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Research Article

Study on Prevention and Control of Confined Water Hazard in Deep Resource Exploitation: Scientific Basis of "GCD-D" Design

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Deep mining of resources has destroyed the stress balance of original rock, formed water gushing channel, and caused the outburst of confined water, thus causing disaster. At present, "Ground Controlled Directional Bedding Branch Drilling (GCD-D)" grouting has achieved remarkable results in controlling water disasters. However, "what is the scientific design principle of GCD-D?" This key scientific question has not yet been answered by systematic science. According to the regional engineering geology and hydrogeological conditions of North China-type coalfields, this study uses the methods of analogy, theoretical analysis, and model analysis to demonstrate and analyze and obtains six basic principles for the selection of the target layer for the layout of "GCD-D." The design principle of "GCD-D" was put forward for the first time. The results can provide a scientific theoretical basis for the control of confined water disaster in deep mining of North China coalfields.

1. Introduction

The mining area in the eastern margin of North China-type coalfield has entered the stage of deep coal seam mining. The Ordovician limestone strong water-rich aquifer in the basement of North China-type coalfield is a direct or indirect water filling source threatening the deep coal seam mining [1, 2]. At present, the treatment methods of confined water in the floor of deep coal seam mining include drainage and pressure reduction-mining under pressure, curtain closure, and grouting transformation. With the increase of mining depth year by year, the treatment of confined water disaster in the floor of deep coal seam mining is gradually transiting to the comprehensive grouting treatment mode based on "GCD-D" [3].

Directional drilling originated in the United States in the early 20th century. With the needs of oil exploration and production, it has promoted the rapid development of directional drilling technology [4–6]. In the 1950s, the former Soviet Union completed multibranch drilling for the first time [7]. In the sixties and seventies of the 20th century, western countries formed a complete system for the development of drilling tools for directional drilling. The application of computer-aided directional drilling technology in the 1980s marked that directional drilling technology has entered a mature period [5].

The development of domestic directional drilling technology began in the 1950s. The first directional drilling in China was completed in Yumen Oilfield in 1956 [8]. From 1977 to 1982, 316 directional drilling wells were completed in China. After entering the 21st century, domestic directional drilling technology has developed rapidly. In 2005, a "CGDS–I" near-bit geosteering drilling system prototype was developed [9]. After that, the Drilling Technology Research Institute of Shengli Oilfield successfully developed MWD and gamma meter while drilling [10]. Through the continuous efforts of domestic scientific researchers, "GCD-D" has also been widely used in coal mine water control, gas drainage, geothermal wells, and others [11–16].

The high-pressure grouting transformation of surface directional drilling requires a certain degree of pressure resistance of the rock stratum. Therefore, the transformation of deep rock stratum greater than 400 meters has better effects. At present, there are still technical defects in the comprehensive grouting treatment process based on "GCD-D." For example, there are still a lot of scientific problems in the design, process, and mode of grouting treatment that need to be further studied [17]. Based on the methods of theoretical analysis, practice summary, and simulation experiment, this study scientifically demonstrates the design basis of key factors such as the selection of target layer for ground directional bedding hole grouting reinforcement, bedding hole orientation, bedding hole spacing, and grouting pressure and puts forward the "the principle of scientific design of the GCD-D" for the first time.

This achievement has been popularized and used in QJ Coal Mine of North China coalfield. The "the principle of scientific design of the GCD-D" has been used to control the limestone aquifer in the floor of 11# coal seam in this area. The results show that the E1101 coalface, E1102 trial mining face, E1103 coalface, and E1105 coalface have all realized safe mining. The research results will provide a scientific basis for the prevention and control of karst confined water disaster in deep coal seam mining in China.

2. Overview of Research Area

The Carboniferous-Permian coal seams are mainly mined in the North China-type coalfields in China. During the mining process, the water damage of the floor limestone aquifer is generally threatened, and water damage accidents occur from time to time. Floor grouting reinforcement has always been the main engineering and technical means of coal seam mining under pressure [18–21].

The upper Ordovician, Silurian, Devonian, and lower Carboniferous are generally absent in North China-type coalfields, and the Carboniferous-Permian strata directly cover the thick limestone of the Middle Ordovician. The main strata of coal seam floor include limestone and mudstone interbedding of Taiyuan Formation, aluminous mudstone of Benxi Formation, limestone strata of Ordovician Fengfeng Formation, and Majiagou Formation (Figure 1) [22, 23].

According to the stratigraphic structure of North China-type coalfield, the floor disturbance and damage zone is produced after coal mining, and it is easy for the fissure zone to directly conduct the floor aquifer when the aquiclude is thin. At the same time, it is easy for potential vertical water guiding structures such as faults and collapse columns to directly (or indirectly) connect the thin limestone and Ordovician thick limestone aquifers in the floor Taiyuan Formation, resulting in floor water inrush accidents [24, 25].

