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TECHNICAL ARTICLE

Characteristics of Water Hazards in China's Coal Mines: A Review

Shuning Dong[1,2] · Hao Wang[1,2] · Xiaoming Guo[1,2] · Zhenfang Zhou[1,2]

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Abstract

China's coal mines face very complicated hydrogeological conditions and are affected by many complex water hazards. Based on the condition of the coal seams and an analysis of regional hydrogeological and geological conditions, China's coal-producing regions have been divided into six major hazard regions. This paper summarizes the filling conditions and main types of mine water hazards for these six hazard zones. Then, the most common types of water hazards in China's main coal mining areas (in northern and northwestern China) are analysed. North China's coalfields face a relatively high risk of water hazards due to the fractured karst aquifers below the coal. Coal mining in the northwestern region is affected by sandstone aquifers above the coal seam, which creates a diverse array of water hazards. This paper illustrates the main characteristics of water hazards in China's coal mines, and demonstrates the impact of water hazards in China's coal mines. It also provides a reference for decisions related to coal industry planning and water control technology.

Keywords Coal mine water hazard · Water hazard zoning · Water-filling conditions · Water hazard characteristics

Introduction

Global coal production reached about 8 billion tons in 2016, of which China produced 3.36 billion tons, ranking first among the world's coal-producing countries. Coal accounts for more than 63% of China's primary energy, and it has been forecast that coal will maintain more than 50% of the primary energy portfolio of China over the long term. Consequently, coal mining occupies a pivotal position in China's energy development plan.

Coal mines face five major hazards: water, fire, gas, coal dust, and roof fall. Water (second only to gas) seriously affects coal mine safety in China. About 27% of China's proven coal reserves are threatened by water hazards, and in north China alone, about 160×10^8 t of coal reserves are threatened by confined water in the floor (Pan 2014). Over the past half-century, Chinese mine hydrogeologists have conducted considerable research on characterising and the water hazards and developing control technology; safe and efficient coal mining is now possible (Hu and Tian 2010; Lamoreaux et al. 2014). With the increasing supervision of the Chinese government and the enhanced safety management of coal mine enterprises, the theoretical progress, the technology of water hazard prevention and control, and most important, the frequency and degree of mine water hazard accidents have decreased. However, eliminating the impact of water hazards on the coal mining process remains difficult (Dong and Hu 2007).

The range of coal deposits in China is considerable, and the occurrence and burial conditions vary. Furthermore, the hydrogeological conditions of different regions differ strongly, causing different types of mine water hazards, which makes hazard prevention very difficult. To systematically study the characteristics of coal mine water hazards in China, this paper illustrates the types and characteristics of water hazards in China and provides the basis for the prevention and control of coal mine water.

✉ Hao Wang
wanghao@cctegxian.com

Shuning Dong
dongshuning@cctegxian.com

[1] Xi'an Research Institute of China Coal Technology & Engineering Group Corp, Xi'an 710054, People's Republic of China

[2] Shanxi Key Laboratory of Coal Mine Water Hazard Control, Xi'an 710077, People's Republic of China

Regional Division of China's Coal Mine Water Hazards

The Yinshan, Helan Mountain, Kunlun-Qinling, and Sichuan-Yunnan tectonic belts make the mining conditions of China's coal seams different. Moreover, the geological and hydrogeological conditions of the mines are also different, forming six major water hazard regions (Wang 2012): (1) the Carboniferous-Permian coalfields of north China, which have fractured karstic aquifers below the coal; (2) the Late Permian coalfields of south China, which have karstic limestone below and fractured sandstone aquifers below the coal; (3) the Jurassic coalfields of northeast China, which must deal with water from fractured sandstone strata; (4) the Jurassic coalfields of northwest China, which face challenges from fracture zones; (5) the Mesozoic fissure water hazards of Tibet and western Yunnan; and (6) the Tertiary fissure-pore water hazards of Taiwan (Fig. 1; Wang 2012).

