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Characteristics of Mine Water Inrush and Its Mechanisms — a Case Study in the Ganhe Coal Mine, Shanxi, China

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Abstract Mine water inrush is a primary hazard in the process of coal mining, which is caused by various factors, complex processes and induced mechanisms, and studies on the spatiotemporal evolution of the processes and behavior of mine water inrush disasters may help determine their causes and effects. These studies may also provide an appropriate scientific basis for disaster prevention and control measures. Using a water inrush accident with a maximum flow rate of 730 m^3/h and a stabilized rate of 300 m^3/h, we studied its spatial and temporal characteristics, such as changes in the flow rate, the water level and the water quality following the inrush incident. We determined the phase characteristics of the water inrush process, which were divided into six stages. Based on the geological conditions, crustal stress conditions and hydrodynamic effects, a comprehensive analysis was performed to study the water pathway evolution near the F13 fault and evaluate the nonlinear evolution process from water seepage to water inrush. The research results revealed that the mechanism of water inrush from faults is related to the combined forces of high crustal stress and high hydraulic pressure.
Keywords mine water inrush, spatiotemporal evolution, mechanism of water inrush

Introduction

Coal has long been one of the main energy sources in China. However, the complex hydrogeological conditions present hazards in many coalfields due to the threats posed by a variety of water bodies during the process of mining coal. Unfortunately, mine water disasters have become a normal occurrence in coal mining. The most harmful of mine water disasters is mine water inrush, a phenomenon in which water resources suddenly fill the space of the mine during mining processes. The occurrence of water inrush often results in the degradation of the production conditions and sometimes results in the submergence of tunnels and mines, causing significant personnel casualties and property loss. Statistics released by governmental authorities, such as the State Administration of Coal Mine Safety, have shown that 496 major water inrush accidents occurred in China from 2001 to 2013, causing 3,155 deaths. Even in the USA, underground coal mining is one of the most dangerous occupations (Abay et al. 2013).

In most water inrush accidents, faults play a key role as common water conducting channels. Rock permeability has been closely connected with the scale, mechanical properties and filling status in fault zones (Evans et al. 1997, Tueckmantel et al. 2012, Petrie 2014). Water inrush caused by faults is one of the three main water disasters, which also include collapsed columns and artificial disturbances. Because the process of fault reactivation and development into a water channel under the influence of mining occurs over a long period of time, the time lag of water inrush and fault reactivation has been studied (Li et al. 2010, Xu et al. 2012). In addition, methods of preventing all types of water disasters have been discussed (Miao et al. 2008, Wu et al. 2013). Nevertheless, understanding the behavior characteristics and mechanisms of mine water inrush has been difficult because the induced factors in the water inrush process are diverse and multidisciplinary, and there is a lack of related field data on the geology, hydrology, stress, etc.

In situ observation data collected by the authors has demonstrated that the maximum flow rate of the water inrush accident in the Ganhe coal mine reached 730 m^3/h and had a stable flow rate of up to 300 m^3/h. Based on an analysis of the data, we found that the water inrush occurred in stages that possessed an obvious spatial-temporal correlation. Our research focused on analyzing the spatial-temporal evolution of mine water inrush and its inherent mechanisms based on the geological and hydrodynamic conditions and crustal stress. This research should deepen the understanding of the mechanisms of water inrush and provide a scientific basis for its subsequent control.

Overview of the mine

As shown in Figure 1, the Ganhe mine, which is part of the Huoxi coalfield, is located approximately 23 km north of Hongtong County, Shanxi, on the west bank of the Fenhe River. The mine covers a 35.6 km^2 rectangular-shaped area, trending 9 km long from northeast to southwest and 4 km from northwest to southeast.

The designed production capacity of the mine is 2.1 million tons per year, and the geological reserves and recoverable reserves are 313 million tons and 171 million tons, respectively. There are four main minable seams labeled $1^\#$, $2^\#$, $10^\#$ and $11^\#$. The mining is conducted at two levels: the first level is +80, where seams $1^\#$ and $2^\#$ are extracted, and the second level is -15, where seams $10^\#$ and $11^\#$ are extracted. At present, only the upper seams are extracted. The service duration of the mine is 58.3 years, and the mine was developed with a vertical shaft access.

The whole Ganhe mine is exploited under high hydraulic pressure. The static water level of the Ordovician strata is +517 m, and the lowest elevation of seam $2^\#$ is -70 m. Therefore, the maximum water pressure is almost 5.9 MPa. There are four main aquifers in the coal-bearing sequence: K_8, K_9, K_2 and K_3. The former two aquifers are sandstone aquifers in the lower Shihezi Formation (P_1xs), whereas the latter two aquifers are limestone karstic fissure aquifers in the Taiyuan Formation (P_1t). Beneath the coal-bearing sequence, there are two Ordovician karstic fissure aquifers in the upper Fengfeng Formation and upper Majiagou Formation. Among the aquifers, the average thickness of the K_2 limestone is 9.11 m, and the water level is approximately 505 m, whereas the average thicknesses of the upper Fengfeng Formation and upper Majiagou Formation are 30 m and 60 m, respectively. There are 8 long-term observation boreholes for monitoring changes in the water level and temperature of the Ordovician and K_2 limestones (fig.1).

