < M \leq 80$ m, and $T \leq 0.06$ MPa/m, it is the medium thick aquiclude. In this category, risk of water inrushes is low

In this model, the grouting reinforcement of the floor aquiclude should be adopted, and the grouting layer should be selected in the rocks below the floor failure zone.

- (4) While $80 \text{ m} < M (h_d + h_r < M)$, and $T > 0.1$ MPa/m, it is classified as thick aquiclude. In this category, although the water inrush risk is relatively high, the

actual possibility of water inrushes is not high, unless large geologic structures exist in the floor

In this case, the key method to prevent water inrushes is to explore and prevent large and medium-sized geologic structures.

- (5) While $80\text{ m} < M (h_d + h_r < M)$ and $T \leq 0.1\text{ MPa/m}$, it is the ultra-thick aquiclude. In this category, the risk of water inrushes and the actual probability of water inrushes are very low, unless large geologic structures exist in the floor

In this case, the key method to prevent water inrushes is also to explore and prevent large and medium-sized geologic structures.

3. A Case Study in the Wutongzhuang Coal Mine

3.1. General Situation. The Wutongzhuang coal mine is located in the southern Fengfeng coalfield, and the studied area is No. 6 Panel of mining area located in the south wing of the mine field, which includes working faces of No. 2601, No. 2602, No. 2603, and No. 2604, while No. 2602 working face is the first one with a strike length of 834 m and dip length of 256 m. The elevation of coal seam floor is $-704.3\text{ m} \sim -775.5\text{ m}$, and the buried depth is about 900 m. The coal seam, which has a thickness of 3.7 m, is monoclinic structure, and its inclination is $8^\circ \sim 20^\circ$ with an average of 14° . Normal faults are relatively developed inside the working face, and 5 faults in total are found in the transport roadway and cut-out roadway, with fault displacement of $H = 0.7 \sim 4.2\text{ m}$. Comprehensive mechanized full height mining technology is adopted.

The strata in the Fengfeng coalfield are formations in ages of (from old to new) the Paleozoic Cambrian, the Ordovician (water rich confined aquifer), the Carboniferous-Permian (coal measures), the Jurassic, the Paleogene, and the Neogene.

3.2. Treatment Method of Safe Mining of Deep Coal Seam under Water Pressure. On July 25 of 2014, a water inrush accident occurred in No. 2306 working face of the Wutongzhuang mine, and the peak value of water influx reached $11264\text{ m}^3/\text{h}$. Before coal extraction, a large number of drilling exploration and grouting projects were implemented using the shallow underground floor reinforcement technology [28]. The grouting boreholes almost overlaid the whole working face floor. The high density of boreholes and scale of the project was never seen before in the similar situations, but water inrush accident still could not be prevented.

The cause analysis of this accident shows that the water inrush channel was a deep buried paleosinkhole, while the top of the paleosinkhole was more than 100 meters away from the coal seam, and the existing treatment method applied in the shallow mining case is invalid for this case. At that time, the zonal preact grouting method had just been applied to the deep mining with some successful cases

achieved. This method had been introduced to complete the No. 6 and No. 8 panel mining area successively. In the treated working faces, the underground exploration of the Yeqing and Shanfuqing limestones was carried out. The results show that there were still many boreholes with large amount of water outflow after coal mining; therefore, the goal of cutting off the hydraulic connection between the Ordovician limestone and thin limestones had not been fully realized. This indicates that the zonal preact grouting method still has some defects.

Therefore, the grouting method in the studied area was to be improved, and the supplementary project was designed. Firstly, the grouting in the Ordovician limestone was changed from single-layer to double-layer grouting, and then grouting in two thin layers of limestone is added. Secondly, different directional drillings for grouting boreholes were designed in different grouting layers, so that an exploration and prevention mode of multilevel three-dimensional networks was formed. This greatly improved the accuracy of exploration and made pale-sinkholes or large and medium-sized faults under control, so that the risk of flooding could be eliminated (Figure 7).

After the completion of the project, verification of geophysical and drilling explorations was carried out again, and numbers of boreholes with water inflow were significantly reduced. In a small number of abnormal boreholes, grouting was supplemented until the abnormality was eliminated. Thus, the deep safe mining with water pressure was realized.

3.3. Technology of Deep Safe Mining under Water Pressure. Water inrush prevention technology in deep mining has been formed based on the successful experience of the Wutongzhuang coal mine and is widely applied in the Yangdong, Jiulong, and Xingdong coal mines, where good results are achieved.

