Study on Water-Sand Inrush Mechanism for Mining Under Pore Water in China

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Abstract. In China, pore water is one of the major water hazards of coalmines, accountable for severe pit flooding and human casualties. This article introduced the two types of water-sand conducting channels, primary and man-made, contributing to water-sand inrush when mining under pore aquifer of the bottom Quaternary loose strata; the four situations of water-sand inrush mechanism caused by man-made channels channelling pore aquifer, man-made channels involving pore aquifer via primary channels, and waterproof coal pillar caving when mining on steep-slope coal seam; as well as analysis of the correlation between the critical hydraulic gradient and the coarse particles ratio based on results from penetration test. It is to provide references for countries confronting similar problems and to facilitate international discussions on pore water control.

1. Introduction

China is the largest coal producer in the world, with annual output exceeding 3 billion tons. According to the “BP Statistical Review of World Energy 2010-2018”, among the top 10 coal-producing countries, China has an output surpassing those of the other nine countries combined (the US, India, Australia, Indonesia, Russia, South Africa, Germany, Poland) (Figure 1). Looking at the distribution of known coal resources in the mainland China, the over 500,000 km² of coal-bearing area is divided into six regions, namely northeast and northwest Jurassic, North China Carboniferous-Permian, South China late Permian, Tibet-West Yunnan Mesozoic, and Taiwan Paleogene [1]. These complicated hydrogeological conditions are inherent with as many as 30 common types of water hazards [2].

Since coal mining is still very active in China, especially in North China, and with the increase of mining depth and the continuing extension to deeper parts of coal mines in China, the hydrogeological conditions will become increasingly complicated, aggravating the threat of water hazards to mining and threatening the safety production of coal mine[3-5]. In China, the North China coal-bearing area has overlying Cenozoic Quaternary loose strata of as thick as 200m to 300m on top of the Carboniferous-Permian coal measures strata. Generally, loose strata breed multiple layers of pore aquifers, the bottom of which (known as the bottom aquifer) covers the coal measures strata directly.
Figure 1. Coal output of the top 10 countries in the world

The bottom aquifer is the main stratum of water-sand inrush as coal mining. On Mar. 15, 1997, in the No.1022 working face of Taoyuan coalmine, Huaibei coalfield of Anhui Province, a flooding accident burst caused by Quaternary pore water and cost five lives [6].

In recent years, the coal industry in China intensified the research into water-sand inrush mechanism for mining under water bodies. The achievements will undoubtedly contribute to the global efforts on water hazards control [7-10].

2. Water-sand conducting channels

Water-sand inrush was determined by water source, aquifuge and permeable channel [11-13]. There are two types of water-sand inrush conducting channels when mining under pore water bodies, namely primary and man-made water-sand conducting channels.

2.1. Primary water-sand conducting channels

Refer to water conductive faults, karst (collapse column), pre-existing fractures and other channels for water-sand penetration or pre-existing channels made by force of nature [14]. When the pre-existing channels are exposed by mining activities and connect into the mining panels, water-sand inrush accident would occur [15-16]. It was investigated that almost 80 % mining water-sand inrush incidents were involved with the fractured fault zones and had the features of lagging water-sand inrush in China, during 1955~2000[17].

2.2. Man-made water-sand conducting channels

Coal mining not only forms goaf, but also breaks the stress balance of original rock, which leads to the movement and deformation of overlying strata [18-20]. Through borehole exploration, it is found that the overburden deformation caused by coal seam mining forms “three zones”, which are caving zone, water-conducting fracture zone and bending zone from bottom to top [21-22], as shown in Figure 2, \(H_c\) and \(H_f\) (the height of the caving zone and the water-conducting fracture zone) are the main factors to determine the height of the waterproof coal (rock) pillars \(H_w\) \(= H_f + S\) that should be retained under pore aquifers[23-24].

If the water-conducting fractured zone or caving zone formed by coal seam mining communicates with the porous aquifer above, it constitutes man-made water-sand conducting channels for water-sand inrush. In addition, mining may further stretch tectonic structures, such as faults, and other pre-existing fractures, which will then become more permeable to water [25]. Therefore, the ongoing development of primary water-sand conducting channels in the overlying rock will aggravate the menace of water-sand inrush under pore water bodies.
3. Water-sand inrush mechanism

From the case of coal mine water hazards in China, pore water hazards are mainly caused by the following reasons [6].

3.1. Connection between aquifers and the fractures zone via primary conducting channels

After mining, the water conducting fracture zone and the caving zone channel the pore aquifer in the bottom of Quaternary loose strata (Figure 3) through primary conducting channels (e.g. water-conductive faults, pre-existing fissures, etc.). The quantity and speed of water-sand inrush are subject to the water (sand) conductivity of the pre-existing channels. Case: in the North China coal-bearing region, during mining on the No. 3#22 working face in Qidong coalmine, HuaiBei coalfield, North China coal-bearing region, a large number of primitive high-angle fractures channelled the bottom Quaternary aquifer and water conducting fracture zone. On November 5, 2001, a water-sand inrush burst out a total of 1520m³/h of water-sand and causing hundreds of millions RMB in economic losses. The Production was suspended for more than one year.

![Figure 3: Fracture zones channelling pore aquifer via fault](image-url)
3.2. Water-conducting fracture zone implicating the pore aquifer
During mining, as water-conducting fractured zone implicate the pore water in the bottom aquifer of Quaternary loose strata (shown as Figure 4), the water and sand in it burst into mining and excavation working faces. This situation generates relatively smaller quantity of sand [26]. Case: on November 31, 2002, in the Taoyuan coalmine in Huaihei coalfield, North China coal-bearing region, a disastrous water burst caused by Quaternary pore water, gushing out 500m$^3$ of sand gravel. Over 300-meter tunnel was silted and cost three lives.