Fractured Karst Water Hazards in North China

North China's coalfields are located in the vast region south of the Yinshan tectonic belt, north of the Qinling-Dabie orogenic belt, east of the Helan Mountains tectonic belt, to the Bohai Sea. The region has a sub-humid-arid climate, the annual average rainfall ranges from 400 to 800 mm, and the coal-bearing series are mainly Late Paleozoic Carboniferous-Permian strata. The water source threatened by coal mining is the multilayer thin limestone complex aquifer group of the Carboniferous Taiyuan Formation (multiple thin limestone aquifers with interactive hydraulic connections), and the thick Ordovician limestone aquifer. Water inrush is frequent in coal mines, and the water inflow is large (1000–123,180 m^3/h; Hu 2005). The main hazard-causing factors include faults (Hu et al. 2014), karst collapse columns (Liu et al. 2018), and coal seam floor failures (Kong et al. 2007). These can cause the groundwater in the coal seam floor karst fissure aquifers to enter the mine. North China's relatively complex hydrogeological conditions make these water hazards are particularly difficult to control.

Karst Water Hazards in South China

South China's coalfields are located south of the eastern section of the Kunlun-Qinling tectonic belt and the southern part of the Sichuan-Yunnan tectonic belt to the southeast coast. The region has a humid climate, with annual precipitation ranging from 1.2 to 2 m; the rainy season lasts from May to September. The main coal-bearing strata are Middle and Late Permian strata. Below the bottom of the coal seam, the Permian Maokou limestone, though not very thick, contains karstic voids, while the Changxing limestone is in the seam roof; thus, coal mining is affected by both roof and floor limestone aquifers.

This region has the most complicated hydrogeological conditions of China's coal mining area, making it the most complex of China's coal mining areas. Water inrushes happen frequently, and the volumes of water inrush are considerable (2700–27,000 m^3/h), which easily floods mines, while normal mine water inflow is still large (3000–8000 m^3/h) (Wu et al. 2007). Among the main hazard-causing

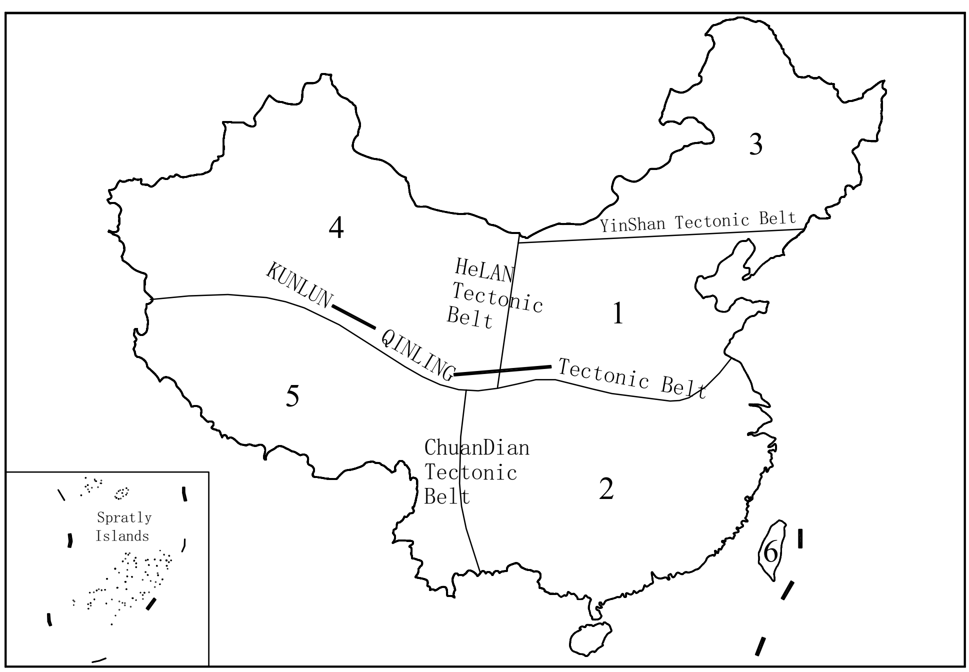

Fig. 1 Zoning of China's coal mine water hazard distribution. 1. The region of karst-fissure water hazards in the Carboniferous-Permian coalfields of North China; 2. The region of karst water hazards in the Late Permian coalfields of South China; 3. The region of fissure water hazards in the Jurassic coalfields of Northeast China; 4. The region of fissure water hazards in the Jurassic coalfields of Northwest China; 5. The region of Mesozoic fissure water hazards of Tibet-western Yunnan; 6. The region of Tertiary fissure-pore water hazards of Taiwan

factors, subsidence of a large area of exposed karst can cause a concentrated infusion of surface water (Lei et al. 2011).

