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TECHNICAL ARTICLE

Evolution of Water Hazard Control Technology in China's Coal Mines

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Abstract

We analyzed the regional nature of China's coal mine water disasters based on three aspects: the main water source, water-conducting passages, and threat level of water hazards. The development of water hazard control technology in China's coal mines, including exploration and assessment of hydrogeological conditions, water inrush mechanisms, and predictive technology were all reviewed. We then focused our discussion on the calculation theory and methods behind mine inflow prediction, methods of dewatering and depressurizing, and technology for mining under water pressure and water-blocking grouting. Finally, we present the evolving trend of coal mine water disaster prevention and control technology, which is characterized by accuracy, transparency, environmental considerations, informatization, and intelligent technology.

Keywords Water inrush mechanism · Mine water inrush · Monitoring and early warning · Prediction of water inflow · Grouting · Directional drilling

Introduction

China is the largest coal producer in the world and accounts for almost half the total coal production worldwide. Moreover, 90% of China's coal is obtained from underground mining (Hu et al. 2010; Wang et al. 1986; Wang et al. 2018). The hydrogeological configurations and conditions associated with underground mining are both complex and varied. Thus, China's coal mining industry has historically struggled with mine water hazards. Coal mine water hazard accidents are frequent in China, and are second only to coal mine gas mishaps (Lin et al. 2020). Over the long course of coal resource mining, China has developed coal mine water hazard control prevention theories, technology, and supporting equipment systems (Cui et al. 2018a, b; Hu 2003, 2005; Zhao et al. 2018). Since the mining depth, technologies, and methods, and geological environments of major coal seams differ throughout both time and space (Lu et al. 2017). Thus, with respect to the theory of mine water hazard control and the associated technologies, there has been a gradual evolution that demonstrates continuous progress (Liu et al. 2012; Wu et al. 2017; Zeng et al. 2017). Herein, we reviewed and systematically summarized the overall development course of: (1) mine water hazard control theory and technology and (2) methods and equipment utilized for coal mine water hazard control since the foundation of the People's Republic of China. In addition, we also analyzed the internal relationship between water hazard control technology and the geological conditions in the coal mining region of a given period. Finally, we discuss the direction of future development and the technical demand of coal mine water disaster prevention and control technology in China.

Basic Types and Characteristics of Water Hazards in China's Coal Mines

China is home to the most complicated geological conditions for coal mining in the world. As such, China's coal mine water hazard types are based on: (1) the various geological and hydrogeological structures associated with coal seams throughout time and space; (2) the spatial relationship between major water-filling sources and the mining seam; (3) the hydrogeological characteristics of water-filling aquifers; (4) water–filling factors in coal mines; and (5) the formation and threat level of water hazards. Furthermore, coal

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mine water hazard types can be divided into the following six regions (Fig. 1).

(1) North China Permo-Carboniferous karst-fracture water hazard region: Distributed mainly in provinces such as Hebei, Shandong, Shanxi, Henan, Shaanxi, Jiangsu, and Anhui. In this region, water inrushes frequently occur in coal mines, the water volume is large or huge (1000 ~ 123,180 m^3/h), and the water-filling source is mainly Ordovician limestone with good water yield and high pressure. Faults and collapsed columns are the major water-conducting passages. In recent years, coal resource extraction has extended much deeper than in the past, making mining conditions more complex and prevention and control of karst water disasters much more critical.

(2) South China Late Permian karst water hazard region: Distributed mainly in southeast China provinces: South Jiangsu, South Anhui, Jiangxi, Hunan, Guangxi, Guangdong, Guizhou, Yunnan, and Sichuan. Water inrushes occur frequently in this region; water volume is large (2700 ~ 27,000 m^3/h); and the major water-filling sources are karst water, meteoric water, or surface water. The major water-conductive passages are karst conduits and karst collapses (Cui et al. 2018a, b).

(3) Fracture water hazard region of northeast Jurassic coalfields: Located mainly in the giant Neocathaysian subsidence zone in east and northeast Inner Mongolia. Coal mines are significantly influenced by surface water in mountain valleys and pore water in loose Quaternary layers. The major water-filling sources are fracture water in sandstone seam roofs or water in loose Quaternary layers. The major water-conducting passages consist of water-conducting fractures formed in overlying roof rocks after coal mining.