The geological structures are rather complex because of the development of faults and collapsed columns. The strikes of the faults are mostly NE or NNE, and the F_{13} fault is located in the middle of the mine with a dip of 70°.

Spatiotemporal evolution of the mine water inrush

Water inrush process

As shown in Figure 2, the water inrush process occurred in multiple stages, from water seepage to water inrush to its decline and stabilization. The whole process can be divided into six stages. The first stage was the water gathering phase or water oozing phase (I), which lasted approximately one hour. In this stage, a small quantity (< 3-5 m^3/h) of groundwater slowly flowed from the top anchor of the right side of the roadway. The second stage was the rapidly increasing water phase (II), in which the water flow rate increased from 3-5 m^3/h to 30 m^3/h and then to 730 m^3/h. This phase lasted for 2 hours and 35 minutes. The third stage was the constant maximum water flow rate phase (III). As a result of the high hydraulic pressure, the maximum flow rate of approximately 730 m^3/h was maintained for 2 days. The fourth stage was the declining water phase (IV), which occurred two days after the water inrush and featured gradually decreasing water levels. On January 23rd, 2013, the water flow rate was 350 m^3/h. This stage lasted approximately 48 days. The fifth stage was the water stabilization phase (V), during which the water flow rate was stable at approximately 300 m^3/h until June 17th, 2013. The sixth stage was the water declining and re-stabilizing phase (VI). Because of the influence of another water inrush accident associated with the adjacent working face 2-112 on June 17th, 2013 with the same water source, the water quantity at the water inrush point declined further and eventually stabilized at approximately 80 m^3/h.

