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Advances in the Research on Mechanisms of the Groundwater Inrush Caused by the Fault Reactivation in Coalmines

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Abstract

In recent years, the accidents of the groundwater inrush caused by the fault reactivation from coal seam floors have been increasing in groundwater-related coalmine accidents in China. Such groundwater inrush accidents have not been prevented effectively, because the mechanism of the groundwater inrush caused by the fault reactivation from coal seam floors has not been clearly recognized. In this paper, there was a new knowledge of the groundwater inrush caused by the fault reactivation from coal seam floors in the domain of prevention and cure water disaster in coalmines firstly, based on the review of the fault reactivation concept in different domains. Then the advances in the research on mechanisms of the groundwater inrush caused by fault reactivation in coalmines were expounded and research findings of the groundwater inrush caused by the fault reactivation with each view were summarized. In the end, the mechanisms of the groundwater inrush caused by the fault reactivation have been clearly recognized on the basis of influential factors of the groundwater inrush caused by the fault reactivation.

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keywords: Coalmine; fault reactivation; mechanism of groundwater inrush; advance

1. Introduction

Among the reported accidents in coalmines in China, more than 80% are related to the faults. Shallow coal resources are exploited completely in the most mining area in China and deep mining is performed

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widely in most of mining area. The probability of the groundwater inrush caused by faults associated with the fault reactivation in deep underground coalmines is more than in shallow underground coalmines [1].

Nomenclature

K_0	permeability coefficient of original fissures in the fault zone
K_{max}	maximum permeability coefficient of original fissures in the fault zone
α	coupling parameter
t_0	time of inrush pathway fully formed
t	time of inrush pathway formed
β	dip angle of a fault
φ_1	friction angle of a fault plane
τ_{max}	shear limit of a fault
P	constrained force of a fault plane
h	thickness of a panel
q	distributed load over the coal seam floor
a	width of a rock block
p'	fluid pressure in fissures of the fault zone
C	cohesion of a fault plane
φ'	internal friction angle
α'	included angle of a micro-unit with dislocation slip traces
σ_1	maximum principal stress of a micro-unit
σ_3	minimum principal stress of a micro-unit
K_1	stress intensity factor of fissure tip in the fault zone
λ	coefficient of horizontal pressure
K	coefficient of concentration
H	mining depth
γ	volume weight of rocks
K_{1C}	fracture toughness of plane strain

If a permeable fault exists, safety pillars against the groundwater will be designed and retained according to the Rule of Mine Prevention and Cure Water Disaster. But for an impermeable fault, the mechanisms of the groundwater inrush caused by faults are not clearly recognized and groundwater inrush accidents are not prevented effectively. As a result, the groundwater inrush occurred.

Based on the review of domestic and foreign literature, it is found that a concept of the fault reactivation occurs in different domains with different emphases. Three categories are as follows:

The first is in the domain of tectonics. The fault reactivation is that earlier fault has been healed. The strata were inclinable to develop continually along inherited faults during the later tectonic movements. Then the fault was reactivated [2, 3]. This is the endogenetic force processes of a cratonic lithosphere transformed by the therm-tectonic in the earth [4].

The second is in the domains of mining engineering, tunnel engineering and underground engineering. Considering the stability of surrounding rock, the fault reactivation is the processes of relative displacements of both fault walls along a fault plane in these domains. This process is considered as shearing motion by Wankui Wang and Xianbiao Mao [5]. Jiwen Wu et al. proposed that the relative positions of both fault walls are changed with displacement discrepancies between of a hanging wall and a heading wall [6].

The third is in the domain of prevention and cure water disaster in coalmines. The fault reactivation is the phenomenon of the groundwater inrush from impermeable faults by mining-induced [7]. Even it is not consider the deformation or displacement of faults. On the basis of previous studies, the author brings new knowledge of fault reactivation in this domain. The fault reactivation is that impermeable faults deform and slip while the high-pressure water plays the role of hydraulic fracturing on fissures of rock masses in the fault zone, and the role of coupling interactions of two effects.

Currently, the concept of the groundwater inrush caused by the fault reactivation has not been clearly recognized in previous studies. So the author has rethought the mechanism of the groundwater inrush caused by the fault reactivation in the domain of prevention and cure water disaster in coalmines. Several studies will be done. The developing processes of the mechanisms of the groundwater inrush caused by the fault reactivation are generalized in this domain. The various viewpoints are enumerated in the research of the groundwater inrush caused by the fault reactivation. Research approaches and methods of the groundwater inrush caused by the fault reactivation are summarized.