(4) Fracture water hazard region of northwest Jurassic coalfields: Located mainly to the north of the Kunlun-Qinling tectonic belt, this region includes Xinjiang, Qinghai, Gansu, Ningxia, north Shaanxi, and southwest Inner Mongolia. In this region, roof water hazards are prominent (Zhao 2019) and the major water-filling sources are fracture water in sandstone seam roofs. The primary water-conducting passages are water-conducting fractures formed in overlying roof rocks after mining (Fig. 2). The Shendong and Shanbei coal basements, which are located on the border between Inner Mongolia and Shanxi Province, are considered China's modern coal mining areas due to large-scale and high-intensity coal mining activities. In recent years, high-strength coal mining has caused water-conducting cracks to develop directly through the sandstone aquifer; thus, it is now close to the loose surface aquifer, and therefore to the surface as well. As such, groundwater and sand may enter the coal mining space via the fracture zone, simultaneously causing more mine water inrush and sand bursting

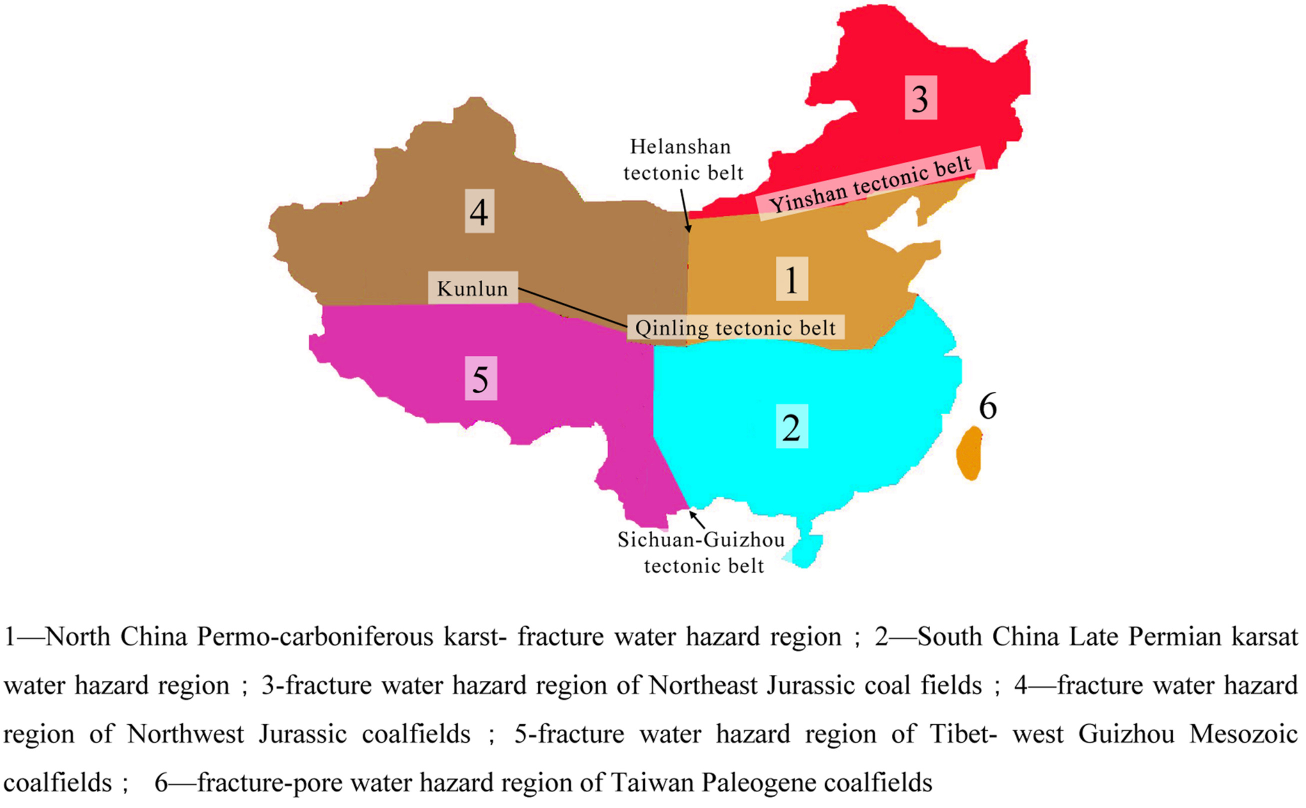


Fig. 1 Division of China's coal mine water hazard types

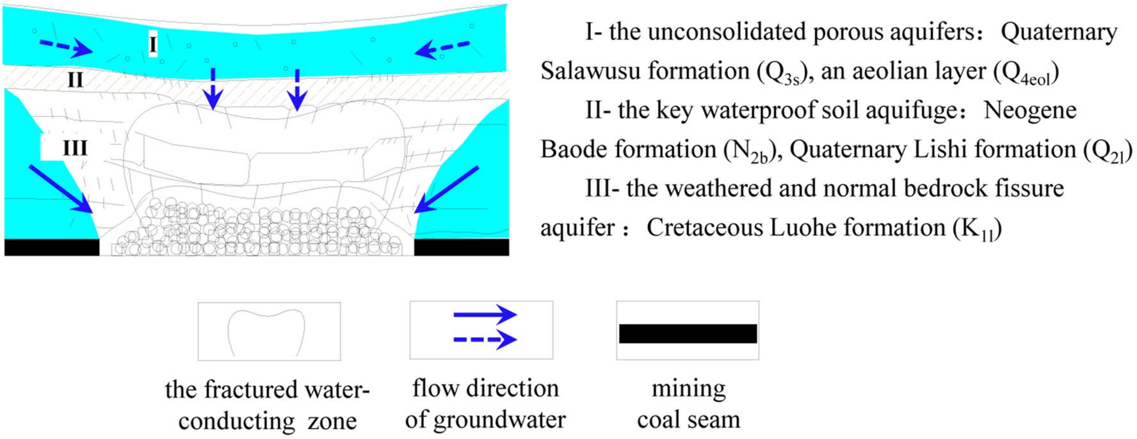


Fig. 2 Schematic diagram of coal seam roof water disaster in western mining area of China

accidents, which in turn can lead to a shortage of groundwater resources. Hence, coal resource exploration activities have inevitably impacted the underground water environment. In summary, this area exhibits two prominent issues: coal seam roof water damage and the influence on water resources (Fan et al. 2016; Hu et al. 2010; Wu et al. 2013).

(5) Fracture water hazard region of Tibet—west Guizhou Mesozoic coalfields: Distributed mainly south of the Kunlun Mountains and west of Xichang—Kunming. The major coal-accumulating period was late Triassic and early Cretaceous. Although the rainfall is relatively large in the region, because there are fewer coal resources and the mining scale is small, the water hazard threat is not presently serious.

(6) Fracture—pore water hazard region of Taiwan Paleogene coalfields: Distributed mainly in Taiwan Province. The region is characterized by moist climate, with an annual precipitation of 1800 ~ 4000 mm. In this region, the coal mines are relatively small and are not seriously threatened by water hazards.

To sum up, water hazards in China's coal mines are mostly in four large regions: north China, south China, northeast China, and northwest China. Consequently, these regions are also the key areas for research on coal mine water hazard control. Because water hazard formation conditions, the threat level of water hazards to production, and the history and scale of coal mining differ among the regions, the development history, technical features, and popularization and application of coal mine water hazard control technology also significantly differ.

Development of Technology to Explore and Assess Mine Hydrogeological Conditions

Development of exploration and assessment technology for characterizing the hydrogeological conditions of China's coal deposits varies with the coal mining horizon, mining areas, and mining mode. In general, the technology has passed through three development stages:

