

Classification of Karst Water Disasters beneath the Lower Coal Group and Prevention and Control Technologies in the Huaibei and Huainan Coalfields

Zhigang Xie¹, Feng Han¹, Shancheng Chen¹, Hai Ding¹, Guangquan Xu², Haitao Zhang²

¹Exploration Research Institute, Anhui Provincial Bureau of Coal Geology, Hefei, China

²School of Earth and Environment, Anhui University of Science and Technology, Huainan, China

Email: 406535191@qq.com

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Abstract

The karst water disasters pose a significant threat to the safe mining of the lower coal group in the Huaibei and Huainan Coalfields. Based on the karst hydrogeological characteristics, the classification of karst water disasters and the prevention and control technologies were studied. Results show that the floor of the lower coal group in the Huaibei and Huainan Coalfields comprises a sequence of karst aquifers, including (from top to bottom) the C₃I, C₃II, and C₃III groups of the Taiyuan Formation and the Ordovician System (referred to as “C₃I”, “C₃II”, “C₃III” and “O”, respectively). On the basis of the degree of hydraulic connectivity, water yield property, permeability, and drainability, the karst aquifer system beneath the lower coal group is divided into a three-layer structure: the C₃I-C₃II aquifer, the lower aquiclude of the Taiyuan Formation, and the C₃III-O aquifer. Based on the differences in aquifer characteristics and water-filling type between the C₃I-C₃II and C₃III-O aquifers, karst water disasters are classified into two types: direct water inrush from thin-bedded limestone (DT-type) and indirect water inrush from thick-bedded limestone (IT-type). Furthermore, due to the contrasting drainability of the C₃I-C₃II aquifer in the Huaibei and Huainan Coalfields, the DT-type is subdivided into the drainable type (D-type) and the undrainable type (U-type). For three types of karst water disasters, three typical prevention and control technologies are proposed: dewatering and depressurization of the aquifer (DDA), grouting reinforcement of the aquifer (GRA), and grouting and sealing of water-conducting channels (GSC). DDA is a direct approach applicable to the C₃I-C₃II aquifer in the Huainan Coalfield. GRA is also a direct approach, characterized by full coverage, and applicable to the C₃I-C₃II aquifer in the Huaibei Coalfield. GSC is

an indirect approach, focused on detecting and sealing water-conducting channels, and applicable to the C₃III-O aquifer in the Huaibei and Huainan Coalfields. The technologies described above are also applicable to other coalfields with similar geological and hydrogeological conditions in North China.

Keywords

Huaibei and Huainan Coalfields, Karst Water Disaster, Prevention and Control Technology, Dewatering and Depressurization, Grouting Reinforcement, Grouting and Sealing

1. Introduction

The Huaibei and Huainan Coalfields, located in the north of Anhui Province, constitute a nationally planned 100-million-ton coal production base and a major coal-fired power generation hub (Ministry of Land and Resources of the People's Republic of China, 2016). In 2025, the raw coal output of the Huaibei and Huainan Coalfields exceeded 100 million tons (Anhui Provincial Bureau of Statistics & Survey Office of the National Bureau of Statistics in Anhui, 2026), providing significant support for the national energy security framework.

The main mineable coal seams in the Huaibei and Huainan Coalfields are hosted in Permian strata. Among them, the lower coal group in the Shanxi Formation (Coal 6, Coal 8, and Coal 10 in the Huaibei Coalfield; Coal 1 and Coal 3 in the Huainan Coalfield) is thick and of excellent quality, with exploitable resource reserves accounting for approximately 20% of the total identified coal resources in the coalfields (Chen et al., 2023; Li et al., 2023; Yang et al., 2023).

However, the karst hydrogeological conditions of the lower coal group floor are complex. The karst aquifers in the Taiyuan Formation, Ordovician, and Cambrian Systems exhibit significant thickness, high confinement pressure, and strong water-yielding capacity characteristics. Furthermore, the development of karst fissures within aquifers displays pronounced heterogeneity, posing a serious threat to the safe mining of the lower coal group (Yin et al., 2021; Zeng et al., 2023). In particular, the development of karst collapse columns, faults, and water-conducting fracture zones further complicates the prevention and control of karst water disasters. Historically, the Renlou, Taoyuan, and Pan'er Coal Mines have suffered multiple floor karst water inrush incidents (Gan, 2018; Yin et al., 2019; Zhang et al., 2022), leading to casualties and substantial economic losses.

The problem of karst water disaster beneath the lower coal group in the Huaibei and Huainan Coalfields has always been a hot spot and focus of research both domestically and internationally. Since the 1960s, research has been conducted on karst development characteristics (Hu, 2016; Xu et al., 2016; Yang et al., 2024), hydrological dynamics of aquifers (Gao et al., 2021; Yao et al., 2025), and the evaluation of the drainability of karst-fissured aquifers (Wei et al., 2023; Xie, 2013; Zhang, 2016). Based on the experience in preventing and controlling karst water

disasters in other mine districts within the North China-type coalfields (Dong, Wang, & Zhang, 2019; Zhang et al., 2020; Zhao et al., 2016), combined with the karst hydrogeological conditions of the Huaibei and Huainan Coalfields, optimization of target strata for ground regional treatment (Xie et al., 2023; Zheng, 2018), determination of branch borehole spacing (Gao, Xie, & Zhang, 2023), control mode (Zhang et al., 2025), optimization of grouting parameters (Zhou, 2015), prediction methods for grouting volume (Xie et al., 2025), evaluation methods for control effectiveness (Xu et al., 2023), and other aspects were systematically studied, with innovations and reforms being implemented. At present, many mines in the Huaibei and Huainan Coalfields adopt the method of ground regional treatment to prevent and control the karst water disasters and have achieved good treatment effects (Liu, 2020; Liu, Liu, & Rui, 2024; Luo et al., 2022).

Based on the characteristics of karst hydrogeological conditions, a comprehensive prevention and control mode for karst water disasters in the Huaibei and Huainan Coalfields has gradually taken shape through technologies such as dewatering and depressurization, as well as ground regional treatment. This mode marks a strategic shift from post-incident remediation to source prevention, and from localized treatment to regional governance. These technological achievements offer valuable insights and references for preventing and controlling karst water hazards in similar coal mines.