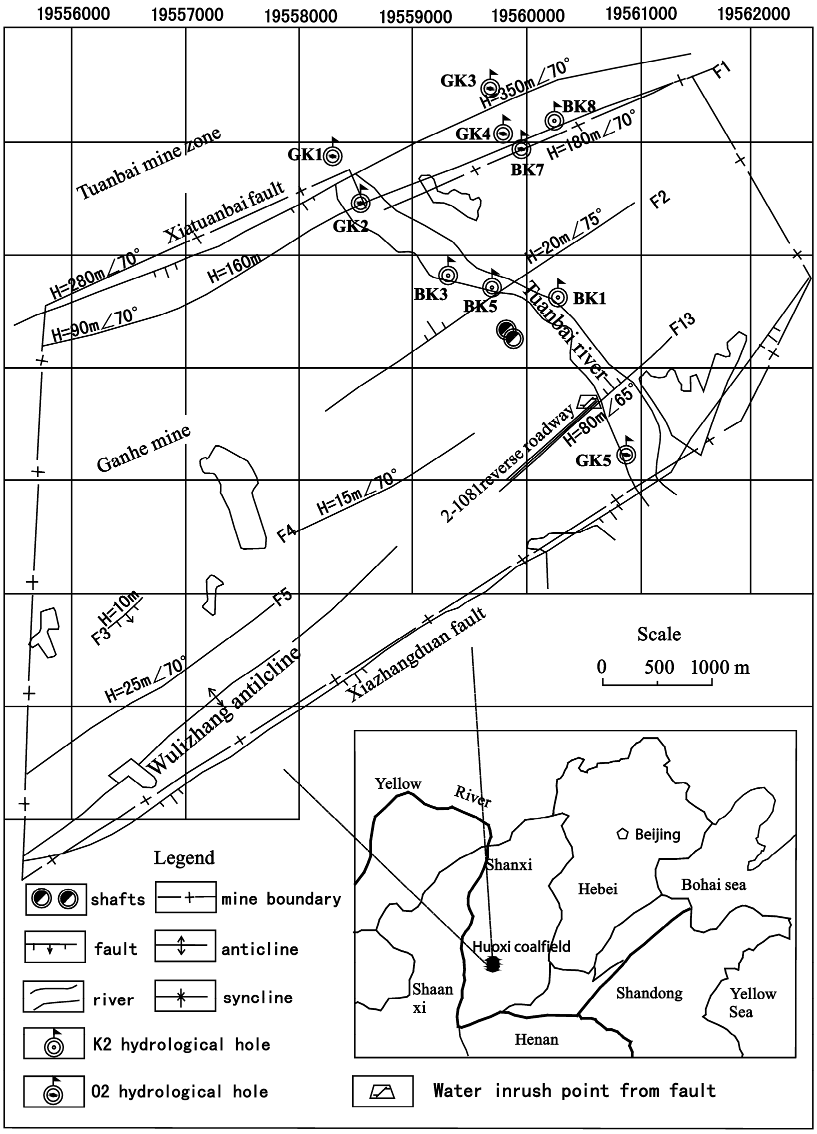

***Fig. 1** Structures of the observation boreholesin the Ganhe coal mine.*

Spatiotemporal dynamics of water inrush quality

After the accident, water samples were promptly extracted for a water quality analysis. As shown in Table 1, the composition of the water samples collected on Nov 27th before the water inrush show a higher concentration of Na^+ and lower concentrations of Ca^{2+} and Mg^{2+}, indicating a water quality of lower salinity than the background data of the main aquifer water and roof sandstone fissure water (table 2). The composition of the water samples extracted on December 4th after the water inrush showed a significant increase in the Ca^{2+} and

Mg^{2+} concentrations and a sharp decrease in the Na^{+} content, which indicated a gradual increase of salinity. The water quality type was SO_4HCO_3-CaMg(Na), which was closer to the water quality of the Permian Taiyuan Group K_2 limestone. After Dec 21st, the salinity increased rapidly to more than 1000 mg/L, which suggested that the K_2 limestone water was gradually mixed with Ordovician limestone water in the inrush water.

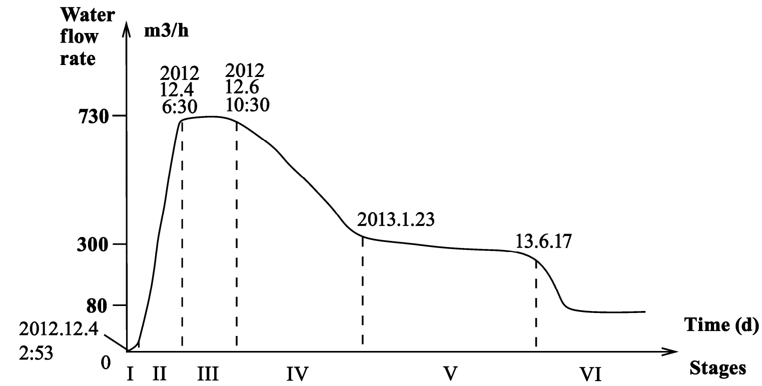

***Fig. 2** Curve of the water inrush flow rate with time*
I - water gathering stage; II - rapidly increasing water stage;
III - constant maximum flow rate stage; IV - declining water flow rate stage;
V - flow rate stabilizing stage; VI – second water declining and stabilizing again stage

***Table 1** Water quality of the mine water inrush (ion concentration unit: mg/L)*

Date	Turbidity	PH	K^{+}+Na^{+}	Ca^{2+}	Mg^{2+}	HCO_3^{-}	SO_4^{2-}	Cl^{-}	M	Total hardness
11.27.2013	Blackish	8.2	206.85	21.17	18.28	367.28	208.3	46.31	894.93	128.14
12.4.2013	Black	7.71	79.79	73.22	39.84	385.35	159.83	51.46	795.77	346
12.5.2013	Transparent	8.15	81.9	74.86	44.18	309.65	219.96	41.58	783.7	368.87
12.6.2013	Transparent	7.61	90.27	93.16	48.35	314.53	262.67	46.38	865.75	431.74
12.7.2013	Transparent	7.45	78.53	95.62	54.55	317.95	255.65	44.5	857.35	463.41
12.1.2013	Transparent	7.51	90	105.91	60.55	301.34	334.04	63.57	960.39	513.81
12.11.2013	Transparent	7.51	71.48	110.19	47.46	309.32	328.81	49.06	920.96	470.61
12.15.2013	Transparent	7.44	64.48	108.16	53.54	298.41	277.51	48.03	859.19	490.57
12.17.2013	Transparent	7.58	74.98	99.08	60.51	296.46	342.03	48.03	928.91	496.59
12.19.2013	Transparent	7.78	62.86	113.35	59.09	317.95	311.77	51.28	925.19	526.38
12.21.2013	Transparent	7.69	82.33	106.06	63.96	300.37	391.63	46.65	1000.31	528.23

***Table 2** Water quality background of the main aquifers (ion concentration unit: mg/L)*

Date	Borehole No	Aquifer	PH	K^{+} +Na^{+}	Ca^{2+}	Mg^{2+}	Cl^{-}	SO_4^{2-}	HCO_3^{-}	Salinity	Water quality type
4.23.1986	116	K_8	7.7	193.22	38.36	14.06	104.36	177.2	296.34	823.54	HCO_3SO_4Cl-Na
8.25.1988	127	K_2	7.7	151.51	35.27	28.09	103.12	301.5	195.14	857.45	SO_4HCO_3(Cl)-Na
12.2.2008	GK5	O_2	7.46	75.63	271.5	42.44	49.99	715.77	247.8	1404.67	SO_4-Ca

Water level elevation changes before and after the mine water inrush. The water levels observed from 6 effective boreholes are shown in fig.3.