Most of the mining areas of Shandong QJ Coal Mine Co., Ltd., are located in Qihe County, Dezhou City, Shandong Province. Only a small part of the southwest corner belongs to Dong'e County, Liaocheng City. The mine field is located in the southwest of the North coalfield of the Yellow River. The mining area is 36.14 km^2, and the approved mining elevation is +30 m~-900 m; coal seams 7, 10, 11, and 13 are mainly mined.

The hydrogeological conditions of the 11 coal seams are complex and are seriously threatened by the limestone aquifers of the fourth and fifth roof, Xujiazhuang limestone aquifer, and Ordovician limestone aquifer. Before mining, water drainage and pressure relief shall be carried out for the fourth and fifth ash aquifers of the roof to make the water pressure reach the specified level before mining coal seam 11. Before mining coal seam 11, the floor must be reconstructed to prevent and control the Xujiazhuang limestone aquifer and Ordovician limestone aquifer so that they cannot gush water into the space where coal seam 11 is mined, so as to safely mine coal seam 11.

3. Methodology

3.1. Selection Method of Grouting Target Layer. In order to ensure the water control effect of grouting reinforcement of coal seam floor, the layer to be reinforced must be determined first. If the reinforced layer is too close to the coal seam, there may be a large amount of slurry leakage during the grouting process, which wastes grouting materials and fails to achieve the purpose of reinforcement. If the reinforced layer is too far away from the coal seam, the drilling quantities are large, and the economic cost is unreasonable. If the reinforced layer is too thin, its strength after reinforcement is still insufficient to resist the pressure of water. If the reinforced layer is too thick, more grouting materials may be consumed, which is time-consuming and will affect the mining progress (Figure 2).

3.1.1. Theoretical Analysis. According to the layout of coal mining face and the hydrogeological conditions of coal seam floor aquifer, the direct water-filled aquifer of mining coal seam floor is analyzed. According to the water inrush coefficient method in the detailed rules for water prevention and control in coal mines, the safe and effective water-resisting layer thickness is determined.

Ensure that after the grouting transformation, a limestone aquifer is properly selected as the target layer of the grouting transformation under the condition of meeting the safe and effective aquiclude thickness.

$$M = \frac{P}{T}, \tag{1}$$

where T is the water inrush coefficient (MPa/m). The water inrush coefficient shall not be greater than 0.06 MPa/m in the section where the bottom plate is damaged by structure and shall not be greater than 0.1 MPa/m in the section where the water-resisting layer is complete without fracture structure damage. P is the actual head value borne by the bottom water-resisting layer (MPa/m). M is the thickness of the bottom water-resisting layer (m).

Based on the effective thickness of the aquiclude defined by the water inrush coefficient method in the "Details of Coal Mine Water Prevention and Control," determine the location of the grouting transformation rock layer. At the same time as grouting to transform the target layer, full