2. Geological Setting

The Huaibei and Huainan Coalfields are located in the southeast corner of the Permian Coal-accumulating Depression in North China. They belong to the Xu-Huai Stratigraphic Subregion of the Huang-Huai Stratigraphic Region in the North China Stratigraphic Superregion. The strata, in ascending order, are the Cambrian, Ordovician, Carboniferous, Permian, Jurassic, Paleogene, Neogene, and Quaternary Systems. The main coal-bearing strata range from the Permian Shanxi Formation to the Upper Shihhotse Formation, with the lower coal group located within the Permian Shanxi Formation. The floor of the lower coal group successively includes the Taiyuan and Benxi Formations of the Carboniferous System, as well as the Laohushan, Majiagou, Xiaoxian, and Jiawang Formations of the Ordovician System. This stratigraphic configuration classifies the Huaibei and Huainan Coalfields as part of the karst fissure water disaster zone typical of the Carboniferous-Permian Coalfields in North China (Hu & Tian, 2010).

The Huaibei and Huainan Coalfields are located in the Xu-Huai Coal-bearing Tectonic Belt of the North China Coal-bearing Area. They are bounded by the Tan-Lu Fault Zone in the east, the Yingshang-Dingyuan Fault in the south, and extend beyond the provincial boundary to the north and west (Figure 1(a)). According to the characteristics of tectonic deformation during the Yanshanian period and overburden strata, the Huaibei and Huainan Coalfields are divided into three main tectonic units: the Huaibei Fault-Depression Belt, the Bengbu Fault-Uplift Belt, and the Huainan Fault-Fold Belt.

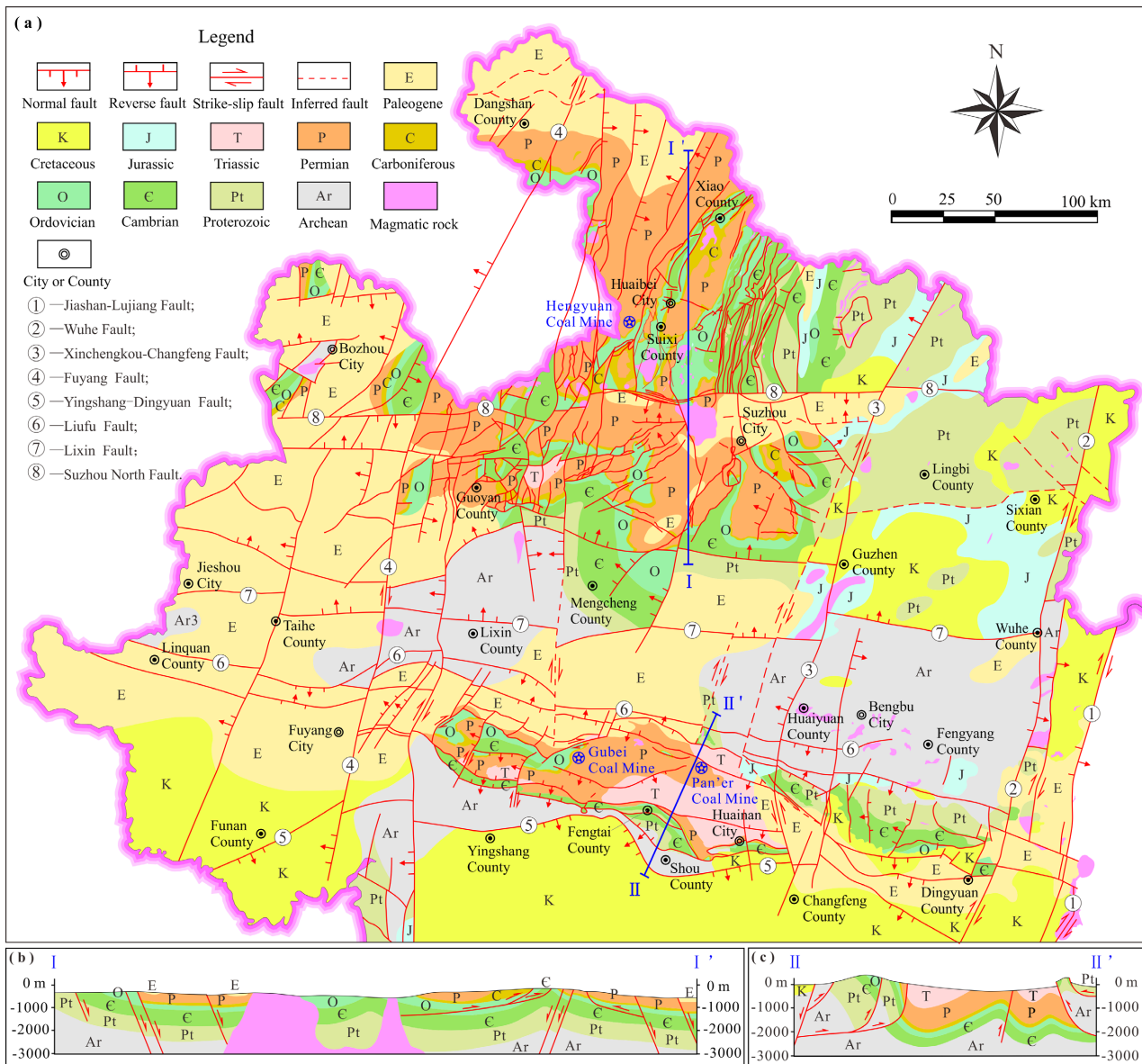


Figure 1. Bedrock geological map of the Huaibei and Huainan coalfields.

The Huaibei Coalfield is situated within the Huaibei Fault-Depression Belt, with its southern boundary demarcated by the Lixin Fault adjoining the Bengbu Fault-Uplift Belt (**Figure 1(a)**). The structure in the area is affected by the east-west, northeast, and Xuzhou-Suzhou Arcuate Structures, among which the east-west and north-east structures constitute the main structural pattern. Due to the superposition of multi-stage tectonic movements, the east-west and north-northeast major faults in the area crisscross vertically and horizontally, forming a network of fault block structures (**Figure 1(b)**).

The Huainan Coalfield is situated within the Huainan Fault-Fold Belt. Its northern part is adjacent to the Bengbu Fault-Uplift Belt, bounded by the Liufu Fault, and its southern part is connected with the Hefei Depression, with the Yingshang-Dingyuan Fault as the boundary (**Figure 1(a)**). The structure in the

area is controlled by the Bengbu Uplift in the north and a thrust nappe in the south, forming a large-scale synclinorium that trends northwestward. The synclinorium comprises several secondary folds with gentle and broad geometries, hosting Carboniferous and Permian coal-bearing strata overlain by Cenozoic unconsolidated strata (**Figure 1(c)**).