This technology presents an idea of comprehensive water inrush prevention for the aquifers of Ordovician limestone and thin limestones in time and space domains. In the full time domain, this technology integrates all aspects of technical operations and quality control, from evaluation of water inrush, prediction, coal floor exploration, grouting treatment, grouting inspection, to operation monitoring, and quality guarantee. This technology also has the three-dimensional water inrush prevention system of construction, including surface and underground, multilayer and multilevel network treatment, and double target layer inspection in a full space domain (Figure 3).

3.4. Applications in the Wutongzhuang Coal Mine

3.4.1. Assessments of Hydrogeological Conditions. The chemical composition, structures, lithologic combination, and fractures in the Ordovician limestone control its water bearing characteristics. Vertically, the Ordovician limestone can be divided into three formations and eight intervals. Among them, the third formation is located at the top, and its thickness is 103 m with relatively shallow burial and rich water content. After further exploration and evaluation, the layers

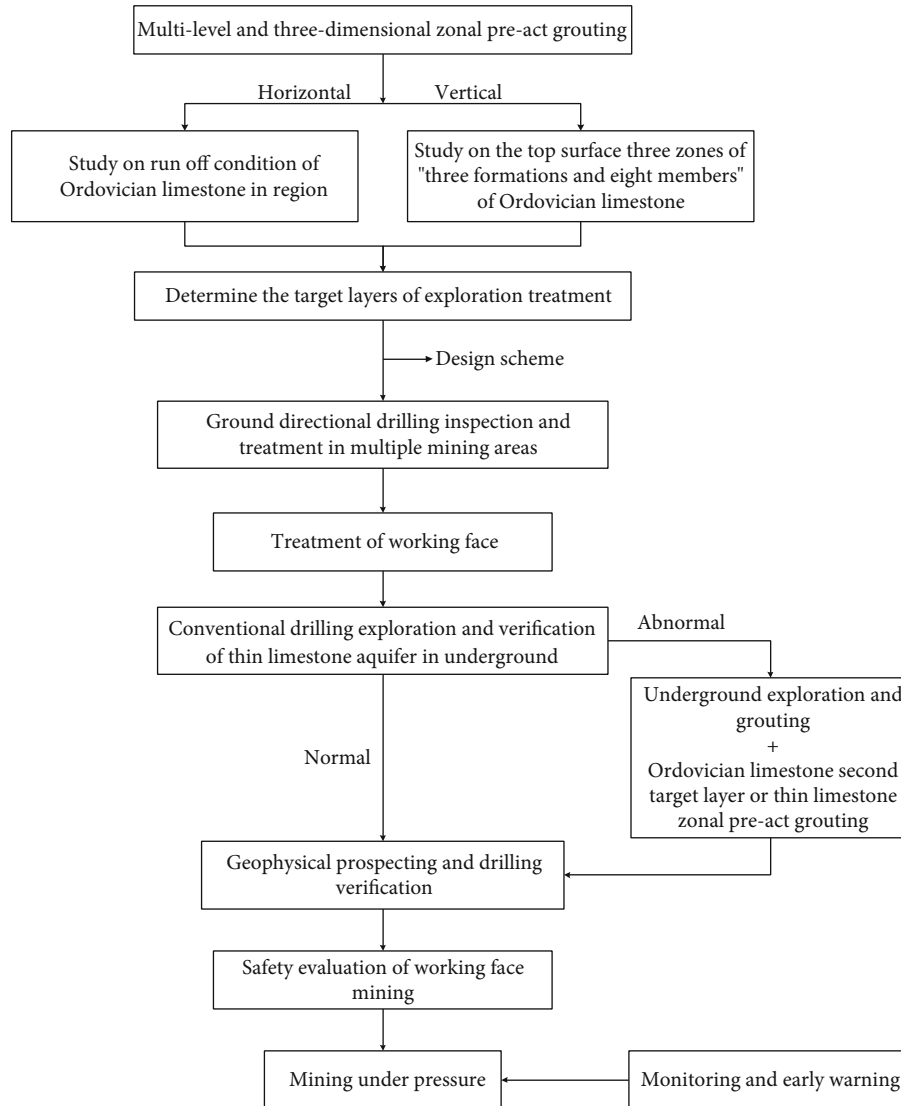


FIGURE 7: Workflow chart of multilevel and three-dimensional regional treatment mode of water inrush from coal floor in deep mining.

of 40-60 m and 20-30 m below the top surface of the Ordovician limestone contain abundant water, and they are the ideal layers for grouting.