2. Developing process of the mechanisms of fault reactivation

There are several different stages of the researches of the groundwater inrush caused by the fault reactivation. An early research (1990) is that some structures which still remain residual tectonic stresses are reactivated. And the groundwater inrush is caused on the basis of the tectonics theory [8]. Since then researchers paid more attention to rock stability analysis. Because the fault is deformed, slipped and reactivated, these cause the groundwater inrush accidents. For example, Xiaozhao Li analyzed that the groundwater inrush caused by the fault reactivation is induced by mining when the permeable faults are water-bearing and permeable in the initial state [9]. The reasons are as follows. In the domains of tunnel engineering, the natures of structural rock masses are changed by powerful additional tangential stresses and surrounding rock changed near the fault zone. And original fissures are developed and new fissures are generated and opened. In addition, the obvious space-time effects between the fault reactivation and the groundwater inrush are found too. At this stage, stimulating factors are understood differently by some scholars. For example, Jingming Wang considered that the fault reactivation is motivated by mining factors in a mining district [10]. The reactivated fault has all kinds of damaging effects under the water pressure and water rising along the fault plane. Langjie Li considered that the fault reactivation is motivated by water pressure factors and the relative movements between the key stratums of both fault walls are produced [11]. Moreover, there is a research that the fault reactivation is motivated by water pressure factor only from the perspective of the water pressure of an aquifer. For instance, Yanfeng Liu and Hanzhou Song considered that the partial permeability of impermeable structural surface will be ameliorated in the long-term at high water pressure [12].

Previous researches for describing the fault reactivation are summarized. These all have the sequencings between the fault reactivation and the groundwater inrush. That is to fault reactivation firstly, then groundwater inrush. Recently, some researches began to focus on coactions of the stress field and the seepage field rather than simply considered the stress field changed by the rock pressure. For example, Yaoqing Hu found that the closure and impermeable fault is well filling and cementation and its

permeability is increased by the effects of the rock pressure, solid-fluid coupling and mining. Then the pathway is formed and the groundwater inrush occurs [7].

3. Emphases of the mechanisms of fault reactivation

From the perspective of the groundwater dynamics, the fault reactivation is related to time. As time goes on, the groundwater inrush occurs only. Guoyong Yang et al. tried to introduce time parameters into permeability coefficient with considering the time effect (see the equation 1). The permeability of the fault zone will be changed when permeability coefficient changes. The process of a pathway formed by the fault reactivation and variation rules of the permeability are described [13].

$$K = \begin{cases} K_0 e^{\alpha t}, t < t_0 \\ K_{\max}, t \geq t_0 \end{cases} \quad (1)$$

From the perspective of the fractals, a fault plane has fractal characteristics. Guangming Yu and Heping Xie tried to introduce the fractals into the research of the fault reactivation. They deduce fractal dimension formulas of the faults which are reactivated by mining and their residual shear strength after reactivation. The mechanisms of the fault reactivation are provided [14]. Additional stresses will be concentrated near the fault zone when influence sphere of mining reach to the fault. If the fault cannot bear, shear failure of the fault will occurr, stability of both fault walls will lose and integral slippage of the fault will produced. Then the groundwater inrush occurs.

From the perspective of the rock mass structures of both fault walls, the groundwater inrush from the coal floor was analyzed by using the theory of the key stratum in strata control by Minggao Qian [15]. It is obtained that faults are opened and failure under the water pressure. Limit of the fault reactivation is solved by the equation 2 and shear limit of a fault is solved by the equation 3.

$$\beta \geqslant \varphi_1 \quad (2)$$

$$\tau_{\max} = \frac{2P_{\max}}{h} = \frac{3qa}{4h} \quad (3)$$

From the perspective of the mining engineering, the mechanisms of fault reactivation are analyzed by using the theory of the rock pressure. Xingli Lu and Quansheng Liu gave the criterions of fault reactivation that tangential and normal deformation of the fault plane occurred or not [16]. Fault reactivation is motivated by the abutment pressure around a coal face. Qingfeng Li recognized that the process of a compressive fault transformed into shear fault or tensile fault under the bearing pressure and gave two forms as fellow [17]:

- When the maximum principal stress of the fault is the tensile stress, the compressive fault is transformed into the shear fault.
- When residual shear stress (τ') of the fault zone greater than or equal zero, the compressive fault is transformed into the tensile fault (see the equation 4).