In the Huaibei and Huainan Coalfields, approximately 260 boreholes penetrated the carbonate strata of the Taiyuan Formation, and 80 boreholes penetrated the carbonate strata of the Ordovician System. In addition, a considerable number of boreholes did not completely penetrate these carbonate sequences. Based on these boreholes, over 810 pumping and injection tests were conducted, including 630 tests in the Taiyuan Formation and 180 tests in the Ordovician System. These boreholes are distributed across the entire study area, and the stratigraphic data, hydrogeological parameters, and groundwater level data derived from them provide a solid foundation for this study. Three coal mines—Pan'er, Hengyuan, and Gubei—employing different prevention and control technologies for karst water disasters, were selected as case studies for detailed analysis.

3. Hydrogeological Characteristics

The floor of the lower coal group in the Huaibei and Huainan Coalfields successively hosts the Permian Shanxi Formation, Carboniferous Taiyuan Formation, Benxi Formation, and Ordovician strata. Among these, the Taiyuan Formation and Ordovician karst aquifers constitute the primary water-filled aquifers affecting the mining of the lower coal group.

3.1. The Taiyuan Formation Karst Aquifer

The Taiyuan Formation in the Huaibei and Huainan Coalfields is primarily composed of a set of marine-continental alternating sequences, with lithologies predominantly consisting of gray to dark gray crystalline limestone, bioclastic limestone, as well as dark gray sandy mudstone, shale, sandstone, and coal.

The thickness of the Taiyuan Formation ranges from 88.34 m to 209.9 m. Specifically, in the Huainan Coalfield, it varies between 88.34 m and 160.19 m, averaging approximately 120 m; whereas in the Huaibei Coalfield, it ranges from 135.00 m to 209.90 m, with an average of about 160 m.

Additionally, the Taiyuan Formation generally contains 10 to 13 layers of limestone (designated L1 to L13, respectively), and in some areas, the number of limestone layers can reach as many as 15. The total thickness of limestone ranges from 40 m to 70 m. Among these, L3, L4, and L12 are stable in spatial distribution and relatively thick, serving as key marker beds of the Taiyuan Formation (**Figure 2**). The Taiyuan Formation aquifer can be divided into the C₃I, C₃II, and C₃III groups from top to bottom, each containing 3 to 6 layers of limestone.

The specific well yield of the Taiyuan Formation in the Huaibei and Huainan Coalfields ranges from 0.000009 to 11.4 L/(s·m), indicating water-yielding capacity from weak to extremely strong and reflecting heterogeneous development of

karst fractures. There are obvious differences in water yield properties among different groups of the Taiyuan Formation.

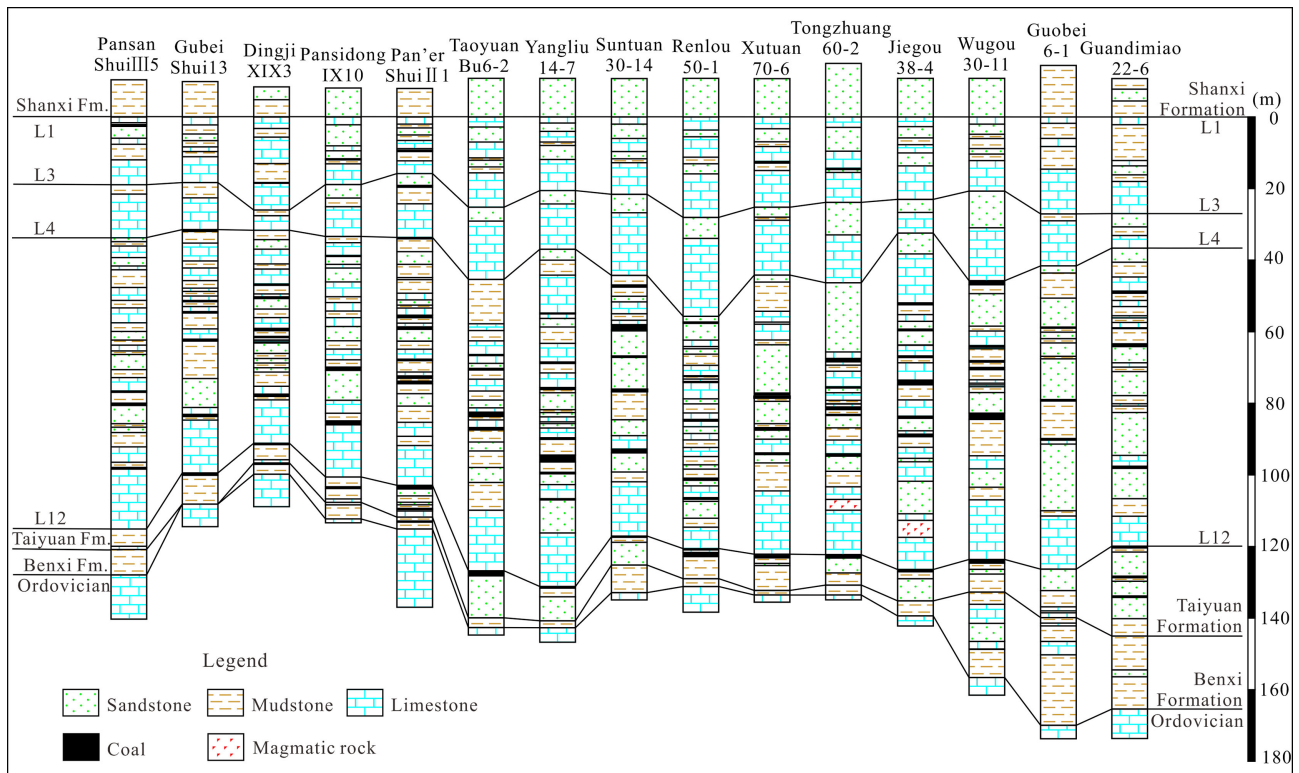


Figure 2. Comparison of carboniferous strata in Huaibei and Huainan coalfields.

The C₃I group contains four layers of limestone (L1 to L4), with specific well yield ranging from 0.000009 to 4.146 L/(s·m) and hydraulic conductivity ranging from 0.000042 to 5.22 m/d, exhibiting weak to strong water-yielding capacity, classified as impermeable to medium-permeable rock layers.

The C₃II group contains six layers of limestone (L5 to L10), with specific well yield ranging from 0.00013 to 0.002 L/(s·m) and hydraulic conductivity ranging from 0.0002 to 0.008 m/d, exhibiting weak water-yielding capacity, classified as impermeable to micro-permeable rock layers.

The C₃III group contains three layers of limestone (L11 to L13), with specific well yields ranging from 0.000045 to 11.4 L/(s·m) and hydraulic conductivity ranging from 0.0002 to 1.548 m/d, exhibiting weak to extremely strong water-yielding capacity, classified as impermeable to medium permeable rock layers.