Mechanism of water inrush

One of the authors was at the site when the water inrush occurred. The field observations and comprehensive analyses of the geological and hydrogeological conditions and mine pressure processes should help in the determination of the mechanisms of mine water inrush. The geological data available for the mine showed that the F_{13} fault was to the east of the three alleys and connection roadway 108, the waterproof coal pillar near the water inrush point decreased greatly to less than 20 m, while the throw of the F_{13} fault increased to approximately 80 m, resulting in the contact of the coal seam with the K_2 limestone of the Taiyuan Formation for a short distance (fig.4). In addition, the redistributed stress caused by the roadway excavation produced additional extrusion fractures in the surrounding rock, especially at the top of the rock mass on both sides, which further extended the water channel.

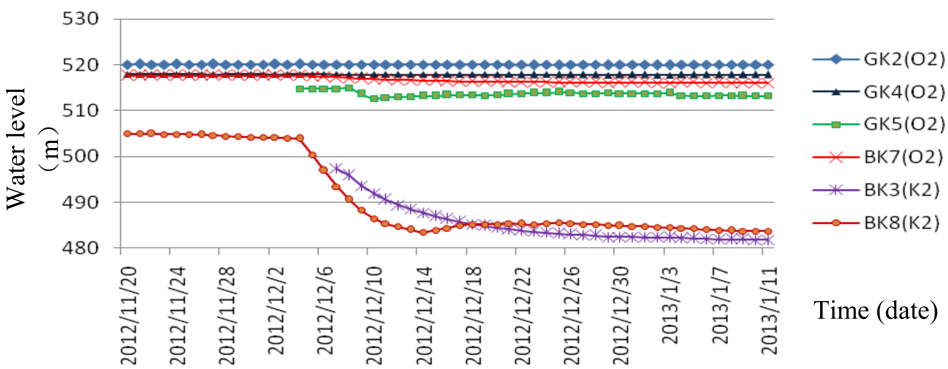

***Fig. 3** Curve of the water level with time in the observation boreholes.*

All of these fractures along with the F_{13} fault and its associated fractures produced a strong deformation and damage due to the joint action of the high hydraulic pressure and high crustal stress. The F_{13} fault was activated and produced numerous new water conducting fissures. The fissures connected, and the strata became offset, which led to the snapping of the anchor cable. A large water channel rapidly formed along the bolt hole and began to seep. Simultaneously, small particulate matter was taken away by the water flow, and the channels were eroded and hollowed, causing the channels to open even more. Because of the accumulated water quantity and potential, the channels were thoroughly penetrated, and torrents of water poured from the walls of the left side through the combined effect of the 4.12 MPa water pressure and high crustal stress. The comprehensive results from the analyses revealed that the water inrush was caused by an activated fault combined with the influence of high crustal stress and high hydraulic pressure.

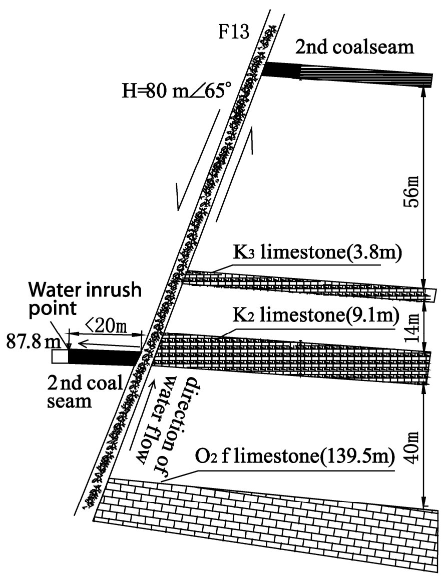

***Fig. 4** The geological section map near the water inrush point.*

Conclusions

(1) Mine water inrush disasters are destructive and are caused by various factors, complex processes and induced mechanisms. However, studies on the spatial and temporal characteristics of mine water inrush processes may help provide a comprehensive understanding of mine water inrush mechanisms and offer a scientific basis for subsequent disaster prevention and control measures.

(2) The example of the Ganhe mine water inrush disaster revealed that the mine water inrush process has obvious stages, and the mine karst medium was strongly inhomogeneous and anisotropic.

(3) Based on the geological conditions, mine pressure conditions and hydrodynamic effects, we comprehensively analyzed the complex nonlinear evolution process that enlarged the water inrush channels and changed the water flow from seepage to water inrush. Even faults that would normally be impervious to water could be activated under the associated influence of the above factors, and enlargement of the water channels could eventually result in water inrush from activated faults, especially under the combined forces of high crustal stress and high hydraulic pressure.

Acknowledgements

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