Stage 1—1950s to the end of the 1960s: During this time, the primary water hazard threat, which originated from the floor of a limestone aquifer, was to a large-scale mining operation in the Permo-carboniferous seams of north and east China. Thus, research was conducted on: the hydrogeological and dewatering conditions of the Taiyuan Group's thin limestone aquifer in Hebei province's Fengfeng coalfield (Li et al. 1997), hydrogeological conditions and the law of karst water abundance in the Jingjing mining area (Pang et al. 1982), the water-filling features and the approaches for water control in coal deposits within the southern Taihang Mountains, and hydrogeological conditions in the Jiaozuo mining area (Li et al. 1983). Preliminary investigations were conducted on the hydrogeological characteristics of the Carboniferous system's thin limestone aquifer in the Taiyuan Formation, as well as the aquifer's groundwater recharge, runoff, and discharge conditions. In addition, the hydrogeological conditions of the thick (> 500 m) Ordovician limestone aquifer in the coal seam floor were studied. This aquifer was vertically divided according to its water yield characteristics and exploration. Hydrogeological studies included using a karst spring catchment area as a typical unit, water drainage tests of large flow through underground group holes, and combined underground and surface monitoring and analysis of the groundwater flow field. In the mid- and late-1960s, research was conducted on prediction of water-filling factors, mine water control, and orientation of hydrogeological exploration in coalfields (Dong et al. 2007). This enabled preliminary prediction of the coal deposits' water-filling factors and sub-areal mine inflow in the major south China, late Permian coalfields, and thus oriented subsequent hydrogeological exploration and water control in other regions.

Stage 2—1980s and 1990s: The goal during this period was to develop efficient high water pressure control technology in the seam floor that was compatible with large-scale mining of the Permo-carboniferous coal resources in north China. Using key scientific and technological research projects, i.e. the Sixth and the Seventh Five Year Plans, and the integral control industrial test of Ordovician limestone water in north China's coalfields for reference (Wang et al. 1987), the hydrogeological conditions of the north China coalfields were explored and systematically studied. Furthermore, since coal deposit hydrogeological exploration was transitioning from small to large scale—i.e. from mining and working districts to mining regions, exploration research changed its focus from the surface to underground. Thus, the technology and the methods associated with exploration of mine hydrogeological conditions changed from single hydrogeological survey and testing to integrating chemical exploration, geophysical exploration, and drilling and hydrogeological testing (Zi 1990a, b). Thus, a technical system of integrated exploration methods for hydrogeological conditions in a mining region, a mining district, and even a local abnormal hydrogeological body was born.