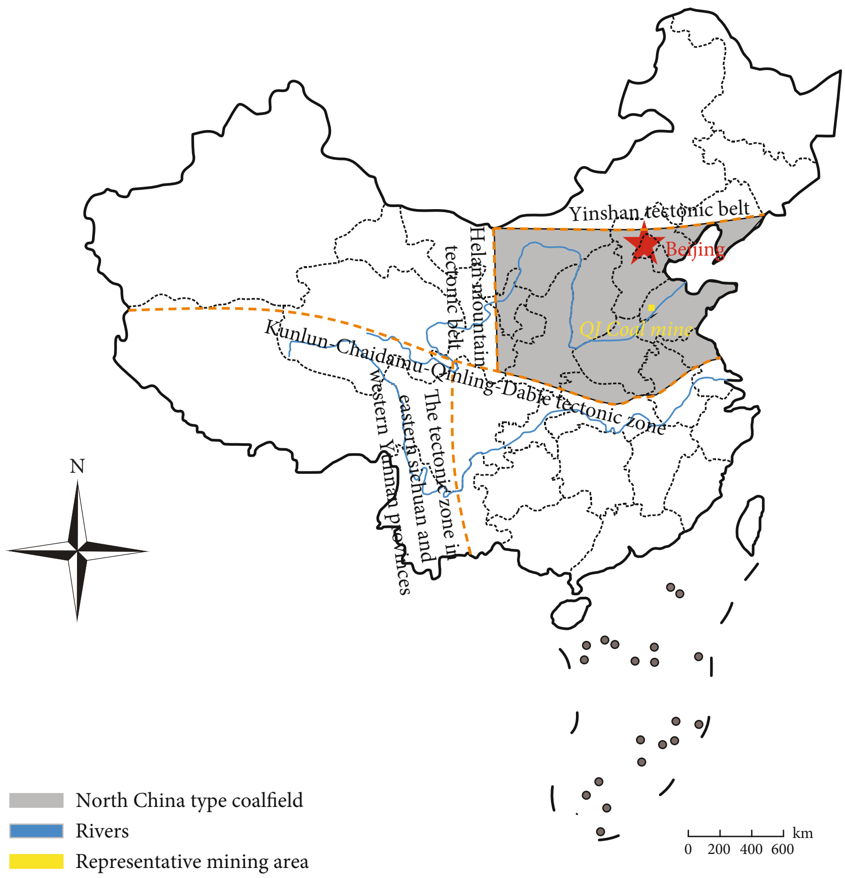

Figure 1: Regional location map of North China-type coalfield.

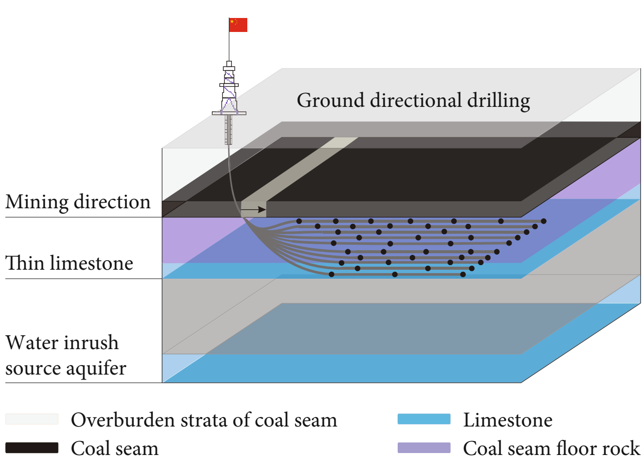

Figure 2: Schematic diagram of grouting transformation target layer of "GCD-D."

coverage grouting should be carried out on similar water conducting channels such as fault structures, fracture zones, and collapse columns that are suspected to have water-conducting effects. After the grouting transformation of the target layer, the water inrush coefficient can be taken as 0.1 MPa/m under the condition that the thickness requirements of the safe water-resisting layer are met, and the faults and other water-conducting geological structures in the study area are completely repaired. At this time, the thickness (M) of the floor aquiclude obtained can not only satisfy the establishment of equation (1) but also meet the requirements of the detailed rules for water prevention and control in coal mines.

3.1.2. Determination of Grouting Reinforcement Target Layer by Analogy Method

(1) Slurry controllability

The fractures of thin limestone aquifer in deep mining coal measure strata are relatively developed, which are easier to be sealed by grouting than other lithologic strata. Compared with single limestone with relatively large thickness, it is easier to control the slurry during reconstruction in thin limestone.

(2) Water storage form of limestone aquifer

The water in limestone aquifer generally exists in fissures or karst cavities, and the grouting plugging effect is good.

(3) Grouting volume

For thin limestone, the grouting amount is relatively controllable. Under the condition of limited grouting amount, the grouting effect is better than that of reconstructing the limestone aquifer with larger thickness. In the reconstruction of thick limestone aquifer, not only a lot of grouting is needed, but also the grouting effect cannot be effectively controlled. For example, the coal bearing base of North China coalfield is Ordovician limestone aquifer, with a thickness of about 700 m. According to the comparative analysis of grouting effects in recent years, there are still some key scientific problems unsolved in the grouting transformation of the top of Ordovician limestone aquifer. For example, the slurry diffusion distance is uncontrollable, the evaluation system of grouting effect is not perfect, and the investigation effect of karst and structural development is not good.

To sum up, when the target layer for grouting transformation is selected for coal measure strata, firstly, according to the six principles of determining the target layer of grouting reinforcement, the formation combination mode is comprehensively analyzed. Secondly, the thickness of the safe water-resisting layer is determined according to the detailed rules for water prevention and control in coal mines. Finally, under the condition of meeting the thickness of the safe water-resisting layer, a thin limestone aquifer is selected for reconstruction.

3.2. Scientific Basis of "GCD-D" Orientation Design. The precise layer control technology of "GCD-D" can be used to pass through the faults and natural fractures in the target layer to the greatest extent, explore the suspected water diversion channel, and penetrate the thin limestone fractures and faults in the bottom plate. Carry out high-pressure grouting on the water channel to block the hydraulic connection with the lower Ordovician limestone aquifer, and transform the thin floor limestone aquifer into an effective aquiclude to prevent the floor aquifer from gushing water to the coalface.

Whether the connection between the strong aquifer and the coal seam can be effectively isolated and the purpose of reconstructing the thin limestone of the floor can be achieved depends on whether the layout direction and spacing of "GCD-D" are reasonable.