Water Hazards Caused by Fractured Zones in Northeast China

The northeastern Jurassic coalfields are located to the north and northeast of the Yinshan tectonic belt, and in the vast Neocathaysian subsidence belt of eastern Inner Mongolia. The main coal-bearing strata are the Late Jurassic-Early Cretaceous coal-bearing strata, while the local area (i.e. the Sanjiang-Muleng River region) has offshore coal-bearing strata. This region has a humid-sub-humid climate, and coal seams are overlain by Jurassic sandstone fracture aquifers and Quaternary unconsolidated aquifers. The coal mines are affected by the surface water of the rivers of mountain valley and water from Quaternary unconsolidated layers. The main hazard-causing factors are the water-conducting fractured zone (Ma et al. 2019), which may cause the water in roof aquifers, goaf, and rivers to enter the mine. Although this water does not routinely impact daily mine production, occasional flooding does occur which can have severe consequences.

Water Hazards Caused by Fractured Zones in Northwest China

Located north of the Kunlun–Qinling tectonic belt and west of the Helan Mountain tectonic belt, northeast China's coal-bearing series are mainly Jurassic coal-bearing strata. The region has an arid/semi-arid climate, with an average annual rainfall of 25–400 mm. The main hazard-causing factor is the presence of water-conducting fractured zones (Liu et al. 2019; Ma et al. 2019), which can cause water from surface rivers, the Quaternary aquifer, and Jurassic sandstone aquifers to enter the mine from above (Zhao and Jin 2017). The height of the water-flowing fractured zones and the water yield property of the aquifers differ between different mining areas, so the impact of the roof aquifer on the mines also differs. Several mines have very little water inflow, a number of mines have extremely large inflows, and the maximum mine water inflow can exceed 5000 m^3/h (Wang et al. 2014a, b). Therefore, various forms and mechanisms of water inflow are characteristic of this region.

Other Water Hazard Regions in Coalfields

This mainly refers to the water hazards of Tibet-West Yunnan and Taiwan. The region of Mesozoic fissure water hazards in Tibet-West Yunnan is distributed in the vast region south of the Kunlun Mountains and west of Xichang-Kunming. Administratively, this region belongs to Tibet, Yunnan, and other provinces. The Tertiary fissure-pore water hazards occur on Taiwan. The coal mines in this region are characterized by small-scale exploitation and so the water hazard threat is generally not serious.

In summary, of the six regions with increased water hazard probability in China, the regions of north and south China have the most complicated hydrogeological conditions; as a result, the risk of karst water hazards is high and water control is difficult. Many aquifers affect mining in the northwestern region, and correspondingly, the pattern of water hazards are diverse. In the northeast and other regions, the influence of roof aquifers and surface water is dominant, while the impact of water hazards and the difficulty of hazard prevention are low.

Water-inflow Factors and the Impact of Mine Water Hazards

Water-inflow Factors

Three water-inflow factors affect coal mines: the water-inflow source, inflow channel, and inflow intensity (Dong et al. 2014). The main sources of inflowing mine water are precipitation, surface water, groundwater, and water in the goaf. The groundwater can be divided into pore water, fracture water, and karst water. The water-inflow channel refers to the path the water takes to enter the mines, which include channels formed by roadway excavation, fractured zones above (the coal roof strata) or below the coal seam, water-conducting karst collapse columns, water-conducting faults, and inadequately closed boreholes. The water-inflow intensity reflects the complexity of the hydrogeological conditions of a particular mine. Based on the mine-water inflow, mine hydrogeological conditions can be divided into four types (Wu et al. 2013): extremely complex ($Q > 2100$ m^3/h), complex (600 $m^3/h < Q \leq 2100$ m^3/h), moderately complex (180 $m^3/h < Q \leq 600$ m^3/h), and low complexity ($Q < 180$ m^3/h) (see Table 1).