$$\tau' = \sigma_1(\sin\alpha' - \cos\alpha'\tan\varphi') - \sigma_3(\cos\alpha' + \sin\alpha'\tan\varphi') + p'\tan\varphi' - C \quad (4)$$

4. Research approaches and methods of fault reactivation

4.1.Simulation experiment of physical analog

The simulation experiment of physical analog describes accurately the development process of the fault reactivation. The mechanisms of the fault reactivation are analyzed under deep mining by using the 2D similar model experiment by Jianping Zuo [18]. Based on data monitoring the fracture zone is appeared in the fault footwall and faults begin to reactivate due to an abutment pressure around a coal face. When large concentrated stress is generated near the fault zone, faults are dislocated relatively and slip. This is the fault reactivation. Suping Peng et al. proved that faults are reactivated easily when the direction of the rock pressure before a working face is parallel approximately to the strike of the front faults [19]. So faults are not activated easily when the direction of the rock pressure before the working face is perpendicular to the strike of the front faults. Only when the working face was advanced to the vicinity of the fault, the fault reactivation occurs.

4.2.Methods of numerical analysis

The author believes that numerical analysis can only be a quantitative calculation and qualitative analysis. The fault reactivation is simulated by Lilian Chong et al. with using the RFPA software of FEM [20]. It is obtained that impermeable faults are transformed into permeable faults under certain mechanics and hydraulics boundary conditions. In addition, the processed of the fault reactivation are analyzed by Haibo Bai with using the FLAC software of FDM [21] and the processed of the fault reactivation are simulated by Xingli Lu et al. with using the UDEC software of DEM [16].

4.3.Methods of theoretical analysis

Theoretical analysis is a way to study the mechanisms of the fault reactivation. Wankui Bo and Xianbiao Mao considered that a fault dip affects the shear stress and normal stress of a fault plane. The effects of the fault reactivation and the mechanical mechanisms for the influences of the fault dip on the fault reactivation are analyzed. And they judged that the mechanism of the fault reactivation is a mechanism of compression-shear failure [5]. Zilin Li considered that an abutment pressure around a coal face is the fundamental factor of the fault reactivation, built the mechanical model of the fault reactivation (see the equation 5) and gave the conditions of joints initiation and extending [22].

$$K_1 = (\lambda\sigma_1 - \sigma_3)\sqrt{\pi\beta} = (\lambda K\gamma H - \sigma_3)\sqrt{\pi\beta} \geq K_{1C} \tag{5}$$

5. Analysis of influential factors of fault reactivation and rediscovered of fault reactivation

Through the development of mechanisms of the groundwater inrush caused by the fault reactivation, it is can be found that influential factors of the groundwater inrush caused by the fault reactivation are understood differently by scholars. For example, Liming Yin and Weijia Guo considered the fault reactivation is fracture and caving of rock masses in the fault zone and its affected zone by mining effects [23]. Huiyong Yin and Jiuchuang Wei also considered the faults around the coal face are reactivated by mining effects [24]. And they provided the mechanisms of the groundwater inrush caused by the fault reactivation. It is that fissures of rock masses in and around the fault zone are re-expanded and opened by the fault reactivation, permeability of the fault zone is changed and original impermeable faults can be transformed into permeable faults. To sum up, mining is stimulating factor. But based on the analysis typical examples of the groundwater inrush from faults which include the cases of the groundwater inrush caused by the fault reactivation, the author obtained other factors e.g. the seepage field. In this regard, some scholars have the same findings. For example Yaoqing Hu found other factors e.g. rock pressure, mining, solid-liquid coupling, etc [7].

The mechanical mechanisms of the groundwater inrush caused by the fault reactivation are studied in detail. For example, Haijun Zhao et al. analyzed that the stratum are moved by excavation [25]. And this causes the fault reactivation. The mechanical mechanisms of the groundwater inrush caused by the fault reactivation are explained as follows. The static equilibrium of a fault plane is broken by excavation under additional stress and shear stress of the fault plane is increased. And this will change the relative displacement of both fault walls along the fault plane and their shear displacement will be changed significantly. Shear strength of the fault zone, deformation modulus of the fault zone materials and fracture aperture of the original fissures in and around the fault zone are the kernels of mechanism study.

On the basis of factor analysis of the fault reactivation, the groundwater inrush caused by the fault reactivation is caused by combined actions of the seepage field and stress field. That is obtained on analysis of typical cases of the groundwater inrush from faults. So the author rediscovered the mechanisms of the groundwater inrush caused by the fault reactivation from new and more comprehensive perspectives (see the figure 1).