Under the influence of depositional environments and tectonic movements, significant differences exist in the water yield property of the Taiyuan Formation karst aquifer between the Huaibei and Huainan Coalfields.

Due to tectonic movement and denudation, the Huaibei Coalfield is divided into several independent coal-accumulating units (**Figure 1(a)** and **Figure 1(b)**). The hydrogeological system is hydrologically open, with recharge sources including lateral recharge, areal precipitation, and vertical recharge from the overlying

basal Cenozoic aquifer. Consequently, the karst aquifer has relatively abundant recharge conditions, with specific well yield ranging from 0.0034 to 11.4 L/(s·m) and water-yielding capacity ranging from weak to extremely strong.

The Huainan Coalfield is structurally dominated by a synclinorium in the middle, with thrust nappe on both the northern and southern sides (Figure 1(c)). The hydrogeological system is hydrologically closed, and recharge of the karst aquifer mainly depends on lateral recharge, with only local bedrock outcrop areas receiving vertical recharge from the basal Cenozoic aquifer. Therefore, the recharge conditions are relatively poor, with specific well yield ranging from 0.000045 to 2.521 L/(s·m), and water-yielding capacity ranging from weak to strong.

3.2. The Ordovician Karst Aquifer

The Ordovician strata in Huaibei and Huainan Coalfields are mainly composed of gray, dense, thick-bedded cryptocrystalline and fine-crystalline dolomitic limestone and calcitic dolomite, exhibiting purity, hardness, and brittleness. Locally, breccia is present with purplish red and grayish green argillaceous bands (Figure 3). Additionally, the strata exhibit significant thickness variations, ranging from 150 to 250 m in the Huainan Coalfield and from 200 to 500 m in the Huaibei Coalfield.

Stratigraphic system			Thickness /m	Lithology	Lithological characteristics
System	Series	Formation			
Ordovician	Middle	Laohushan	HB:34~50 HN:10~15		Calcitic dolomite : light gray to gray, medium-to thick-bedded, with thin limestone.
		Lower	Majiagou	HB:150~207 HN:56~147	
					Calcitic dolomite : gray, thick-bedded, local phase change dolomite.
					Dolomitic limestone : gray, thick-bedded, locally containing flint nodules (bands).
	Xiaoxian		HB:157~250 HN:80~120		Argillaceous limestone : yellow, thin-bedded, with a small amount of dark gray argillaceous bands.
					Dolomitic limestone : gray to gray yellow, thick-bedded, local dolomitic content is higher.
					Dolomite : gray-white, medium-to thick-bedded, with thin limestone.
				Argillaceous limestone : gray, thick-bedded, with grayish green argillaceous bands.	
				Limestone : gray to grey-green, thick-bedded, aluminum-containing, with gray-green argillaceous bands.	
				Breccia limestone : micro-bedding development, Huainan coalfield is characterized by high magnesium carbonate rock.	
	Jiawang	HB:4~19 HN:4~34		The purple, yellow-green shale and dolomitic limestone are interbedded, and the dolomitic limestone in Huainan coalfield is slightly higher.	

Note : HB stands for Huaibei Coalfield, and HN stands for Huainan Coalfield.

Figure 3. Comprehensive histogram of the Ordovician system in the Huaibei and Huainan coalfields.

The Ordovician limestone in the Huaibei and Huainan Coalfields exhibits pronounced karstification with reticulate fracture networks, locally developed karst fractures, and calcite vein fillings.

The Ordovician karst aquifer in the Huaibei Coalfield exhibits a specific well yield of 0.000364 - 19.445 L/(s·m) and a hydraulic conductivity of 0.000095 - 70.475 m/d. In the Huainan Coalfield, the specific well yield ranges from 0.000119 to 13.732 L/(s·m), with hydraulic conductivity ranging from 0.00004 to 9.233 m/d.

The results indicate a water-yielding capacity ranging from weak to extremely strong, reflecting extreme heterogeneity in karst fracture development.

Accordingly, the rock units are classified as impermeable to strongly permeable. The Ordovician strata are widely exposed in areas such as Xiangshan, Jiagou, and Laohu Mountain in Huaibei Coalfield, as well as Bagong Mountain and Shungeng Mountain in Huainan Coalfield, where they receive direct recharge from atmospheric precipitation. Additionally, extensive bedrock outcrops of Ordovician limestone exist across the Huaibei and Huainan Coalfields, allowing for vertical recharge from the basal Cenozoic unconsolidated aquifer (**Figure 1**).

Given its large thickness, relatively strong water-yielding capacity, and favorable recharge conditions, the Ordovician limestone constitutes a serious mining hazard for the lower coal group. Statistical data show that Ordovician karst water is the primary source of karst water inrush during mining of the lower coal group in the Huaibei and Huainan Coalfields.

4. Classification of Karst Water Disasters

4.1. Basis for Classification

Comprehensive analysis of the karst geological characteristics reveals that the floor of the lower coal group in Huaibei and Huainan Coalfields consists of a sequence of karst aquifers. From top to bottom, these are the C₃I, C₃II, and C₃III groups of the Taiyuan Formation (referred to as “C₃I”, “C₃II”, “C₃III”, respectively), and the Ordovician System (“O” for short).

The hydrogeological exploration in Huaibei and Huainan Coalfields reveals strong hydraulic connections and similar water yield and permeability characteristics between the C₃I and C₃II aquifers. In the relatively enclosed hydrogeological system of the Huainan Coalfield, the C₃I and C₃II aquifers exhibit dominant static reserves with poor recharge conditions, resulting in high drainability; in contrast, the Huaibei Coalfield features an open hydrogeological system where the C₃I and C₃II aquifers are characterized by low drainability due to abundant recharge and active runoff. In addition, a strong hydraulic connection and similar hydrogeological characteristics are also observed between the C₃III and O aquifers. Given the large thickness and superior recharge conditions of these aquifers, the C₃III and O aquifers exhibit low drainability (**Table 1**).

Based on aquifer indexes, such as the degree of hydraulic connectivity, water yield property, permeability, and drainability, the karst aquifer system beneath the lower coal group in the Huaibei and Huainan Coalfields is divided into a three-layer structure: the C₃I-C₃II aquifer, the lower aquiclude of the Taiyuan Formation, and the C₃III-O aquifer (Xie et al., n.d.), as shown in **Figure 4**.