Types of Mine Water Hazards

The hydrogeological conditions of the mines in each of China's six distinct coal mine water hazard regions also differ, the kinds of water-inflow sources are numerous, and the water-inflow channels can be complicated. The water hazards can be classified according to inflow conditions (i.e. the water-inflow source, the water-inflow channel, and the relative position of the aquifer and coal seam) (Dong 2010; Table 2); by their source (surface water, pore water, fissure water, karst water, and goaf water); and by the nature of the water-conducting channel (faults, fractures, karst column collapse, and inadequately closed boreholes). Finally, according to the relative position of the aquifer and the coal

Table 1 Classification of water-inflow factors

Factors	Classification
Water-inflow source	Precipitation, surface water, groundwater (in pores, fissures, and karst voids), and goaf water
Water-inflow channel	Roadway, water-flowing fractured zone, karst collapse column, fault, and inadequately closed boreholes
Water-inflow intensity	Extremely complex ($Q > 2100$ m^3/h), complex (600 $m^3/h < Q \leq 2100$ m^3/h), medium complexity (180 $m^3/h < Q \leq 600$ m^3/h), low complexity ($Q < 180$ m^3/h)

Table 2 Types of mine water hazards

Classification basis	Types of mine water hazards
Water-inflow source	Surface water hazard, pore water hazard, fissure water hazard, karst water hazard, and goaf water hazard
Water-inflow channel	Water-conducting fault water hazard, water-conducting fractures water hazard, karst collapse column water hazards, and water-conducting inadequately closed borehole water hazard
Relative position of aquifer and coal seam	Roof water hazard and floor water hazard

seam, water hazards can be divided into roof and floor water hazards.

Environmental Impact of Mine Water Hazards

Coal mine water hazards not only threaten mine safety but also induce severe environmental problems. These environmental problems include: mine water pollution, water resource loss, trace metal enrichment of the soil near the mine, and environmental and geological problems resulting from water level rebound in abandoned coal mines (Sun et al. 2020). In northwest China, water resources are scarce, and coal mining has caused a large amount of water loss. The water production per ton of coal can reach 0.78 m^3/t, which has caused serious drops in the water table, rivers drying up, springs disappearing, and even desertification in some mining areas. Acid mine drainage (AMD) is the most important mine water pollution problem in China, and mainly occurs in the old mining areas of southwest, south, and north China (Wu et al. 2009), e.g. the provinces of Guizhou, Jiangxi, and Shanxi. AMD treatment is relatively rare, and mainly relies on aeration and the addition of $Ca(OH)_2$ or $CaCO_3$ to the water to increase the pH of the mine water (Zhang 2018). In summary, China currently focuses more on issues such as water loss and water level drop, and less on the impact of AMD.

Water Hazard Types and Typical Regional Characteristics

North and northwest China are the main coal production bases, and where water hazard accidents are happening with increased frequency. Different occurrence conditions of coal seams and the underlying hydrogeological conditions determine the characteristics of the different types of water hazards.

Types and Characteristics of Water Hazards in Northwestern China

The water sources of the fissure water hazards of the Jurassic coalfields of northwest China are mainly roof aquifer(s). These include the Jurassic sandstone, Cretaceous sandstone, unconsolidated Quaternary, burnt rock, weathered bedrock, and other coal seam roof aquifers. Water enters the mines through fractured zones formed by the mining, as well as inadequately sealed boreholes, fault structures, and subsidence reaching the land surface. In the process of coal mining, the overlying roof strata gradually deform and collapse, thus leading to the diversity of mine water hazard types.

Pore and Fissure Aquifer Water Hazard

This kind of water hazard mainly originates from the Jurassic, Cretaceous aquifer, and unconsolidated Quaternary roof aquifers, when the fracture zones created by the process of coal extraction connects with the aquifer (Fig. 2). Because of differences in the nature and water abundance of different strata, the development of these fractured zones is complex, and thus, the severity of the water hazard varies. The typical areas of this type of water hazard are the: Jurassic Zhiluo Formation of the Ningdong area (Chu 2017), the Cretaceous Luohe Formation of the Huanglong area (Liu and Wang 2013), and the Quaternary Sarauzu Formation of the Shendong area (Miao et al. 2010). In specific mines, the water inflow may exceed 2000 m^3/h.