This chapter mainly discusses the scientific basis for the azimuth design of "GCD-D."

3.2.1. The Relationship between the Determination of Geological Structure by Analogy and the Selection of Orientation of "GCD-D." The ash karst fissure, fracture zone, fault water-conducting zone, water-rich area, and special vertical water-conducting structure area of Taiyuan Formation in North China-type coalfield are the main channels leading to water inrush in deep mining. In particular, the vertical water-conducting fault and fold axis fracture are the key points for water prevention and control of coal seam floor. They have direct water relations with Ordovician limestone in the downward direction and receive a large amount of supply from Ordovician limestone water. The upward high water pressure and strong water content threaten the mining fracture floor of the coal seam.

The fault and its two sides are often associated with the development of derived structural fissures, which are often the same as the fault strike, forming a structural fault zone. The water-conducting fault zone is not only a water-conducting channel but also a water-collecting gallery, connecting the upper and lower aquifers, with large and stable water inflow. During the formation of folds under the action of horizontal stress, a series of secondary structures are associated and derived, mainly including joints and cleavage structures. Bedding joints are developed on both wings due to strong interlayer shear. Tensile joints are mainly formed on the outside of the turning end due to tension. The core is strongly squeezed, and axial cleavage is developed.

The influence of fault and fold axis should be fully considered when arranging "GCD-D." Fractured floor rock formations have large lateral and longitudinal water guide differentiation. If the horizontal section of a single drill hole is drilled along the vertical fracture trend, there will be fewer fractures connected, which is unfavorable to the water plugging and reinforcement effect of grouting transformation, while drilling along the inclination of vertical fractures can connect more fractures along the axis of faults and folds and obtain better diffusion radius. Therefore, the trajectory of the horizontal section of the borehole should intersect the fault at a large angle as far as possible, and the same should be true for the fracture of the fold axis.

The thin limestone of the coal seam floor has the greatest impact on the safe mining of the coal seam due to the vertical water-guiding fractures and fissures, so the "GCD-D" is used to communicate multiple fractures at a large angle in the horizontal direction, which is the main dominant drilling direction, so as to achieve the grouting purpose of blocking the water guiding channel and transforming the coal seam floor (Figure 3).

3.2.2. Analysis of the Influence of Bedding Plane on the Selection of Borehole Orientation. The purpose of directional near-horizontal bedding grouting for the thin limestone aquifer is firstly to block the water channel such as fault and karst collapse column and secondly to reinforce and transform the thin limestone of the coal seam floor. The fault and "axial fracture strike of fold structure" have important influence on the azimuth design of "GCD-D" horizontal section. In addition, in order to achieve the purpose of grouting reinforcement and reconstruction of the thin limestone aquifer in the coal seam floor, the influence of the weak bedding structural plane of the thin limestone should also be considered. Due to the change of limestone sedimentary environment or the change of sedimentary materials, the bedding structural plane is produced. The bedding plane has low cementation strength and is a weak plane in the stratum. It is often dissolved before the limestone matrix, and the layer connectivity is good. The interlayer dissolution easily forms a fissure water storage space. On the other hand, under the action of tectonic movement, a series of folds will be formed. With the process of forming fold structures, the bedding planes on both wings of the fold will be staggered by interlayer shear, and broken intercalation will be formed in the areas with concentrated stress, which will become the fissure water storage space of limestone.

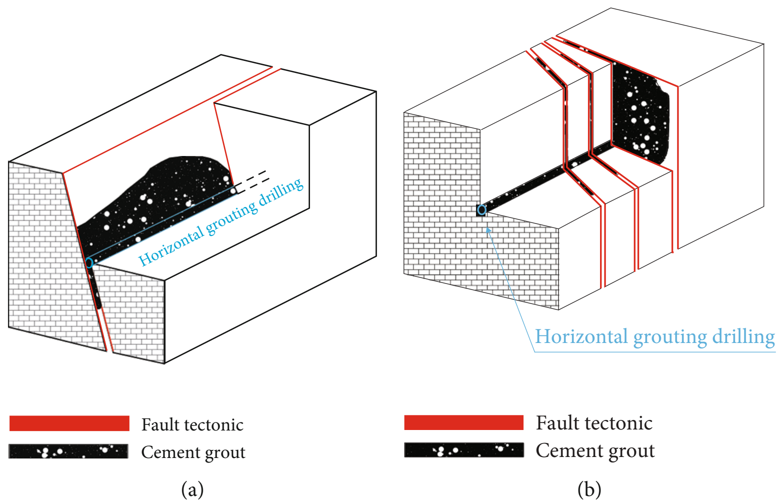

FIGURE 3: Schematic diagram of grouting effect at different intersection angles between ground controlled directional bedding hole orientation and fault.