Stage 3—into the twenty-first century: with the westward shift of China's key coal production region, the mining of shallow, thick coal seams in arid and semiarid areas has greatly intensified. Water hazards from thick roof sandstone strata and loose Quaternary aquifers are the major water hazard threat for mining in this region (Li et al. 2017). Therefore, technical analysis methods, such as additional hydrogeological exploration, hydrological testing, numerical simulation, hydrochemistry, and parameter inversion were used to specify the water inrush mechanism in the Hongliu region and surrounding mines. Simultaneously, roof water hazard control in typical mines throughout the eastern Ningxia mining area and Shanxi, Shaanxi, and Inner Mongolia mining areas served as examples for the introduction of sedimentary and environmental geology into the exploration and investigation of mine hydrogeological conditions (Dong et al. 2020). Theories and methods from stratigraphy, basin sedimentology, and hydrogeology were incorporated, as was regional field hydrogeological investigation, drilling, and logging; single, multiple, and group well pumping testing; hydrological geochemical exploration; and paleogeographic lithofacial analysis. It was concluded that the sedimentary environment was the major factor controlling the hydrogeological conditions of the seam roof aquifer (Yang et al. 2019). Furthermore, the water content of water-filling aquifers in mines is very uneven in a given plane, and lateral bands and vertical alternating deposits coexist. Finally, it was during this time that the connection between sedimentary facies and the special distribution of aquifers, aquicludes, and water abundance was understood. However, the mining areas in western China are located in arid and semi-arid areas. Many problems arise during large-scale coal mining, e.g. mining subsidence, drying of springs, reduced river flow, and intensified desertification (Fan et al. 2017, 2018; Wang et al. 2008). These problems threaten the sustainable development of China's western industrial coal base.

Water Inrush Mechanism and Development of Water Inrush Forecasting Technology

Systematic research on the water inrush mechanism started in China in the 1980s. At that time, the National Natural Science Foundation of China projects consisted of those listed in Table 1, which also lists the specific focus of each study. The mechanism and formation conditions of all the study topics resulted in the formation of numerous concepts, such as the "water inrush coefficient" (Liu 2009), "original rising height", "progressive water head rise" (Wang 1999), "failure at zero position" (Wang 1993), "in-situ tensile fracture" (Wang 1988), "intensive permeable passage" (Shi 2009), "stress relation between water and rocks" (Deng 1990), and "lower three zones" (Wang et al. 1986). These principles have been used to investigate the water inrush mechanisms associated with mining disturbance, fluid structure interactions, aquiclude damage, fractures, and high water pressure.

Since the onset of the twenty-first century, due to intense exploitation of Jurassic coal resources in west China, studies on the development and evolution of water-conducting fracture zones in rocks overlying the working face roof have been carried out under various mining conditions. Examples include, but are not limited to, fully mechanized mining of very thick coal seams, mining of inclined seams, and intensive mining of shallow seams. Investigations were conducted into the structure control mechanism for stability and deformation/failure of the overlying roof rocks due to mining, the critical layer control mechanism, sub-key and composite key layers for water-conducting fracture zones in overlying rocks

Table 1 Main research projects of mine water disaster prevention and control in China (1980s)

Project category	Main project title	Focus of project study
China Natural Science Foundation Project	Research on the stress mechanism of karst water inrush in coal mines and prevention of water inrush disasters Research on mechanical mechanism of water inrush disasters in coal mines Simulation of progressive rise of confined groundwater and prediction of water inrush in coal mines and so on…	Mechanism and formation conditions of water inrush disasters in the seam floor Interaction between water pressure and aquicludes Aquiclude's resistance mechanism to high pressure water Intrusion and failure mechanism of high pressure confined water for seam floor aquicludes Superimposed stress characteristics of coal mining on floor aquicludes Mechanism that determines the effect of superimposed stress on floor aquiclude stability Structural characteristics' resistance mechanism and aquiclude mechanical properties for high pressure water
China Coal Science Foundation	Assessment of the effect of water inrush prevention of seam floor aquiclude in karst coal mines Effect of natural hydraulic fracturing of water inrush in coal mines Nonlinear kinetic model of the formation mechanism of water inrush from seam floor Research on the industrial test project of the comprehensive control of Ordovician limestone karst water in North China coalfields and so on…	

within the mining face roof, and the formation mechanism of interlayer water. These studies have deepened the theoretical understanding about the formation mechanism of water hazards associated with the working face roof, and have served as a guiding reference for efficiently controlling seam roof water hazards (Qian et al. 2010).