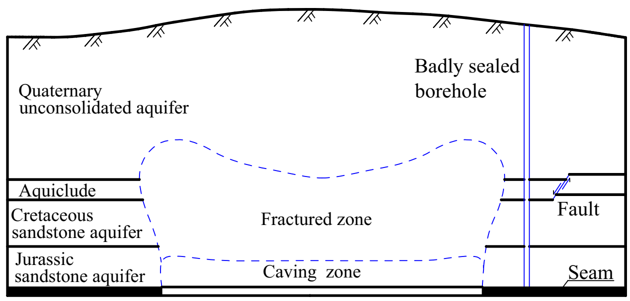

Fig. 2 Schematic formation of water hazard in pore and fracture aquifer

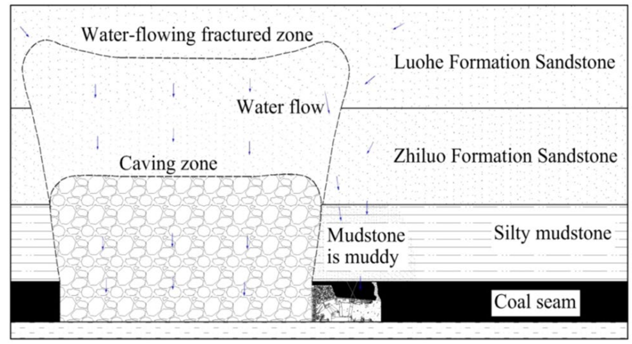

Fig. 3 Schematic diagram of the formation mechanism of water and sand inrush from deep bedrock aquifer

Fissure Water Hazards of Burnt Rock and Weathered Bedrock

Burnt rock is a special type of rock formed by the spontaneous combustion of a thick coal seam near the surface, which burns surrounding strata (Fan et al. 2016), while weathered bedrock mainly originates from the Jurassic bedrock strata in this region. Many of the ZhiLuo Formation and Yan'an Formation strata show extreme to moderate weathering and have developed fissures (Zeng et al. 2018), caused by the physical or chemical action of the strata; these equip the formations with good permeability and water abundance. This results in increase water flow into the mine, and flooding accidents may even occur. A typical mine affected by this type of water hazard is the Jinjie mine, where the normal mine water inflow reaches 5,499 m^3/h, making it the mine with the highest water inflow in China (Wang et al. 2014a, b).

Water and Sand Inrush

Water and sand can rush into some mines from the thick unconsolidated layer above the shallow coal seam (Fang et al. 2016). In this type of hazard, the water inrush is accompanied by a sand burst; the main source of water and sand is the Quaternary Sarauzu Formation aquifer. Since part of this region is located in a valley, the bedrock above the working surface is thin, the loose layer is thick, and the main lithology is medium to fine sand (Zhao and Wang 2017). Water and sand have strong fluidity, and thus, once the cracks formed by mining connect with the aquifer, a water and sand inrush occurs. This type of water hazard is most prominent in the Yu-Shen-Fu mining area because the coal seam there is shallow and the overlying bedrock is thin. Water and sand inrush occurs easily when underground mining affects the near-surface strata, even causing a "skylight" area.

Water and Sand Inrush from the Bedrock Aquifer Above Deep Seams

This kind of water hazard forms when the: water-flowing fractured zone produced by coal mining links with the Cretaceous aquifer so that aquifer water enters the mudstone of the coal seam roof. Over time, the mudstone becomes muddy and disintegrates to form mud fluid. The collapse of the roof mudstone and old roof forces the mud fluid to break into the coalface along the breaking channel (Fig. 3). A typical example of this type of water hazard is the water and sand inrush that occurred on April 25, 2016, at the ZF202 working face of the Zhaojin coal mine in the Huanglong Coalfield (Guo et al. 2019). The total volume of inrushing sand in the working face reached 2290 m^3, which was extremely disastrous.

Water Hazard from Bed Separation of the Seam Roof

This water hazard features a combination of soft and hard rock layers in the mine roof strata. A separation space forms between the soft and hard rock because of differences in their curvature and crushing coefficient. The swelling and erosion of the mudstone aquiclude in response to water exposure gradually fills the fractures, allowing water storage in the bed separation space. When the roof fails, this water bursts into the mine, resulting in a water inrush. The instantaneous flow of this type of water hazard can reach thousands of cubic meters per hour. Although the inrush typically only lasts a few hours to five days, it often submerges part of the underground mine. This type of water hazard occurs in the Ningdong coalfield, where the sandstone aquifer of the Zhiluo Formation recharges the bed separation space formed by the mudstone interlayer. This leads to frequent water inrush events, which greatly influences coal mining there (Cao 2017). Similar water hazards exist in the Huanglong coalfield (Fang and Jin 2016).