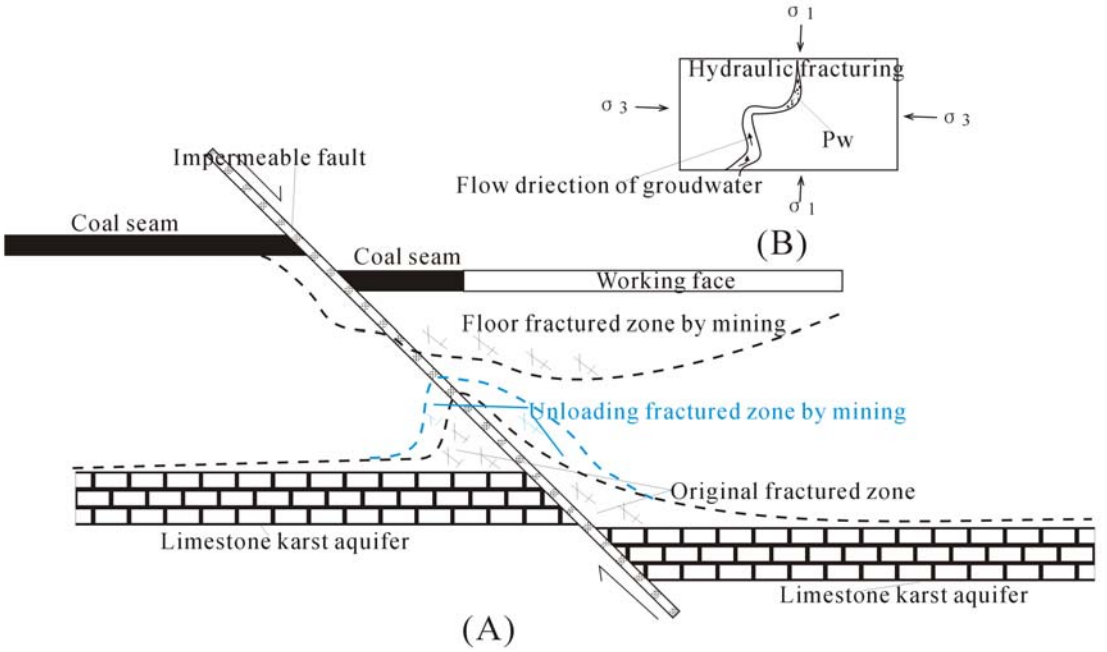

Fig1. Schematic mode of groundwater inrush caused by the fault reactivation from coal seam floors in coalmines

In the original geological states, the high-pressure water has risen to a certain height along the natural joints and fissures of the aquifuge and it is full of the free surface for the fissure tip. The mechanical equilibrium is kept by the water pressure of the aquifer and in-situ stresses together. The mechanical equilibrium of the fault plane is broken by stimulating factor such as mining. Then strong hydrodynamic actions of high-pressure water make hydraulic fracturing impact on original fissures in and around the fault zone. And original fissures are opened, extended and connected further. At the same time, the stress field of rock masses is changed by mining-induced. Unloading fissures are developed and extended and the rock masses of the fault will be sheared and slid. The groundwater inrush occurs on the coupling interaction. And this is the essence of the groundwater inrush.

6. Conclusions

- The mechanisms of the groundwater inrush caused by the fault reactivation are studied and summarized which is recognized that a seepage field is an influential factor of the groundwater inrush caused by the fault reactivation. Thus, a new knowledge of the mechanisms of the groundwater inrush caused by the fault reactivation was found. The groundwater inrush caused by the fault reactivation is the result of the coupling interaction between the seepage field of the aquifer and the stresses field of mining by mining stimulation.
- Research directions of the groundwater inrush caused by the fault reactivation are building of coupled model. Currently, there are a lot of research contributions of single factor analysis. And mechanical models are studied and built maturely with considering the stress field. The general trends of the research are as follows. It is from microscopic view to macroscopic view. And microscopic damage and fracture mechanics of rock masses in both fault walls will be considered and microcosmic development of water flowing fractured zone will be studied. The key problems of no continuity, nonlinearity, heterogeneous and anisotropism will be solved.
- For deep mining, the influences of characteristics of high pressure water and high ground stress will be emerged. When the predictions and forecast of the groundwater inrush can be built for the underground mining operation. The time effect on the groundwater inrush caused by the fault reactivation will be considered. Such as the forecast of lagging water inrush.

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