The C₃I-C₃II aquifer contains 10 layers of thin-bedded limestone. Of these, the L1 - L2 and L5 - L10 layers generally exhibit thicknesses below 5 m with weak water-yielding capacity (Wu et al., 2015; Xie et al., n.d.; Yang, 2015; Zhao, 2015), posing no threat to mining of the lower coal group. In contrast, the L3 and L4 layers typically range from 5 to 10 m in thickness with weak to strong water-yield-

ing capacity (Wu et al., 2015; Xie et al., n.d.; Yang, 2015; Zhao, 2015), serving as the direct water-filling aquifer for the mining of the lower coal group.

Table 1. Comparison of hydrogeological characteristics of karst aquifers beneath the lower coal group (Wu et al., 2015; Xie et al., n.d.; Yang, 2015; Zhao, 2015).

Aquifer	Water yield property	Permeability	Drainability	Hydraulic connection
C ₃ I	Weak to strong	Impermeable to medium-permeable	Huainan Coalfield: drainable; Huaibei Coalfield: undrainable	Strong hydraulic connection with C ₃ II
C ₃ II	Weak	Impermeable to micropermeable	Huainan Coalfield: drainable; Huaibei Coalfield: undrainable	Strong hydraulic connection with C ₃ I
C ₃ III	Weak to extremely strong	Impermeable to medium-permeable	Undrainable	Strong hydraulic connection with O
O	Weak to extremely strong	Impermeable to strongly permeable	Undrainable	Strong hydraulic connection with C ₃ III

The C₃III-O aquifer is primarily composed of thick-bedded limestone. Specifically, the L11 and L13 layers exhibit thicknesses below 5 m with weak water-yielding capacity; whereas both the L12 layer and Ordovician limestone exceed 10 m in thickness with water-yielding capacity ranging from weak to extremely strong (Wu et al., 2015; Xie et al., n.d.; Yang, 2015; Zhao, 2015). Owing to the considerable vertical separation from the lower coal group, the C₃III-O aquifer presents negligible direct hydrogeological risk to mining operations. However, under specific structural conditions, such as hydraulically conductive karst collapse columns or faults, it may function as an indirect water-filling aquifer during extraction of the lower coal group.

The lower aquiclude of the Taiyuan Formation, situated between the C₃I-C₃II and C₃III-O aquifers, has an average thickness of 17 m. Its lithology is predominantly mudstone, with a rock compressive strength generally exceeding 30 MPa, classifying it as moderately hard to hard rock. Owing to its considerable thickness and high compressive strength, it effectively blocks hydraulic connectivity between the C₃I-C₃II and C₃III-O aquifers.

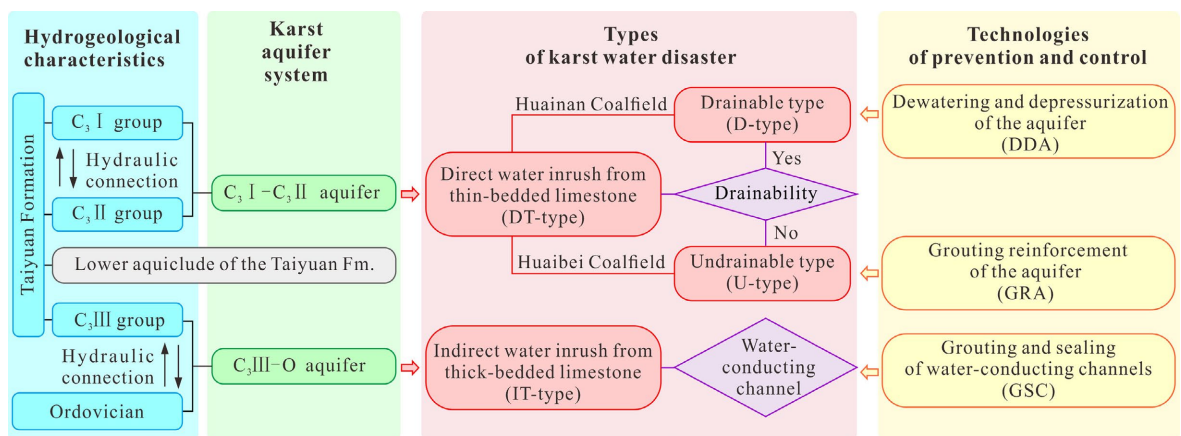


Figure 4. Classification of karst water disasters and prevention and control technologies in Huaibei and Huainan coalfields.

4.2. Types of Karst Water Disasters

Based on the differences in aquifer characteristics and water-filling type between the C₃I-C₃II and C₃III-O aquifers, karst water disasters in Huaibei and Huainan Coalfields are classified into two types: direct water inrush from thin-bedded limestone (termed “DT-type”) and indirect water inrush from thick-bedded limestone (termed “IT-type”), as shown in **Figure 4**.

1) DT-type karst water disaster

For DT-type karst water disaster, the primary target for prevention and control is the C₃I-C₃II aquifer. As a direct water-filling aquifer with a thin-bedded nature, the C₃I-C₃II aquifer is generally managed through direct intervention methods, such as dewatering and depressurization, as well as grouting reinforcement.

Based on the contrasting drainability of the C₃I-C₃II aquifer in Huaibei and Huainan Coalfields, this type of karst water disaster is further subdivided into the drainable and undrainable types (referred to as “D-type” and “U-type”, respectively), as illustrated in **Figure 4**.

The C₃I-C₃II aquifer in Huainan Coalfield is drainable (Xie et al., n.d.), belonging to a D-type karst water disaster. For such disasters, dewatering and depressurization of the aquifer (“DDA” for short) can be adopted, involving the construction of a dewatering roadway underground to dewater and depressurize the aquifer, thereby effectively preventing and controlling karst water inrush.

The C₃I-C₃II aquifer in the Huaibei Coalfield is undrainable and belongs to a U-type karst water disaster (Wu et al., 2015; Zhao, 2015). For such disasters, grouting reinforcement of the aquifer (“GRA” for short) can be implemented through a ground regional treatment method, involving multi-branch horizontal borehole grouting to reinforce the aquifer, enhance the compressive strength of the floor, and thereby effectively prevent and control karst water inrush.

2) IT-type karst water disaster

For IT-type karst water disaster, the main target for prevention and control is the C₃III-O aquifer. As an indirect water-filling aquifer with a thick-bedded nature, the C₃III-O aquifer is typically addressed through an indirect control strategy, i.e., grouting and sealing of water-conducting channels.

Since the development degree of water-conducting channels determines the necessity and approach to the prevention and control of such disasters, the precise identification of water-conducting channels becomes the critical pathway for their prevention and control.