Moreover, a number of mines in the northwestern region also face the threat of goaf water, while in some areas floor water is more prominent. In short, in the arid and semi-arid areas of western China, most mines are exposed to relatively simple hydrogeological conditions, while in the northwest, the types of water hazards tend to be more complex (Sun et al. 2016), and preventing water inflow increases gradually becomes more difficult.

In the Ordos Basin, which is the most important coal production base in China (Dong et al. 2020), mostly Jurassic coal seams are mined. Above these coal seams, there are the Jurassic Yan'an, Zhiluo, and the Cretaceous Luohe Formation sandstone aquifers, as well as the Quaternary aquifer, though some of these formations may be missing in specific mines. In the northeast portion of the basin, coal seams generally have shallow burial depths. During mining, water and sand rush into the mine from the Quaternary Sarawusu Formation and burnt stone aquifers. Part of the mines in the west and south of the basin are affected by bed separation water disasters. Most of the mines in the basin are affected by the sandstone roof aquifer of the Jurassic Zhiluo Formation and the Cretaceous Luohe Formation sandstone roof aquifer. Various types of mine water hazards affect northwestern China, and their degree of impact also varies, making water hazard prevention and control very difficult.

Water Hazard Types and Characteristics of North China

The exploitation of coal resources in areas with karst fissure water hazards in the north China Carboniferous-Permian coalfields has the longest history in China and the earliest mechanized mining. With the depletion of resources in several mining areas, coal mining is gradually turning to deep seams (Hu 2010). In this region, the aquifer is dominated by karstic floor aquifers, including the thin Carboniferous limestone, Ordovician limestone, and thick Cambrian limestone aquifers. The main water channels are fault structures or karst collapse columns, for which the mining-induced failure zone below the mine floor and inadequately sealed boreholes may be responsible (Jin 2003).

Coal mining causes notable disturbance and damage to the seam floor, forming a disturbed and damaged zone. The depth of the disturbance may directly affect the thin lower limestone aquifer or the thick Ordovician limestone aquifer. Moreover, the faults, karst collapse columns, and inadequately sealed boreholes may form centralized water-inflow channels. These cause the high-pressure karst aquifer water to burst into working faces (Fig. 4); the water-inflow intensity is closely related to the nature of the water channels and the water pressure of the aquifers. With increasing mining depth, the hydrostatic pressure of the karst aquifer below the coal seam increases, making the threat of a water hazard more severe (Hu 2010; Wang 1999).

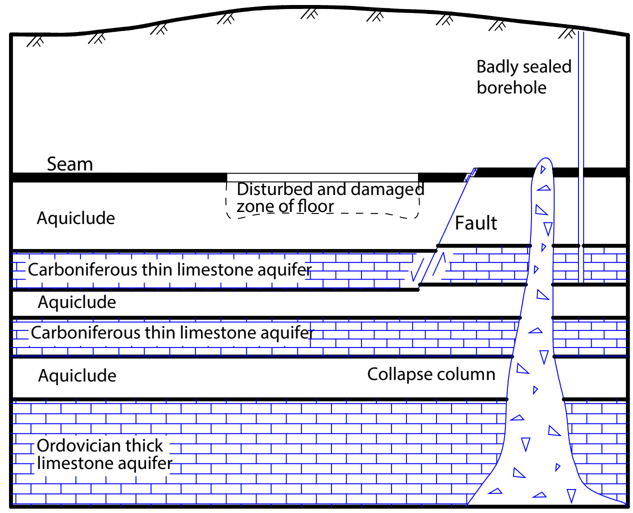

Fig. 4 Schematic diagram of water conduction in working face in North China water hazard region