On the premise that the track of "ground-oriented near-horizontal bedding hole" penetrates the main water-conducting fault of the coal seam floor at a large angle, it should be drilled near horizontal along the grouting target layer as far as possible. A single hole can penetrate multiple bedding structural planes so as to achieve a better grouting reinforcement effect on the interlayer fissures (Figure 4).

3.2.3. Analysis of the Influence of In Situ Stress on the Selection of Borehole Orientation. The in situ stress field is a three-dimensional unequal pressure stress field, which is composed of the vertical self weight stress (σ_v), the maximum tectonic stress (σ_H), and the minimum tectonic stress (σ_h). In most areas, the two tectonic principal stresses are located on the horizontal plane or near the horizontal plane. The maximum horizontal principal stress (σ_H) increases linearly with depth and is generally greater than the self-weight stress (σ_v).

The minimum horizontal principal stress (σ_h) also increases linearly with depth and has a large difference from the maximum horizontal stress (σ_H).

The self-weight stress increases linearly with the increase of depth, which is generally equal to the self-weight of the overlying rock mass. In the mining process of deep mines, according to the size of the stress value, it can be generally divided into two cases: (1) $\sigma_H > \sigma_v > \sigma_h$ and (2) $\sigma_H > \sigma_h > \sigma_v$.

The orientation of the splitting crack produced by high-pressure grouting is basically consistent with the orientation of the maximum principal stress; that is, the included angle between the drilling trajectory of the horizontal section of the grouting borehole and the direction of the maximum horizontal principal stress is very important for the spatial distribution of the splitting crack. According to the relationship between the orientation of the horizontal stage of directional grouting and the orientation of the maximum principal stress, there are two types of splitting cracks after high-pressure grouting under extreme conditions: transverse cracks and longitudinal cracks. If the directional horizontal hole is perpendicular to the direction of the maximum horizontal principal stress, a transverse crack perpendicular to the horizontal hole will occur.

If the direction of the directional horizontal hole is consistent with the direction of the maximum horizontal principal stress, longitudinal cracks extending parallel to the direction of the directional horizontal hole will be generated (Figure 5).

However, in the actual process of directional bedding high-pressure grouting of thin limestone on the floor, due to the complexity of in situ stress orientation, the existence of natural fissures, the bedding staggering rate of thin limestone bedding drilling, and the layout of engineering construction site, it is difficult to make the orientation of grouting directional horizontal hole parallel or vertical to the direction of minimum principal stress, and there is often a certain included angle, thus forming a more complex fracture distribution pattern.

When the included angle between the grouting horizontal hole track and the maximum principal stress axis is small, the overall cleavage fracture is mainly a single fracture with the maximum principal stress axis with long extension and small joint width, and the fracture shape is single, which is not conducive to the purpose of grouting to transform the fractured aquifer.

When there is a large included angle with the maximum principal stress axis, complex fracture morphology will be generated, and multiple single, long, and narrow fractures will be generated near the borehole. Due to the mutual elimination of stress and pressure, multiple fractures close to each other will be generated due to steering during extension away from the wellbore. When the horizontal borehole trajectory is nearly perpendicular to the maximum principal stress axis, T-shaped fractures will often be generated, thus forming a large fracture range. The grouting can effectively fill the fissures of the aquifer.

The existence of natural cracks also has an impact on the cracks produced by high-pressure grouting in horizontal boreholes. The extension direction of the cracks formed by slurry splitting near the borehole may be consistent with or

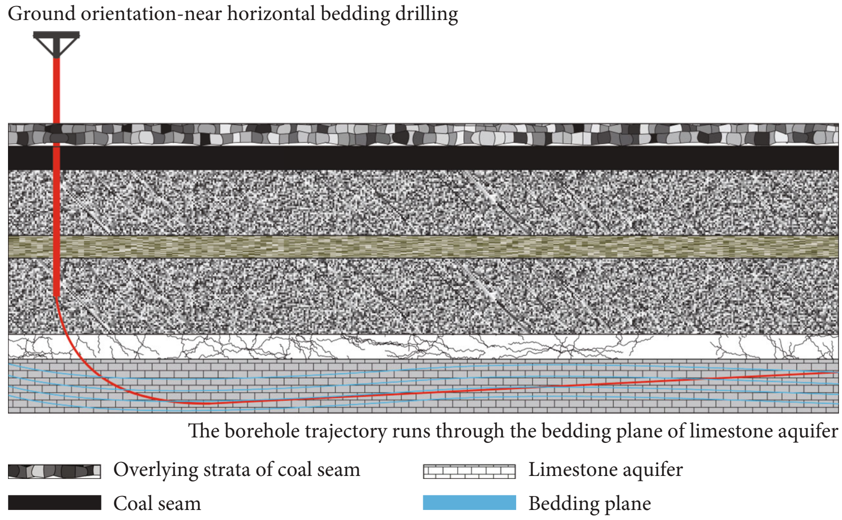

Figure 4: Schematic diagram of directional bedding drilling crossing the bedding plane of thin limestone.