Once the water-conducting channels are confirmed, grouting and sealing of water-conducting channels (“GSC” for short) is generally adopted through a ground regional treatment method, which utilizes multi-branch horizontal boreholes to detect and seal potential water-conducting channels, thereby mitigating karst water inrush risks.

5. Technologies of Prevention and Control

For the three types of karst water disasters in Huaibei and Huainan Coalfields—

namely, the D-type, U-type, and IT-type—three prevention and control technologies are proposed: dewatering and depressurization of the aquifer (DDA), grouting reinforcement of the aquifer (GRA), and grouting and sealing of water-conducting channels (GSC), as shown in **Figure 4**.

5.1. Dewatering and Depressurization of the Aquifer

1) Applicable situations

In the Huainan Coalfield, the C₃I-C₃II aquifer—a direct water-filling aquifer with a thin-bedded structure—is of the static reserve type, characterized by limited recharge, runoff, and discharge. These features meet the criteria for a drainable aquifer, supporting its classification as a D-type karst water disaster. For D-type karst water disasters, DDA is generally adopted. Typically, an underground dewatering roadway is constructed to actively dewater and depressurize the aquifer. This reduces the floor water inrush coefficient below the safety threshold, thus ensuring the safe mining of the lower coal group.

2) Typical cases

The 11223 working face of the lower coal group in the East 1 mining area of Pan'er Coal Mine is situated on the northern flank of the Panji Anticline in the Huainan Coalfield (**Figure 1(a)**), with an overall structural configuration of a monocline. The C₃I-C₃II aquifer acts as the direct water-filling aquifer during the mining of the lower coal group.

Hydrological data collected from 13 underground vertical boreholes constructed in the East 1 mining area (**Figure 5**) indicate that the C₃I-C₃II aquifer is characterized by rapid attenuation after an initially high water yield. The total stabilized water yield from the 13 boreholes is only 0.5 - 0.7 m³/h, with an average of 0.6 m³/h. Additionally, based on pumping and injection tests from ground boreholes, the specific well yield of the C₃I-C₃II aquifer ranges from 0.000009 to 0.007 L/(s·m), indicating weak water-yielding capacity. Therefore, the recharge, runoff, and discharge conditions of the C₃I-C₃II aquifer are poor, demonstrating drainable characteristics.

In the East 1 mining area, a dewatering roadway was constructed along the L1 Layer in the floor of the 11223 working face. Within the dewatering roadway, 14 drilling chambers were developed, each housing 3 to 5 boreholes, resulting in a total of 66 inclined boreholes drilled into the C₃I aquifer and 2 observation boreholes drilled into the C₃II aquifer. Additionally, three cross-cuts were excavated in the eastern, central, and western sections of the dewatering roadway. Each cross-cut featured a fan-shaped arrangement of 5 to 11 boreholes, totaling 23 bedding-plane boreholes drilled within the C₃I aquifer, with the termination stratum at the L3 Layer. Collectively, the underground dewatering roadway and boreholes, combined with ground observation boreholes and underground vertical boreholes, form an integrated “Dewatering-Monitoring-Evaluation-Verification” dewatering system (**Figure 5**).

During the dewatering process at the 11223 dewatering roadway, the water yield

exhibited significant fluctuations, with a maximum value of $20.9 \text{ m}^3/\text{h}$ and a minimum of only $0.5 \text{ m}^3/\text{h}$. After a period of dewatering, the water yield gradually stabilized, showing a stepped decline pattern, and eventually stabilized at $5.6 \text{ m}^3/\text{h}$. Concurrently, the groundwater level in the karst aquifers experienced a substantial decline. Among them, the groundwater level of the $C_3\text{I}$ aquifer dropped to between -289.80 m and -300.30 m , representing a maximum drawdown of 302 m ; groundwater levels of the $C_3\text{II}$, $C_3\text{III}$, and O aquifers also decreased to varying degrees (Figure 6). Calculations confirmed that the water inrush coefficient of the 11223 working face was less than 0.06 MPa/m , meeting the criteria for safe mining.

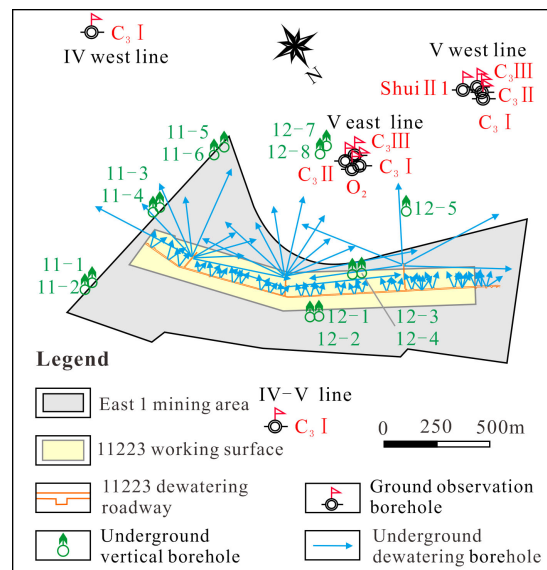


Figure 5. Layout of the dewatering and depressurization project in east 1 mining area.

Throughout the mining period of the 11223 working face, no incidents of water inrush occurred. Safe mining of the working face was achieved, providing valuable reference experience for mining the lower coal group in the Huainan Coalfield.

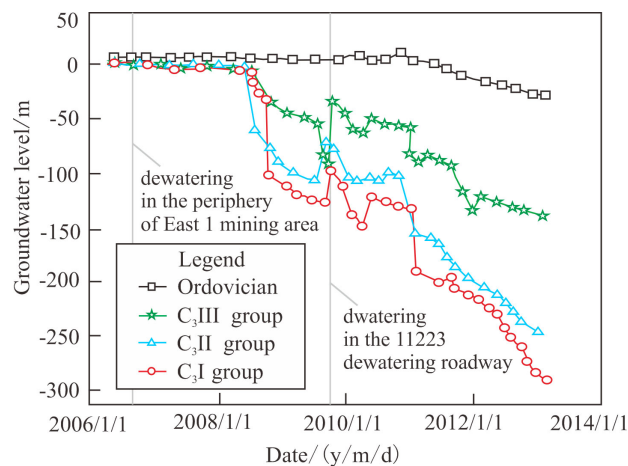


Figure 6. Groundwater level duration curve of boreholes in the V west line.

5.2. Grouting Reinforcement of the Aquifer

1) Applicable situations

In the Huaibei Coalfield, the C₃I-C₃II aquifer—also a direct water-filling aquifer with a thin-bedded structure—demonstrates active groundwater circulation with favorable recharge, runoff, and discharge. These features satisfy the criteria for a non-drainable aquifer, confirming its classification as a U-type karst water disaster. For U-type karst water disasters, GRA is typically adopted. Generally, a ground regional treatment method is implemented to grout and reinforce the aquifer. This achieves aquifer transformation into an effective aquiclude, thereby fundamentally eliminating water inrush risks at their source.