The main water inrush source in north China is the Ordovician limestone aquifer, which in this region was divided into three Groups and eight members. Among these, the middle and lower series are more complete, while the upper portion of the middle series and the upper series are absent in most areas. The total thickness of the Ordovician reaches ≈ 300–1600 m (excluding the Pingliang and Beiguoshan Formations), and the sedimentary center is in Jinan, Feicheng, Xingtai, and Fengfeng city. The lithology is that of a stable carbonate stratum, representing a relatively stable shallow sea facies sediment. The Ordovician sedimentary characteristics are different in the western Helan Mountains and the Pingliang area than in other areas; the total thickness can reach 1800 m, and shows characteristics of a subsidence zone. In this region, regression started in the Late Cambrian. From the early Ordovician Yehli Stage to the early Ordovician Lianjiashan Stage, the sea regression peaked. The old Qinling-Huaiyang land expanded further, resulting in the absence of Ordovician strata in western and southern Henan province, as well as the absence of Lower Ordovician in Ying-Gong and Jiaozuo mining areas. The Ordovician limestone in the Datong mining area eroded from the south to the north and from top to bottom, while gradual thinning was absent. The influence of the Ordovician limestone aquifer on these mines is mainly determined by the regional characteristics of water abundance and water pressure of the limestone aquifer, its thickness, its water abundance, the water-isolating property of different intervals of the aquifer, and the thickness and filling degree of the paleo-weathering crust on the top of the aquifer (Li 1981). Based on in depth research on Ordovician aquifers, a series of water hazard assessment and treatment methods have been developed (Hu et al. 2010; Wu et al. 2016).

Dong et al. (2018) discussed a case of water inrush through the coal seam floor in the Dongpang coal mine in north China (Dong et al. 2018). This mine primarily extracts the #2 coal seam in the Shanxi Formation of the Permian Period. A karst collapse column acts as a passageway for the pressurized groundwater in the Ordovician limestone to flow up into the underground working area, causing an inrush in the #2903 working panel. The maximum water flow was 70,000 m^3/h, which quickly flooded the entire mine. In response to this water, a vertical watertight plug was successfully constructed within the karst collapse column to restore the flooded mine to full operation. Similar water inrush incidents from the Ordovician aquifer caused by karst collapse columns and faults occur frequently in China (Mu et al. 2020; Wang et al. 2018a, b). These events threaten the lives of miners and are the north China's coalfield main problem.

Types and Characteristics of Water Hazards in Other Regions

In south China, karstic limestone aquifers are distributed in both above and below the coal seams. In particular, the Permian Maokou limestone is very thick and has an abundance of water. Moreover, the karst is very developed, which means that water can pour into mines from different directions, such as the roof and the floor. Additionally, because of the influence of tectonic development and the Quaternary unconsolidated aquifer, the hydrogeological conditions are very complex, and water hazards are a longstanding problem (Zhao and Wang 2017).

The water-filling conditions in the Jurassic coalfields of northeast China are similar to those of northwest China. However, because of the early mining history, a great amount of water has accumulated in old mines and these are the main threats to mine safety. The roof aquifer has little water, and the roof water hazard is mainly affected by the impact of the shallow Quaternary unconsolidated aquifer and the surface water. Because the main coal mining areas of China are located in northwest and north China, the South China and northeast water hazard regions are not discussed in detail.

Conclusions

Based on an analysis of the hydrogeological conditions of Chinese coal mines, the types of water hazards in China were partitioned. The types of water hazards and the typical regional water hazards characteristics in China are summarized below:

1. The hydrogeological conditions of Chinese coal mines are complex, and the types of water hazards can be divided into six major water hazard regions. The karst-fissure water hazard region of the Carboniferous-Permian coalfields in north China is dominated by the groundwater in the floor limestone aquifer. However, the karst water hazard region of the Late Permian coalfields in south China is affected by the coal seam roof and the limestone floor aquifer. The other four regions are mostly affected by water hazards from roof sandstone aquifers.
2. The water-filling factors of China's coal mine water hazards include water source, water-filling channel, and water-filling intensity. These are associated with many types of water hazards according to different combinations of water-filling factors. North China is mainly threatened by water hazards from collapsed pillars, faults, etc. that allow water inrush from the mine floor limestone aquifer. There are various types of coal mine floods in northwest China, and their impacts are different.
3. In western China, coal mines face various roof water hazards. The water hazards will become increasingly severe, and it is therefore necessary to further strengthen the management, theoretical level, and technical level of water hazard prevention and control in coal mines. During the planning of the national coal base, the threat of water hazards for the safety of miners should be fully considered, and the mining of coal in areas should be prioritized where the aquifers are less disturbed and the threat of water hazards are less. At the same time, research on the environmental governance of mine water (e.g. such as acid mine water) should be strengthened in north and south China.

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