![Figure 4. Fracture zone channelling pore aquifer](image)

3.3. Caving zone implicating the pore aquifer
The caving zone caused by mining activities directly channels the pore aquifer in the bottom of Quaternary loose strata (Figure 5). This situation generates large quantities of water and sand in a rather forceful way because caving zone has bigger pores and stronger permeability [27-28]. Case: on September 28, 1974, at 704 working face in Yi’an coalmine of Xuzhou, North China coal-bearing region, a severe water-sand inrush from pore aquifer of the bottom Quaternary loose strata produced water gush at 453.6 m$^3$/h and sand of 1600 m$^3$. Most tunnels were silted and the coalmine suffered heavy economic losses.

![Figure 5. Caving zone implicating pore aquifer](image)
3.4. Waterproof coal pillar caving under the condition of steeply-inclined seam

Once a goaf space is created during mining, the roof strata cannot cave as mining proceeds (Figure 6a). As a result, the waterproof coal pillar will cave and fill the goaf space by force of gravity and mine pressure (Figure 6b). If such caving cannot be stopped in time, water and sand in the overlying pore aquifer will enter into the coal mining face through the channels caused by waterproof coal pillar caving. A water-sand inrush hazards is thus imminent and may cause ground collapse or other geological disaster [29].

Here is a case. On July 31, 1965, in No.1 coalmine of Xinhe, Xuzhou coalfield, North China coal-bearing region, the waterproof coal pillar caved during mining steeply-inclined coal seam. Water-sand from the pore aquifer of the bottom Quaternary loose strata gushed into the coal mining face, silting 1200-meter tunnel with a total of 5788m³ sand. The coalmine suspended production for 58 days and caused three deaths. At the same time, a large surface collapse with a diameter of 42-59m appeared on the ground (Figure 7).

![Figure 6. Coal pillar caving](image1)

![Figure 7. Case of coal pillar caving](image2)

When mining under pore water bodies, the direct cause of water-sand inrush is man-made channels (e.g. water-conducting fractured zone, caving zone and the space left by waterproof coal pillar caving) channelling pre-existing channels (water-conducting faults and pre-existing fractures, etc.). Both types of water-sand conducting channels are formed subject to the lithology of overburden rock and the hydrogeological conditions of the pore aquifer of the bottom Quaternary loose strata [30].

4. Simulation test of water-sand inrush

From past water-sand inrush accidents in China coalmines, it was concluded that the deciding cause of accident is the mutual effects exerted by water head pressure in pore aquifer, caving of overlying mining plate, and fissures. Many experiments have proved that the “critical hydraulic gradient” of water-sand inrush is closely correlated with fissure size in the overlying mining plate and the physico-mechanical properties of the soil mass in pore aquifer [31-32]. When fissure size goes up, critical hydraulic gradient goes down. The critical hydraulic gradient causing destructive seepage in pore aquifer will decrease exponentially with fissure width increases [33-35], see Fig. 8.
In addition, laboratory results have obtained the correlation between the critical hydraulic gradient ($J$) that causes destructive seepage in the pore aquifer and the content ratio ($\omega$) of coarse particles (diameter $>2$mm) in the pore aquifer, which is $J=159.81\omega^{-1.3712}$, ($R^2=0.85$).

1. When $\omega \in 15\% \sim 35\%$, the critical hydraulic gradient $J$ linearly decreases. The form of penetration destroy in pore aquifer is soil flow or suffusion erosion.

2. When $\omega \geq 35\%$, the critical hydraulic gradient $J$ significantly decreases. Right now, the penetration destroy in pore aquifer is piping form. The reason is that when coarse particles ratio ($\omega$) is over 35%, fine particles, which is of low content ration, cannot fill in the pores between coarse particles. The coarse and fine particles are not closely bound and the constraint force in-between is not strong enough, allowing fine particles easily move between pores. As a result, lower fine particles content creates smaller constraint force between coarse particles, thus compromising the capability of pore aquifer in resisting penetration destruction. Fine particles will be easily driven out with penetration water flow. Penetration in pore aquifer inrushes in piping form.

5. Conclusions

Based on above analysis, conclusions can be drawn as follows:

1. Water-sand inrush is the main hazards in mining under porous aquifer. There are two types of channels for water-sand inrushing that one is primary conducting channels such as water-conducting fault, pre-existing fractures, etc., another is men-made conducting channels include caving zone and water-conducting fractures caused by mining activities, the goaf space caused by waterproof coal pillar caving, etc.

2. There are many factors affecting water-sand inrush mining under pore aquifer. However, from the cases of coal mine water hazards in China, there are four situation of water-sand inrush such as water-conducting fracture zone channelling the pore aquifer of the bottom Quaternary loose strata through primary conducting channels, water-conducting fracture zone implicating the bottom aquifer, caving zone implicating the bottom aquifer and waterproof coal pillar caving as mining steeply-inclined seam. The intensity of the water-sand inrush is closely correlated with lithology of the overlying strata and hydrogeological conditions of the bottom aquifer.

3. Penetration tests have revealed that the “critical hydraulic gradient” which causes water-sand inrush is correlated to the size of mining fractures in overlying strata and the physio-mechanical properties of the pore aquifer. The larger the water-sand conducting fractures, the smaller the critical hydraulic gradient; when coarse particles content in pore aquifer is over 35%, the critical hydraulic gradient will decrease significantly and penetration in pore aquifer is piping form.

Acknowledgment(s)

This article is funded by National Natural Science Foundation of China (41773100, 41373095), Research Project of Wanbei Coal-Electricity Group Co. Ltd (2019) and Research Project of Huaibei Mining Group Co. (2019).
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