The treatment stratum for GRA is clearly defined—it is exactly coincident with the target stratum, generally the L3 layer, which is located within the C₃I aquifer. As a direct prevention and control approach, GRA typically focuses on grouting reinforcement of the C₃I aquifer to achieve full coverage of the treatment area.

In addition, implementing GRA in the shallow zone of the C₃I-C₃II aquifer severs the primary recharge sources, allowing DDA to be adopted in the deep zone to prevent and control karst water disasters. The integrated DDA-GRA mode implemented in the 105-mining area of Yangliu Coal Mine in Huaibei Coalfield has demonstrated efficacy in the prevention and control of water disasters.

2) Typical cases

The II633 working face of Hengyuan Coal Mine spans the Wenzhuang Syncline in Huaibei Coalfield (**Figure 1(a)**)—a region characterized by well-developed fault structures and complex hydrogeological conditions. This working face is primarily threatened by karst water disasters from the underlying L3 and L4 layers of the C₃I-C₃II aquifer, where the confined karst water exhibits high pressure and strong water-yielding capacity.

In the II633 working face, a ground regional treatment project was adopted to reinforce the C₃I-C₃II aquifer and mitigate the risk of karst water inrush. A borehole group (D2), comprising nine horizontal branch boreholes, was designed to target the L3 layer. The borehole trajectories were arranged along the stratum dip and spread out in a fan-shaped pattern, as illustrated in **Figure 7**. The borehole spacing was controlled within the range of 50 m to 70 m to ensure complete overlap of grout diffusion radii across the treatment area.

During drilling, a water pressure test was carried out every 100 m. When the absorption rate obtained from the water pressure test exceeded 0.01 L/(min·m·m), high-pressure grouting was immediately implemented. Additionally, when drilling fluid loss exceeded 15 m³/h, grouting was also performed after advancing an additional 5 - 10 m. The D2 borehole group cumulatively consumed 12958 t of cement, with final grouting pressures reaching 8 - 12 MPa, maximizing the filling of karst fissures in the L3 layer. The pre-grouting absorption rate ranged from 0.0013 to 0.02 L/(min·m·m), while the post-grouting absorption rate ranged from 0.00006 to 0.0009 L/(min·m·m), reflecting an average 95% reduction. All post-grouting absorption rates fell below the 0.01 L/(min·m·m) threshold, demonstrating a significant improvement in aquifer integrity (**Table 2**).

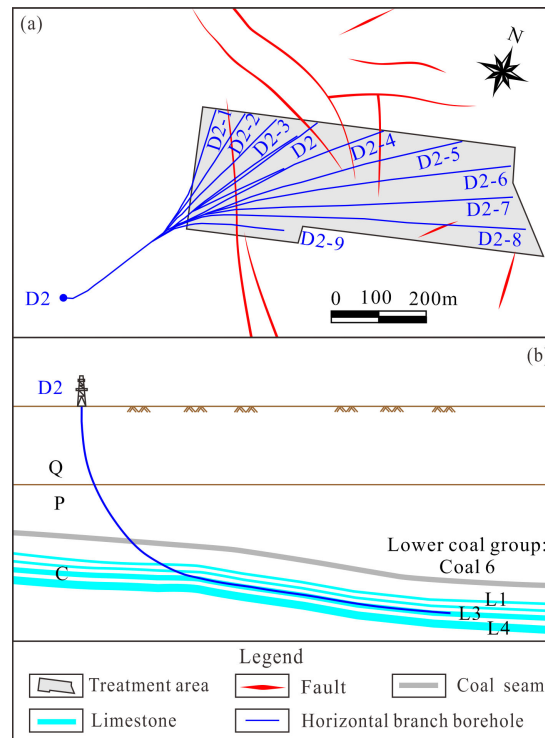


Figure 7. Layout of karst water disaster prevention and control project in II633 working face.

Table 2. Comparison of absorption rates before and after grouting in branch boreholes.

Borehole	Grouting sequence number	Pre-grouting absorption rate $L \cdot \text{min}^{-1} \cdot \text{m}^{-2}$	Post-grouting absorption rate $L \cdot \text{min}^{-1} \cdot \text{m}^{-2}$	Reduction ratio (%)
D2	1	7.62E-03	3.26E-04	96
	2	4.84E-03	2.02E-04	96
	3	1.82E-02	8.43E-04	95
D2-3	1	5.20E-03	2.27E-04	96
	2	1.99E-02	9.17E-04	95
D2-2	1	3.75E-03	1.68E-04	96
D2-1	1	3.10E-03	1.35E-04	96
D2-4	1	2.38E-03	1.20E-04	95
	2	9.26E-03	5.74E-04	94
D2-5	1	3.14E-03	1.76E-04	94
	2	5.70E-03	2.72E-04	95
	3	4.58E-03	2.24E-04	95
D2-6	1	2.57E-03	1.31E-04	95
	2	8.44E-03	4.69E-04	94
	3	1.24E-02	7.25E-04	94
	4	4.72E-03	2.62E-04	94
D2-7	1	1.29E-03	6.62E-05	95
D2-8	1	1.26E-03	5.64E-05	96

After project completion, the treatment effectiveness was validated through a dual-method approach combining parallel electrical resistivity tomography using a multi-electrode array and underground verification drilling. The geophysical survey identified two low-resistivity anomalies within the treatment area, which were subsequently confirmed to be largely devoid of water during drilling. Among the 14 verification boreholes, all recorded well yields below 4 m³/h, indicating highly effective grouting.

5.3. Grouting and Sealing of Water-Conducting Channels

1) Applicable situations

Under normal geological conditions, the C₃III-O aquifer in the Huaibei and Huainan Coalfields poses a negligible direct hydrogeological risk to the mining of the lower coal group. However, when geological structures such as karst collapse columns or faults reduce the separation distance or bring the C₃III-O aquifer into direct contact with the lower coal group, vertical or lateral water-conducting channels may form. As an indirect water-filling aquifer with a thick-bedded nature, the C₃III-O aquifer is classified as an IT-type karst water disaster. For IT-type karst water disasters, GSC is generally adopted. Typically, a ground regional treatment method is implemented to detect and seal potential water-conducting channels. This cuts off the hydraulic connection between the C₃III-O aquifer and the lower coal group, thereby preventing catastrophic water inrush into the mining face.