The thin limestone aquifers are heterogeneous, their thicknesses gradually increase from the top to the bottom, and the average thicknesses of the Yeqing, Shanfuqing, and Daqing limestones are 2.5 m (with the maximum of 5.4 m), 5.5 m, and 5-6 m (with the maximum of 10 m), respectively. After evaluation, these three aquifers can all be used as drilling and grouting target layers. And the Yeqing and Shanfuqing can be used as ideal layers for underground verification of the grouting results and supplementary grouting.

3.4.2. Comprehensive Exploration and Treatment in Three-Dimensional Network

(1) *The Preact Grouting of Layer from 40 M to 60 M below the Top Surface of the Ordovician Limestone.* According to

the design, zonal preact borehole grouting was carried out in No. 6 panel, including totally 2 main boreholes and 25 horizontal branch boreholes in the Ordovician limestone (Figure 8), and the branch boreholes were planned and drilled in a fish bone shape (the coss-section is as shown in Figure 7), with a borehole spacing of 50-60 m. A total of drilling distances of the boreholes was 21437 m, which borehole leakage occurred 24 times, with a total of 34845 tons of cement slurry injected. After zonal treatment, karst fissures at the top of the Ordovician limestone aquifer in No. 6 panel were effectively sealed.

(2) *Grouting Treatment and Verification in the Yeqing and Shanfu Limestones.* Geophysical methods were used to detect No. 2602 working face. According to the detection results, 17 verification holes were designed with a total drilling length of 2337 m (the coss-section is illustrated in Figure 7). However, due to the large amount of water influxes from many boreholes with high water pressure