In terms of water hazard forecasting, the “MTS-1 coal mine water inrush precursor detector” was developed in 1988 (Zhang 1990) to monitor abnormal physical field changes in the strata prior to a water inrush. In the late 1990s, the “KTJ-1A multi-parameters water inrush monitor” was developed, which has been used to monitor the physical and mechanical parameters of rocks and groundwater in real time during coal mining. Since the twenty-first century, multiple research projects such as “real-time monitoring and early warning system of water inrush hazards in coal mines” and “research on monitoring and early warning technology and equipment of water hazards in coal mines” were successfully completed. Furthermore, FBG communication technology is now implemented for water inrush field monitoring in coal mines (Jin et al. 2011). Water temperature, pressure, and stress–strain sensors have been used in the complicated underground environments of coal mines to form a real-time monitoring system with multiple points and parameters for water inrush. The monitoring and early warning system consists of: an analytical, monitoring, and early warning system of an inrush point in a working face, an integrated display system (based on networked water inrush monitoring database) for visualizing monitoring data from water inrush in the seam floor, an auxiliary identification system of dangerous water inrush sources in the mining face, hydrogeological body visualization, a water inrush monitoring database, and an inrush monitoring data integration system. Finally, a basic emergency response plan framework for water hazards has been set up and the methods, principles, and plan to set water inrush alarm levels have been formulated. Comprehensive 3D monitoring and intelligent early-warning technology designed to detect karst water damage to the coal seam floor is also undergoing underground engineering tests in Hebei and Shanxi Provinces. This system consists of a multi-frequency continuous electrical water-inflow monitoring source and "tunnel-ground-borehole" joint micro-seismic technology that monitors the water-filling channel during mining, and provides intelligent early warning of a water disaster.

Development of Mine Water Hazard Control Technology

Theory and Methods of Mine Inflow Calculation

From the 1960s–1980s, physical simulation and electrical network analog technology were adopted to study the hydrogeological properties of aquifers. Mine inflow analog computation was performed, while numerous other analytical methods were applied to steady and unsteady flow in order to determine hydrogeological parameters and subsequently calculate and forecast mine inflow. As karst water hazards became progressively more serious, research was amplified on methods to calculate karst water volumes in north China's coal mines. Flow movement equations in karst conduits were developed and potential solutions were investigated. As computers became more available, studies were conducted on numerical simulation technology and theory, such as: hydrogeological simulations of coal deposits, finite element solution of a phreatic flow-associated equation, and research on the physical governance of groundwater flow in coal mines. Simple numerical simulation technology started being used to calculate and assess mine inflow, and was popularized and applied in mining areas such as Handan, Feicheng, and Yuanbaoshan (Zi 1990a, b).

From the 1990s to the end of the twentieth century, studies were carried out on water resource planning, assessment, and utilization in mining areas, and the effects of mine dewatering on water supply in mining areas (Zhang et al. 1991). Theories and concepts associated with groundwater systems were studied and widely applied. Linear and nonlinear groundwater flow, black box theory, and Grey relational analysis were broadly used in assessing and forecasting mine inflow (Hu et al. 2016). Due to the complexity of hydrogeological conditions in mining areas and the uncertainty of different factors influencing mine inflow, research on random theory and different random methods entered a new stage (Hu et al. 2003, 2016). Thus, different assurance rate-based random mine inflow simulation and prediction theories and methods were studied and applied. New technologies, such as genetic algorithms (Hu 1999), artificial intelligence, and expert systems were broadly explored and implemented. Research on groundwater's systemic response to coal mining and an expert system for predicting and forecasting groundwater hazards in coal mines also entered a new stage. Numerical techniques, such as 3D models, finite elements and differences, and boundary elements became mature, broadly popular, and applied (Hu et al. 1997).

More recently, hydrogeological information systems began being constructed in large mining areas, in response to information technology development (Zhang et al. 2000). Mine inflow prediction changed from static inflow prediction to dynamic prediction (Hu et al. 2016). Organic combinations of inflow prediction and mining engineering was achieved. Finally, inflow prediction also changed from the whole mine to the working face, mining district, and roadway (Zhao et al. 2019).

Depressurization by Dewatering and Mining Under Water Pressure

From the 1960s to the 1980s, because coal mining depths were relatively shallow, depressurization by dewatering and mining under water pressure were the major water control methods in coal mines. The relationship between the dewatered and drained water volume of the major water-filling aquifers and the drawdown (the s-q relation curve) was studied through methods, such as pump tests and underground water drainage tests. Based on this relationship, the volume of water to dewater and drain a given area, under specific drawdown conditions, was predicted and analyzed. The major water hazard inducing aquifers were dewatered and drained in ahead of mining through surface or underground boreholes, so as to achieve safe mining of the coal seams. During this period, the dewatering technology of a thin limestone aquifer in a north China coal seam floor was vigorously studied through numerous research projects. By studying the relationship between the thickness and lithology of a seam floor aquiclude, the water pressure of the thin limestone aquifer underlying the aquiclude, and the mining face dimension, the water inrush coefficient empirical formula for mining under water pressure was put forward, and the coefficient was used as the technical standard for depressurization by dewatering.