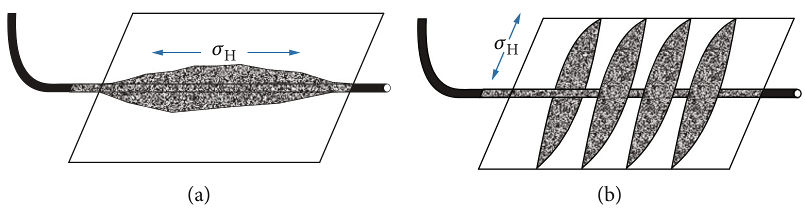

Figure 5: Schematic diagram of fracture orientation under different layout trajectories of horizontal boreholes: (a) longitudinal crack parallel to horizontal borehole extension; (b) transverse crack perpendicular to horizontal borehole.

through the natural cracks, but at a distance from the borehole, the cracks tend to extend to the direction of the minimum principal stress.

Therefore, in order to achieve a better fracture range, communicate more natural fissures, and obtain a better effect of grouting transformation of the target layer, the orientation consistent with the minimum horizontal principal stress axis or with a large included angle is the dominant layout of the horizontal well grouting drilling trajectory.

3.2.4. Analysis of the Influence of Original Rock Hydrodynamic Field in the Reconstruction Layer on the Setting of Bedding Hole Orientation. When the deep coal seam floor limestone aquifer is reformed by splitting grouting, the flow direction of the original rock hydrodynamic field in the reformed layer also has a certain impact on the bedding directional drilling.

In order to effectively fill the natural fissures and karst caves of the aquifer, it is necessary to ensure the effective filling of the bedding grouting slurry. Therefore, in the process of controlled directional drilling on the ground, first of all, the bottom of the deflecting section and the near-horizontal section should be effectively blocked to form a supply water-blocking wall in the flow direction of the original rock hydrodynamic field in the reconstruction layer so as to cut off the supply water from the original rock hydrodynamic field. Secondly, near-horizontal drilling along the trend of the reconstructed layer forms the dynamic coupling between the flow direction of the natural hydrodynamic field and the high-pressure splitting grouting of the surface controlled directional drilling, which promotes the full diffusion of the slurry.

Therefore, in the deep coal seam floor limestone aquifer reconstruction, the bedding directional near-horizontal drilling trajectory should be combined with the influence of the hydraulic field of the reconstruction layer on the orientation setting of the bedding drilling as far as possible, so that the bedding directional near-horizontal drilling can be drilled along the flow direction of the original rock hydraulic field, under the conditions of combining the factors such as faults, fold axis fractures, weak bedding structural planes of the reconstruction layer, and in situ stress, It is also possible that the drilling direction of the bedding hole and the tendency of the reconstruction layer are nearly the same, as shown in Figure 6.

3.3. Scientific Basis for Design of Bedding Hole Spacing and Grouting Pressure. The spacing setting of near-horizontal branch boreholes is based on the physical and mechanical parameters of rock strata, regional structural conditions, grouting pressure threshold, and other parameters and is obtained by numerical simulation test.

In order to ensure the effect of grouting transformation, we can use "RFPA2D-FLOW" to carry out numerical simulation according to the geological and hydrogeological conditions of the transformation layer in the study area and obtain the effective diffusion radius of the slurry under different grouting pressures of the transformation layer in

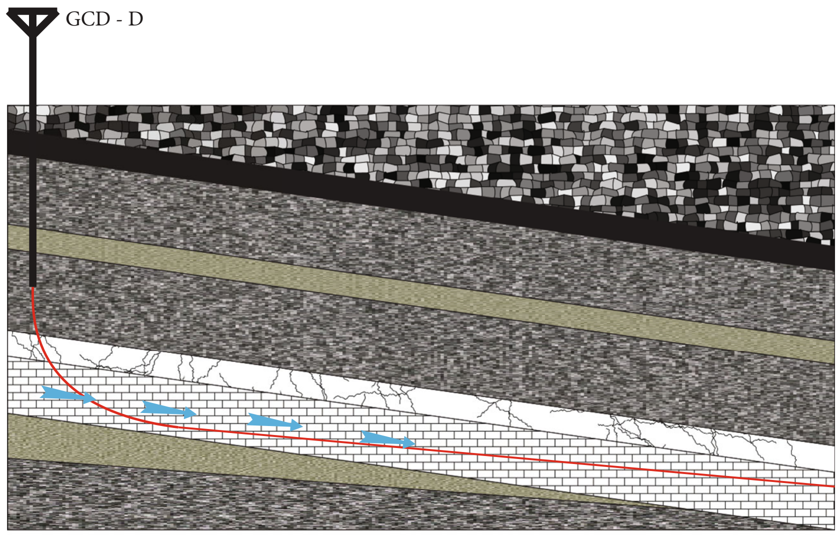

Figure 6: Schematic diagram of directional drilling arranged according to the inclined direction of the transformed rock stratum.

the study area, so as to set the effective grouting pressure of the limestone transformation layer of the deep coal seam floor and the scientific spacing of the bedding boreholes, so as to achieve the purpose of grouting transformation.