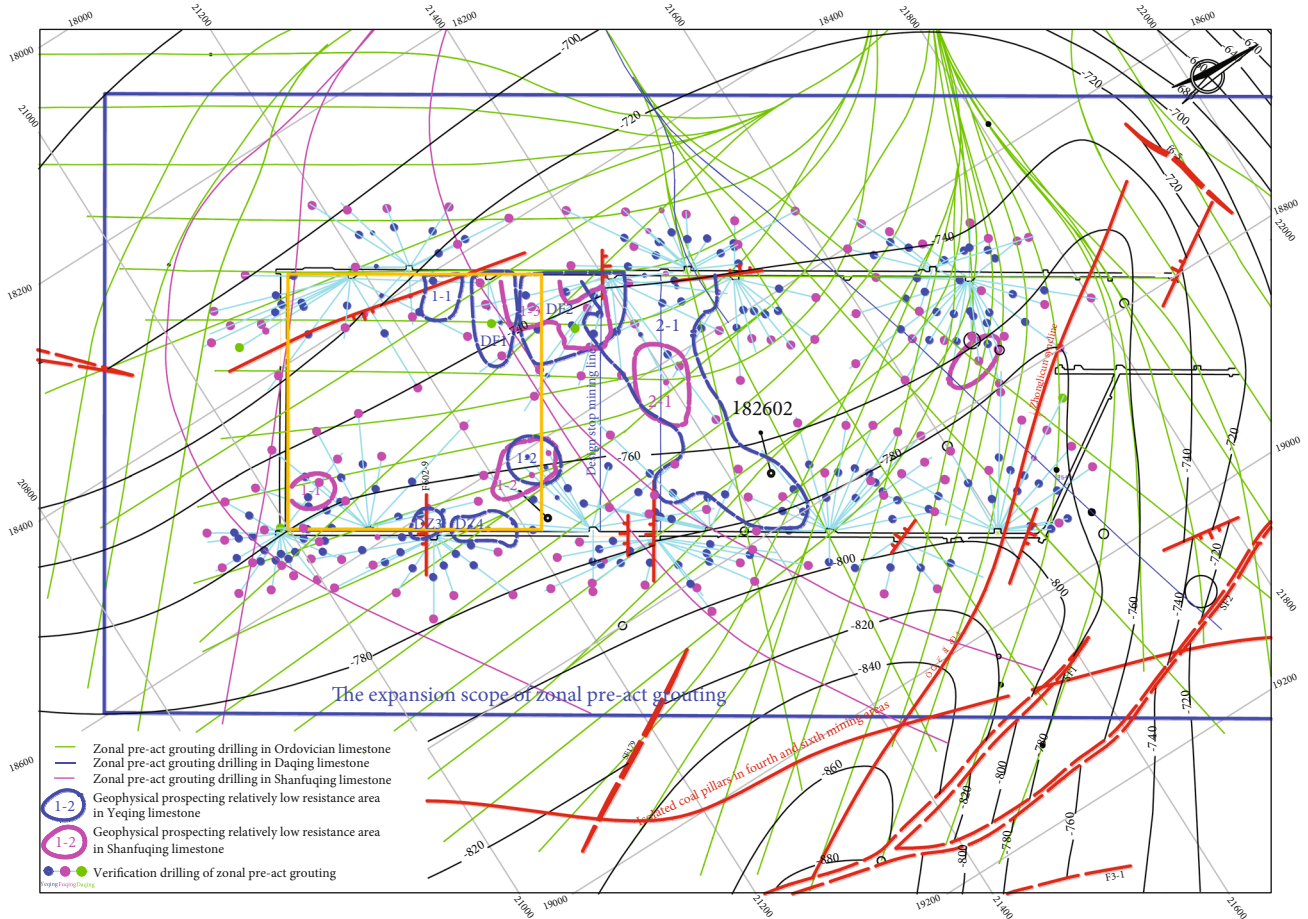


FIGURE 8: Schematic diagram of the exploration and treatment project in No. 2602 working face of the Wutongzhuang mine.

and high water temperature during drilling, additional verification boreholes had to be continuously added. Eventually, 106 boreholes were drilled with a total drilling length of 12671 m and 998.77 tons of cement slurry injected.

The effect of underground verification project was reexamined. In the original design and construction, 70 boreholes were designed to drill through the Yeqing and end in the Shanfuqing limestone. While the aquifers were exposed, most of the boreholes had abnormal water influxes and abnormal temperature, and water sampling in these boreholes showed that these aquifers exhibited water characteristics of the Ordovician limestone. This indicates that the Yeqing and Shanfuqing aquifers were connected to the Ordovician aquifer. When the drilling went through the Yeqing limestone, 57 out of 70 boreholes had water influxes. 15 boreholes had water influxes over $10\text{ m}^3/\text{h}$, and 3 boreholes had water influxes over $60\text{ m}^3/\text{h}$. The highest water temperature was 45.7°C , and the water pressure was close to the highest level of the Yeqing aquifer. After drilling to the Shanfuqing limestone, 67 out of 70 boreholes had water influxes, 28 boreholes had water inflow over $10\text{ m}^3/\text{h}$, and 6 boreholes had water inflow over $60\text{ m}^3/\text{h}$. The highest water temperature was 45.9°C , and the water pressure was close to the highest level of the Shanfuqing aquifer.

Comprehensive analysis of the hydrological data of the verification holes and the water discharge test data were conducted. It shows that the Shanfuqing aquifer still received water recharge from the Ordovician limestone, and the vertical recharge of the Ordovician limestone aquifer has not been completely cut off by the treatment project. Hence, it is necessary to further supplement the treatment project.

(3) *The Supplemental Grouting to Seal the Top of the Ordovician Limestone and the Daqing and Shanfuqing Thin Limestones.* Based on the above grouting treatment, an optimized design for supplemental grouting was given. The layer of 20–30 m below the top of the Ordovician limestone was designed to grout and to cross with the existing grouting layer, i.e., 40–60 m below the top of the Ordovician limestone. And the horizontal branch boreholes in the Daqing and Shanfuqing were designed in a belt-shaped arrangement, forming three-dimensional grouting networks for intensive exploration and treatment. A total of 6 main boreholes and 21 branch boreholes were constructed in the supplementary project, including 16 branch boreholes in the Ordovician limestone, 1 branch borehole in the Daqing limestone, and 4 branch boreholes in the Shanfuqing limestone (Figure 8). A total of 23000.9 m of drilling work were completed, 7066.5 tons of cement injected, and 20 times of borehole leakage occurred. The grouting volume at the

largest leakage point was 1126 tons, and the grouting volume at the other leakage points was less than 1000 tons.

3.4.3. Tests and Assessments of the Treatment Effectiveness

(1) *Assessment of the Thin Limestones.* Before the treatment, the number of boreholes with water influxes accounted for a large proportion: 69.8% of the total 106 boreholes in the Yeqing, 92.4% in the Shanfuqing, and 100% in the Daqing. After the treatment, it was verified that the number of boreholes with water influxes was very small, the water volume was less than 10 m³/h, the fissures in the thin limestones were filled, and the hydraulic connection was effectively cut off.

(2) *Drilling Verification and Assessment of the Geophysical Abnormal Areas.* After the completion of the regional grouting treatment project, 8 abnormal areas with low resistivity delineated by the geophysical method were eliminated, which were verified by underground drilling. Before mining, the water discharge test was carried out in the Yeqing thin limestone and proved that hydraulic connection between thin limestone aquifers was effectively controlled.