The treatment stratum for GSC is site-specific and must be determined based on specific hydrogeological conditions. Typically, the limestone of the C₃II group is selected as the treatment stratum to achieve decoupling between the treatment stratum (C₃II) and the underlying target stratum (C₃III-O). As an indirect prevention and control approach, GSC generally aims to precisely detect and seal water-conducting channels. In cases where karst collapse columns and water-conducting structures are poorly defined, a dynamic “detection-treatment” integrated construction method may be adopted: first, investigate the distribution patterns of water-conducting channels; then, implement targeted grouting-sealing operations.

2) Typical cases

The North 1 mining area of Gubei Coal Mine is situated at the junction zone between the eastern flank of the Chenqiao Anticline and the western flank of the Panji Anticline in Huainan Coalfield (**Figure 1(a)**). A suspected karst collapse column (designated No.2) was identified by 3D seismic exploration in the North 1 mining area and subsequently confirmed as a karst collapse column through engineering verification. The comprehensive exploration of the ground boreholes demonstrates that the No.2 karst collapse column is rooted in the Cambrian limestone, with its top interface extending to the L12 layer. Its influence zone extends to the Luotuobo sandstone beneath Coal 4 (**Figure 8**), exhibiting a hydraulic conductivity ranging from 0.000138 to 25.8 m/d and a maximum specific well yield

of 6.03 L/(s·m). These properties classify it as a strongly permeable karst collapse column.

In the North 1 mining area, the ground regional treatment project was implemented to seal vertical water-conducting channels to prevent and control karst water disasters. The treatment area, centered around the karst collapse column, was elliptically shaped. Two borehole groups (N8 and N9), with 19 horizontal branch boreholes, were deployed. The project employed a treatment technology of layered grouting: the upper N9 borehole group focused on grouting the L4 layer, while the lower N8 borehole group primarily targeted the L10 layer. In addition, the two borehole groups were arranged in an oblique intersecting pattern on the horizontal plane, constructing a three-dimensional water barrier (Figure 8). The 19 horizontal branch boreholes cumulatively consumed 179,424.13 t of cement.

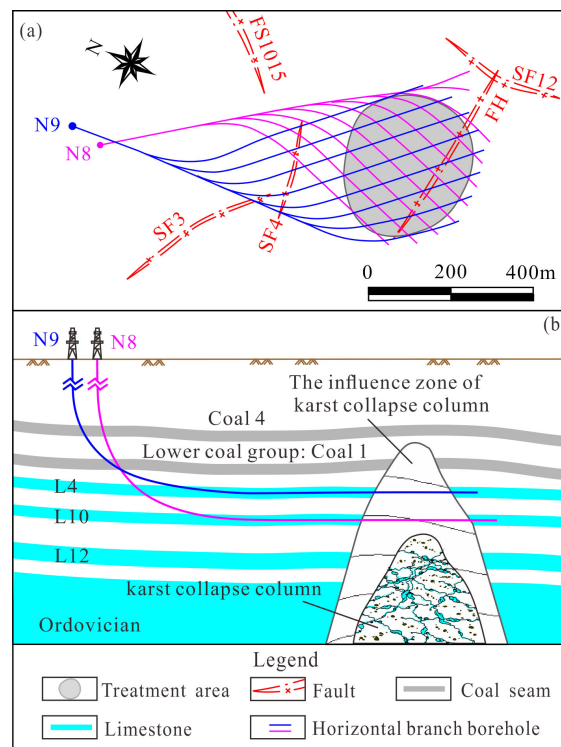


Figure 8. Layout of the karst water disaster prevention and control project in the north 1 mining area.

The post-grouting absorption rate ranged from 0.0003 to 0.0016 L/(min·m·m), representing a reduction of 60% - 85% compared to the pre-grouting levels. Furthermore, re-drilling inspections were conducted on horizontal branch borehole N8-5 and main borehole N9. Their absorption rates were 0.0013 L/(min·m·m) and 0.001 L/(min·m·m), respectively, both below the 0.01 L/(min·m·m) threshold. The water pressure test results confirm that the ground regional treatment project has successfully blocked the water-conducting channels in the karst collapse columns.

A comprehensive prevention and control system of “Investigation-Grouting-Eval-

uation-Validation” has been implemented, achieving effective sealing of the vertically oriented water-conducting channels in the No. 2 karst collapse column. This establishes a geological safety barrier for the safe mining of the lower coal group.

6. Conclusion

Based on the karst hydrogeological characteristics in the Huaibei and Huainan Coalfields, the classification of karst water disasters and the prevention and control technologies for such disasters were studied. The key conclusions are summarized as follows:

1) The karst aquifer system beneath the lower coal group is divided into a three-layer structure on the basis of the degree of hydraulic connectivity, water yield property, permeability, and drainability: the C_3I-C_3II aquifer, the lower aquiclude of the Taiyuan Formation, and the C_3III-O aquifer.

2) Based on the differences in aquifer characteristics and water-filling type between the C_3I-C_3II and C_3III-O aquifers, karst water disasters are classified into two types: direct water inrush from thin-bedded limestone (DT-type) and indirect water inrush from thick-bedded limestone (IT-type). Furthermore, due to the contrasting drainability of the C_3I-C_3II aquifer in the Huaibei and Huainan Coalfields, the DT-type is subdivided into the drainable type (D-type) and the undrainable type (U-type).

3) Three typical prevention and control technologies are proposed to correspond to three types of karst water disasters: dewatering and depressurization of the aquifer (DDA), grouting reinforcement of the aquifer (GRA), and grouting and sealing of water-conducting channels (GSC). DDA is a direct approach applicable to the C_3I-C_3II aquifer in the Huainan Coalfield. GRA is also a direct approach, characterized by full coverage, and applicable to the C_3I-C_3II aquifer in the Huaibei Coalfield. GSC is an indirect approach, focused on detecting and sealing water-conducting channels, and is applicable to the C_3III-O aquifer in the Huaibei and Huainan Coalfields.

The proposed classification and control scheme demonstrates robust applicability within the Huaibei and Huainan Coalfields. However, its transferability to other North China coalfields is constrained by site-specific hydrogeological conditions. Compared with the Huaibei and Huainan Coalfields, other coalfields in North China exhibit considerable variations in hydrogeological conditions, such as aquiclude thickness, recharge conditions, water inflow types, limestone thickness, and development of water-conducting channels. These differences give rise to distinct types of karst water disasters, which in turn necessitate different prevention and control technologies. Consequently, detailed local hydrogeological characterization and site-specific validation remain essential prerequisites for the application of this scheme.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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