In the "RFPA2D-FLOW" analysis system, a numerical calculation model is established. The boundary conditions of the model should simulate the real buried depth conditions. With reference to the measured results of the regional geostress in the study area, the model boundary should consider the self-weight of the rock mass; set the load on the upper boundary; fix the left, right, and lower boundaries of the model; and set the upper and lower boundaries of the model as water-blocking boundaries.

The first step is to run the model to a stable state.

The second step is simulated grouting. In the simulation system, the grouting hole is set in the middle of the reconstruction layer as far as possible, and the grouting simulation under two geological conditions is set.

The first is to simulate the grouting in limestone, and the second is to simulate the grouting under the condition that the bedding grouting borehole passes through the fault. The grouting simulation setting of the two modes is completed in two steps, and the length of the grouting section in each step is 20 m.

The set value of simulated grouting pressure is generally 2.5 times of the water pressure at the grouting point. In order to analyze the diffusion data of slurry in the target layer under the simulated grouting state and in combination with the current mining situation of deep coal seams in the east edge of North China-type coalfield, it is recommended to set 8 MPa, 10 MPa, and 12 MPa grouting pressures, respectively, to simulate the diffusion law of slurry.

Then, set the rock mass parameters of each layer of the model. During the numerical analysis of the model, the setting of model parameters plays an important role in the operation results. In combination with the heterogeneity and other anisotropy of each layer of rock mass in the model, the physical and mechanical property parameters must obey the Weibull distribution, and the correlation between the mechanical properties of micro and macro media is established. At the same time, the Mohr-Coulomb yield criterion is adopted for each layer of rock mass set in the model.

The third step is to run the "RFPA2D-FLOW" analysis system to analyze the system calculation results, so as to obtain the slurry diffusion range in the normal reconstruction layer under the three grouting pressures and the slurry diffusion law under the grouting pressure increasing mode. At the same time, it can also obtain the slurry diffusion range and the slurry diffusion law under the three grouting pressure modes when crossing the fault.

The setting of grouting pressure is determined according to the water pressure value of aquifer. In general, the threshold of grouting pressure should be not less than 2 times of the water pressure of aquifer.

4. Result Analysis

According to the engineering geological and hydrogeological conditions of North China-type coalfield, the demonstration and analysis are carried out based on analogy method, theoretical analysis method, model analysis method, and numerical simulation, and the design principle of "GCD-D" is obtained.

4.1. Selection Principle of Target Layer for Grouting Transformation

(1) After the reinforcement of the target layer, it shall meet the requirements of the detailed rules for water

prevention and control in coal mines and the water inrush coefficient of the floor water inrush risk assessment formulated by each mining area

(2) The distance from the target layer to the coal seam floor should be greater than the thickness of the fracture zone formed by the propagation of the mine pressure to the floor

(3) The reinforced stratum has strong injectability, and the slurry can diffuse in a large area in the stratum. Under the condition of high-pressure grouting, the slurry loss rate is low, and the slurry utilization rate is high

(4) After the reinforcement, the physical and mechanical properties of the floor strata can be effectively changed, the strength and water resistance can be improved, and the water inrush can be effectively prevented

(5) The auxiliary work quantity is small, and the grouting drilling work quantity is small

(6) Above the aquifer threatening safe mining or the top boundary of Ordovician limestone aquifer shall be reconstructed by layers

Based on the above six principles, determine the target layer for grouting transformation of coal seam floor water hazard prevention and control. The location of the grouting target layer should be selected below the mining failure zone of the coal seam floor and above the Ordovician limestone aquifer. Alternatively, the top boundary of the Ordovician limestone aquifer can be directly selected as the target layer for grouting transformation.

4.2. Scientific Basis of "GCD-D" Orientation Design

4.2.1. Influence of Fault Structure on Selection of Borehole Orientation

(1) Method

The track of "GCD-D" shall be drilled near horizontal along the grouting target layer (upper and lower small angle waveform drilling), and a single hole can be penetrated by multiple bedding structural planes.

(2) Principle

When the near-horizontal grouting hole intersects with the fault structure at a large angle or vertically, it can cover multiple fault cracks or multiple cracks for grouting reconstruction, which can improve the utilization rate of a single grouting hole.