(3) *The Integrity and Stability of Aquiclude under the Working Face Floor.* The distance from coal seam No. 2 to the Yeqing, Shanfuqing, and Daqing limestones and the Ordovician limestone is 37-42 m, 71-76 m, 107 m, and 148 m, respectively. The rock types in the floor strata of the aquiclude are medium fine sandstone, siltstone, shale and mudstone, containing both good plasticity and resistance to seepage of soft rock and good resistance to deformation of the stiff rock. The aquiclude has good stratum integrity in its original state. Through grouting reinforcement, rock strength and stability of the aquifers are also improved.

During tunneling in the working face, a total of 5 faults were exposed, which were all normal faults with displacements of 0.7 to 4.2 m. These faults were all exposed and treated by 7-9 verification holes, and the water resistance of the fault zones was strengthened.

(4) *The Risk Assessment of Water Inrush.* The water inrush risk of mining under pressure in coal seam No.2 can be assessed by the water inrush coefficient in Eq. (2) according to the national regulations.

After zonal grouting, 60 m rocks in the top of the Ordovician limestone could be considered as the aquiclude as analyzed above. Therefore, water inrush coefficient was changed from 0.072 MPa/m to 0.0536 MPa/m, less than the critical value of 0.1 MPa/m required by the regulations. Hence, the coal mining operations were allowed.

(5) *Working Face Water Inflow Prediction.* During the extraction of No. 2602 working face, water from sandstone aquifers above coal seam No. 2 and from thin limestone aquifers under coal seam No.2 may enter the goafs of the working face. Using the analogy method and hydrogeologi-

cal analysis method, the normal water inflow from the roof rocks is 26.5 m³/h, and water inflow from the Yeqing and Shanfuqing limestones is 60 m³/h and 35 m³/h, respectively. The total of inflow is estimated 121.5 m³/h with a maximum of 240 m³/h, which belongs to normal water inflow and safely handled by mining operations.

(6) *Dewatering Capacity of the Working Face in the No. 6 Panel.* There are three dewatering systems in total in the No. 6 panel of the mining area, through examination and verification, and the maximum drainage capacity of system is 600 m³/h, which is 2.5 times of the maximum water inflow estimated in the above section. The dewatering capacity fully satisfies the requirements.

3.4.4. Monitoring Methods for Safe Coal Extraction

- (1) Using the thin limestone aquifers as monitoring indicators, three observation points of boreholes, three long-term observation holes, and dewatering system monitoring points were equipped in upper and lower roadways, respectively, forming a dynamic hydrogeological monitoring system. Monitoring results show that no abnormality occurred during the extraction
- (2) 12 monitoring points of microseismic monitoring system and two monitoring substations were installed in upper and lower roadways and cut-out roadway in the working face. During extraction, two abnormalities occurred but were not hydrogeological abnormalities
- (3) In the process of extraction, the existing mining pressure monitoring system was used to intently monitor the variation of water inflow during the first and periodic abutment pressures and the time when the length and width of mining face are approximately equal, as a supplemental system to monitor the water inflow from the floor strata

4. Conclusion

Through theoretical study on water inrush mechanisms and prevention methods and a systematic case study, the following conclusions are drawn for deep mining under water pressure:

- (1) There are multidimensional characteristics of water inrushes from the coal floor in deep mining, including the water migration upwardly driven by the Ordovician confined water, the planar dispersion of the water inrush channel, the stepped increase of the water inrush inflow, the hysteretic flow of the water inrush time, and the exchange and adsorption of the water quality
- (2) The water inrush mechanism is clarified that the permeability, dilatancy, fracturing, and ascending of the water from the Ordovician limestone aquifer form a

planar and divergent flow by the transfer, storage, and transportation of thin limestone aquifers. The corresponding water inrush risk evaluation method is proposed

- (3) Based on the thickness of the aquiclude, the failure depth of the floor and the Ordovician limestone water conducted zone height, and the water inrush coefficient, the floor aquiclude is classified into five categories: ultra-thin, thin, medium thick, thick, and ultra-thick aquiclude formations. Five prevention models of safe mining under water pressure are proposed correspondingly
- (4) The water disaster prevention method with full time-space tridimensional network in deep coal mining is established. Case study shows that water inrush prevention technologies, including underground large-area grouting and four-dimensional time-space comprehensive water disaster control, can achieve an excellent result

Data Availability

The figure and table data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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