During the 1990s, studies on the water inrush coefficient application conditions were significantly enhanced—particularly theoretical and empirical testing on the lithology, physio-mechanical properties, and petrofabric relationship of the layers from the major mining seam to the aquifer, the law of disturbance and damage to the floor aquiclude, and the height of original water head rise in the aquiclude. Indexes for assessing safe mining conditions under water pressure were developed—e.g. "progressive water head rise," "effective aquiclude," and "equivalent aquiclude thickness" (Fig. 3). The water inrush coefficient empirical assessment formulas for mining under water pressure were revised and perfected as depicted in formulas (1) ~ (3) (Fang et al. 2016).

$$\mathrm{T_s} = \mathrm{P/M} \tag{1}$$

$$\mathrm{T_s} = \mathrm{P}/\left(\mathrm{M} - \mathrm{C_p}\right) \tag{2}$$

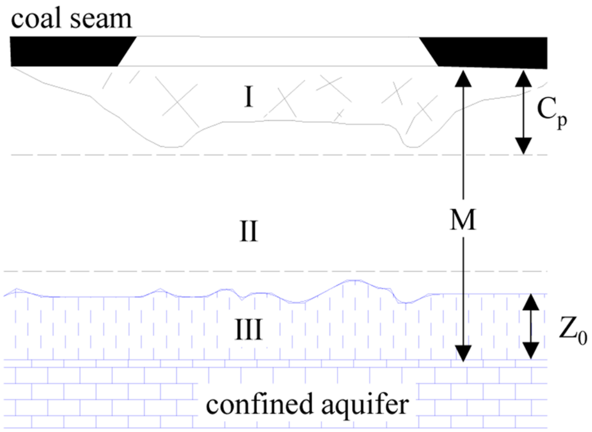
$$\mathrm{T_s} = \mathrm{P}/\left(\mathrm{M} - \mathrm{C_p} - \mathrm{Z_0}\right) \tag{3}$$

where, $\mathrm{T_s}$ = the water inrush coefficient, MPa/m; P = water pressure on the floor aquiclude, MPa; M = the total thickness of the floor aquiclude, m; $\mathrm{C_p}$ = mining-induced damage depth of the floor, m; and $\mathrm{Z_0}$ = the height of original water head rise in the floor aquiclude, m.

Figure 4 Schematic chart for calculating water inrush coefficient under coal seam mining conditions.

Formula (1) is the initial calculation formula of the water inrush coefficient proposed by the Xi'an Institute of Coal Geological Exploration. In the 1960s, the China Coal Research Institute expressed the hydrostatic pressure of the aquiclude unit thickness, and described the cause for water inrush in the seam floor using statistical law. Formula (2) is the first revised water inrush coefficient formula and was proposed by the institute in 1979. It reflects the mining-induced floor failure depth, which the scientific determined should also be taken into account. Formula (3) is the second revised water inrush coefficient formula (Safety Regulations in Coal Mines 1992). Note that in this case, more factors were considered.

Since the twenty-first century, with large-scale exploitation of Jurassic coal resources in western China and the



I-mining-induced damage depth of floor； II-complete waterproof zone； III-height of original water head rise in floor aquiclude

Fig. 3 Schematic chart for calculating water inrush coefficient under coal seam mining conditions