On the premise that the track of "GCD-D" penetrates the main water-conducting fault of the coal seam floor at a large angle, it should be drilled near horizontal along the grouting target layer as far as possible. A single hole can penetrate multiple bedding structural planes and achieve a good grouting reinforcement effect on the interlayer fissures.

4.2.2. Influence of Bedding Plane on Selection of Borehole Orientation

(1) Method

The track of "GCD-D" shall be drilled near horizontal along the grouting target layer (upper and lower small angle waveform drilling), and a single hole can be penetrated by multiple bedding structural planes.

(2) Principle

The track of "GCD-D" should be drilled near horizontal along the grouting target layer as far as possible on the premise that the main water-conducting fault of the coal seam floor is intersected at a large angle. A single hole can be intersected with multiple bedding structural planes to achieve a better grouting reinforcement effect for the interlayer cracks.

4.2.3. Influence of In Situ Stress on Selection of Borehole Orientation

(1) Method

Under the condition of three-dimensional complex in situ stress field, in order to achieve a large fracture range by high-pressure splitting grouting, connect with more natural fissures, and obtain better grouting transformation effect, the borehole trajectory of bedding grouting in deep rock strata should intersect with the direction of the maximum horizontal principal stress as much as possible.

(2) Principle

When the angle between the bedding grouting borehole trajectory and the maximum principal stress is small, the split grouting crack is dominated by the maximum principal stress axial single crack with small crack width, the shape is relatively single, and the controlled range of the split grouting crack is small as a whole, which is not conducive to the bedding grouting transformation of the fissure aquifer.

However, when the bedding path of "GCD-D" intersects with the maximum principal stress at a large angle, multiple single long and narrow fractures will be generated near the bedding hole, and when the intersection angle of the two approaches the vertical state, the "+" and "T" fracture distribution will generally be formed, thus forming a large fracture range.

Some of the fractures can be connected with the natural fractures near the bedding hole, so that the slurry can fully fill the fractures of the aquifer.

4.2.4. Influence of Original Rock Hydrodynamic Field in Reformed Layer on Orientation Setting of Bedding Hole. The trajectory of "GCD-D" in the reconstruction of limestone aquifer at the bottom of deep coal seam should be combined with the influence of the hydrodynamic field of the reconstruction layer on the orientation setting of bedding drilling, so that the "GCD-D" can be drilled along

Table 1: Numerical simulation results of slurry diffusion range.

Simulated grouting pressure (MPa)	Simulated diffusion radius of Xuhui aquifer (m)
8 MPa	27.86 m
10 MPa	46.75 m
12 MPa	51.28 m

Table 2: Spacing of bedding boreholes.

Grouting pressure (MPa)	Spacing of bedding boreholes in Xujiazhuang limestone aquifer (m)
8 MPa	≤55.72 m
10 MPa	≤93.50 m
12 MPa	≤102.56 m

the flow direction of the original rock hydrodynamic field, which is also that the drilling direction of bedding drilling should be nearly consistent with the tendency of the reconstruction layer.

4.3. Scientific Basis for Design of Bedding Hole Spacing and Grouting Pressure. The "RFPA2D-FLOW" simulation system is used to conduct grouting simulation test on the Xujiazhuang limestone aquifer of the working face floor in the study area. The grouting diffusion radius is shown in Table 1.

The bedding hole spacing of "GCD-D" shall not be greater than 2 times of the slurry diffusion radius. At the same time, based on the comprehensive consideration of the karst development degree, the existence of hidden structures, the supply of Ordovician limestone water in the strong water-rich aquifer, the efficient utilization of boreholes, and the economic rationality, it is determined that the design of the bedding hole spacing and grouting pressure for the grouting reconstruction of the Xujiazhuang limestone aquifer in the floor of the first mining area of coal seam 11 in QJ Coal Mine should meet the requirements shown in Table 2.

5. Conclusion

In this study, the selection principle of the target layer for grouting transformation, the scientific basis for the design of the layout orientation of bedding boreholes, the spacing of bedding boreholes, and the scientific basis for the design of grouting pressure are obtained.

The research results can provide a theoretical basis for the prevention and control of high-pressure water disasters in deep resource exploitation.

(1) The paper puts forward six basic principles for selecting the target layer of grouting transformation for water disaster prevention of coal seam floor and the basis for arranging the spacing of branch boreholes along the layer

(2) The relationship between the ground stress, regional structure, bedding plane, original rock hydrodynamic field, and other factors on the orientation of the ground directional bedding hole layout is obtained, and the scientificity of the orientation of bedding hole layout is further optimized

Data Availability

The data used to support the findings of this study are available from the author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

The first author is Yanbo Hu.

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