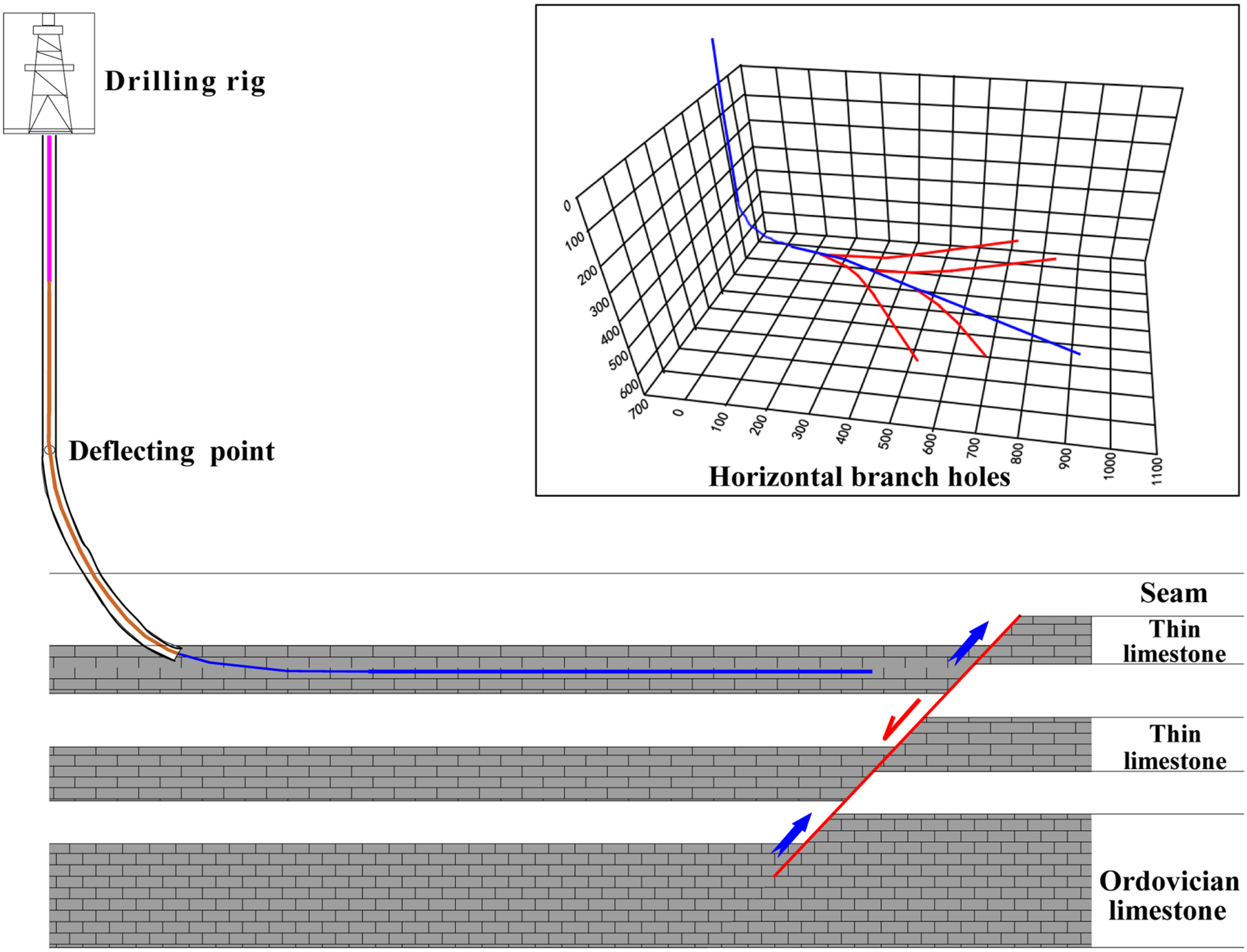


Fig. 4 Schematic long directional inclined nearly horizontal borehole

rapid improvement of underground drilling rig performance for water detection and drainage in coal mines, numerous achievements have been made with respect to using borehole drilling technology for dewatering and drainage in seam roofs and long-distance directional inclined boreholes for dewatering and water drainage. For example, in the Hongliu Mine, located in eastern Ningxia, "reverse dewatering method" was adopted to successfully solve the problem of dewatering in a seam roof's separated layer. Research on using safe coal mining technology above a high pressure confined water body enabled the formation of water hazard control technology for under-pressure mining of lower coal seam groups above double-layered composite high pressure confined karst aquifers. Long directional inclined and nearly horizontal boreholes have been widely applied in advanced aquifer dewatering and drainage in seam roofs and floors in large areas (Cao et al. 2015), greatly enhancing the effect of depressurization by dewatering (Fig. 5).

Figure 3 Schematic of a long, directional, nearly-horizontal borehole.

Grouting and Water-blocking Technology and Methodology

From the 1960s through the 1980s, research was conducted on preventing groundwater hazards by constructing water-isolating curtains by grouting (Bai et al. 2008; Lu et al. 2010). Tests were carried out on blocking water-flowing passages under conditions of dynamic water (Zhu et al. 2015), and blocking water-burst fault points using surface borehole grouting technology. The "three steps" water-sealing engineering technique was adopted to successfully block off a water-conducting karst collapse column under dynamic water conditions and thereby prevent serious mine flooding accidents (Zhao et al. 2004). In the 1990s, a series of related technical research conducted on underground mine floor grouting transformation of aquifers and aquiclude reinforcement (Xiang 1993; Xing et al. 2011; Zhang et al. 2003) provided the necessary technical and equipment requirements to build a complete system from highly efficient, low-cost grouting materials. Grouting under high water pressure via underground boreholes to large-scale grout preparation stations achieved rapid blockage of water-conducting karst collapse columns and underground grouting reconstruction of thin limestone aquifers in large areas. Many technical methods were developed to effectively grout rock strata, including proper selection of grouting materials and technology, and evaluation of grouting effectiveness (Niu et al. 2017).

Since the twenty-first century, research has also been conducted on the technology of rapid rescue, water plugging, and water disaster control for major water inrush disasters in coal mines (Yang et al. 2018; Zhu 2015), and karst water disaster prevention in coal seams, thereby promoting efficient, in-advance, regional governance of water hazard-inducing hidden factors. These studies resulted in reconstruction horizon selection criteria and improved aquiclude water resistance in the seam floor (Hu et al. 2008; Yin et al. 2008). Tracked, directional crawling drilling equipment (Fig. 4), water-resistant drilling, and directional long drilling grouting technology were also developed.

Figure 4 High power tracked directional drilling in coal mine.

Fig. 5 High power tracked directional drilling in coal mine

In 2014, long directional drilling along a coal seam, using a primary hole depth of 1881 m, was successfully completed in the Sihe coal mine, Shanxi Province, China. With high-power directional drilling technology and equipment, in 2019, a new world record of underground directional drilling was set in the Baode coal mine, in Inner Mongolia, using a main hole depth of 3353 m (Shi et al. 2015, 2020).

The technology for replacement of a sediment deposit in a large water-flowing channel (Nan et al. 2008) was realized to block and seal a water-inrushing collapse column by using reverse filtration of cement and aggregate. The technology and equipment consisted of controlled grouting through boreholes to block off the high water pressure inrush passages under large water volume conditions. At present, surface and underground directional inclined borehole drilling technology and horizontal branch boreholes are all being used, and large area in-advance grouting aquifer reconstruction from ground or underground has been realized (Zhao et al. 2015).

Mine Water Hazard Control Technology Demand and Development Trends

Mine water hazard control demand and development trends are closely related to coal production technology as they ensure safety during production. The overall direction of water hazard control in coal mines should be:

(1) Advanced and regional: because modern mining technology is developing towards high production and efficiency—mining and excavation are fast paced and the spatial mining scale in a single slope face is large. Thus, the annual coal production may reach more than 10 million t. Underground mining under these conditions generally requires that hidden geological and hydrogeological dangers must be forecasted, evaluated, and mitigated in advance, prior to preparation and extraction. Therefore, highly accurate geophysical exploration techniques with deep detection capabilities, such as drilling a 1000 m directional, inclined borehole, and automatic recognition of strata are leading trends in technical development.

(2) Accurate and transparent: with the rapid development of unmanned and intelligentized mining technology, increasingly accurate geological and hydrogeological detection is required. This requires that geological and hydrogeological structural properties must be accurately understood, so that the geological and hydrogeological conditions can be visually and transparently depicted. Therefore, there is a demand for highly accurate geological and hydrogeological detection methods. Thus, real time detection techniques and equipment and exchange of mining system information and detection results constitute another trend in technical development.

(3) Eco-friendly, low disturbance: With increasingly stringent regulations for eco-friendly mining, the geological and hydrogeological detection techniques and water hazard control engineering methods must also exhibit minimal disturbance to the surrounding environment. Therefore, the trend is towards surface centralized drilling fields with multi-azimuth and directional, inclined boreholes, multi-directional, long-distance directional drilling technology and equipment, more efficient grouting materials that create very limited pollution; and underground geophysical detection techniques with high anti-interference capacity and environmental suitability.

(4) Informatization and intelligentization: In order to achieve intelligentized mine construction, the following combined functionality must be fully exploited: accurate geological and hydrogeological advanced prediction and forecasting in mines, intelligent and visual monitoring in combination with early warning, water-hazard systems, cloud-computing platforms, and construction and efficient operation of mine water hazard remote diagnosis systems.

Conclusion

China's coal mine water hazard control and development trends have tended to parallel modifications in mining techniques, mining depth, and the geological and hydrogeological conditions and properties of the major coal seams being mined. During the early 1980s, primarily Permo-Carboniferous coal resource were mined. Thus, the mine water hazard control mainly focused on floor karst water hazards, so underground dewatering and drainage techniques, mining technology under water pressure, and grouting reconstruction technology of local geological and hydrogeological abnormal bodies were the predominant technologies. From the late 1990s to the early twenty-first century, most of the coal mining in China moved from the Permo-Carboniferous coal resources in north China to the Jurassic coal resources in west China. In response, advanced pre-dewatering and water drainage in roof sandstone, water and sand burst control technology in shallow seam roofs, and surface and phreatic water control technology in loose Quaternary layers were rapidly developed. Simultaneously, due to the development of high-production, efficient coal mining technology, regional grouting reconstruction technology using both surface and underground directional inclined drilling technology have been developed to ameliorate hidden disaster-inducing geological factors. Water hazard control technology for China's coal mines is developing towards large-scale, eco-friendly, information- and intelligence-based methods.

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