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Numerical simulation of mining-induced fracture evolution and water flow in coal seam floor above a confined aquifer

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ABSTRACT

Coal mining above a confined aquifer involves the risk of water bursting into the mining excavation through fractured floor strata. Understanding the key mechanisms and processes of water inrush related to the fracturing evolution induced by the coupled stress–damage–flow interactions during the mining process is of vital importance for predicting and preventing the hazard accurately and in a timely manner. A micromechanics-based coupled damage and flow modeling approach is presented to simulate the progressive development of fractures and the associated water flow in the floor strata during mining above a confined aquifer. This approach combines a microcrack-based continuous damage model with generalized Biot poroelasticity, in which the macroscopic elastic stiffness, Biot effective stress coefficients and overall permeability are explicitly related to the microstructural microcrack kinetics. The numerical results successfully reproduce the stress re-distribution, acoustic emission (AE) evolution, fracture development, permeability changes and water inrush channel formation in the floor strata during the mining process. The deepest fractured zone with highly enhanced permeability appears under both sides of the mined-out area and extends rapidly downward with the increase of mining distance, eventually penetrating into the underlying confined aquifer to form the through-going water inrush channel where the hydraulic pressure and water flow velocity increase sharply. Moreover, the heterogeneity based on a Weibull distribution law is introduced in the numerical model, and the effects of the homogeneity index and confined hydraulic pressure on the process of water inrush in heterogeneous floor strata are examined. Results from such analyses indicate that for a lower homogeneity index (*i.e.*, more heterogeneous floor strata) or a higher hydraulic pressure, the water inrush is more prone to occur at a shorter critical mining distance. Also, a higher homogeneity index or a higher hydraulic pressure will result in a sudden formation of water inrush, while a lower homogeneity index or a lower hydraulic pressure will cause a more gradual process of water inrush. The present study provides an improved understanding of the mechanisms and processes of water inrushes from underlying confined aquifers and will be helpful in practice to predict and prevent water inrush hazards.

1. Introduction

Most coal mines located in the permo-Carboniferous coalfields in North China are threatened by the Ordovician limestone aquifer under the coal seams [1–3]. The Ordovician limestone strata are a confined karst aquifer containing large volumes of water with a high hydraulic pressure. The floor strata between the aquifer and the coal seams, normally comprising mixed impermeable clay layers with high strength sandstone or carbonate layers, can serve as the geologic barrier (*i.e.*, water-resisting strata) that prevents the upward migration of confined water, but the thickness of such strata is relatively thin, varying from a few meters to dozens of meters. When coal extractions are operated above the aquifer, the water-resisting floor strata may be broken by both hydraulic and mining-induced pressures. This enhances the hydraulic conductivity of water-resisting strata and eventually leads to large uncontrolled volumes of water bursting into mining excavations. This phenomenon is commonly called water inrush or water outburst hazard which not only brings about grievous casualties and heavy economic losses for coal mines but also seriously damage the geohydrological environment due to mine drainage [4–6]. Although the water inrush hazards in coal mine operations have been known for decades, the contributing mechanisms are not clearly indicated [1,3,7]. This knowledge gap has limited our ability

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to address this crucial issue for safer coal extraction above confined aquifers and defines the objective of this study.

In recent decades, the investigations on water inrush mechanisms have been highlighted. A number of empirical criteria and analytical models have been proposed for the analysis and predication of water inrushes from underlying confined aquifers, including the water inrush index, hypothesis of three zones in floor strata, plate model, and key strata model, among others (see the comprehensive reviews by Wang and Park [3]). These theoretical investigations play an active role in evaluating the risk of water inrush hazards in engineering practice. However, the physical mechanisms and processes involved in water inrushes are not readily depicted by these simplified analytical models. There is a lack of knowledge in these studies on the coupled hydraulic and mechanical behavior of rock strata and the hydraulic conductivity changes in rock strata with reference to fracturing characteristics. For a better understanding of water inrush mechanisms and processes, numerous numerical simulations of water inrushes associated with mining processes have been performed with different numerical methods, such as FEM, FDM and DEM [8]. For example, Wang and Park [3,9] carried out a coupled hydro-mechanical modeling of mining above a confined aquifer with $FLAC^{3D}$ to investigate the failure behavior of floor strata under varying geological conditions and mining configurations. Guo et al. [10] proposed a coupled double porosity FEM code called COSFLOW for the prediction of water inflows. Zhu et al. [11] presented a coupled process-based numerical model for mining excavation to analyze the pore pressure change during mining. These numerical investigations show that permeability enhancement induced by mining is the key mechanism promoting water inrushes, and this has contributed to the scientific understanding of water inrush hazards. However, most of these reported numerical models follow the traditional theory of elastic–plastic mechanics and therefore cannot adequately replicate the fracture initiation, propagation and coalescence, together with the formation of a water inrush pathway in rock strata.

Numerical simulations can be a powerful tool for addressing the water inrush issues in coal mines but have specific features that must be incorporated [4]. To our knowledge, the mining-induced redistribution of the stress field leads to the initiation and growth of pre-existing cracks, and potentially creates a fractured zone with high conductivity around the excavations. This fractured zone provides a pathway for confined water inflow, which reduces the effective stresses (increases the pore pressure) in rock strata and in turn further promotes the fracture development [12,13]. Such reinforcing coupling processes can ultimately accelerate a water inrush event. Yang et al. [14] further noted that the water inrushes in coal mines have the same mechanism as the hydraulic fracturing and that they are both related to the fracturing evolution induced by the coupled stress–damage–flow interactions. Therefore, there is a real need for developing numerical models to accommodate the coupling behavior of damage and flow in rocks to closely characterize the physical mechanisms responsible for water inrush hazards induced in mines.

In current studies, however, there are very few numerical models capable of reproducing the fracturing behavior and associated fluid flow in rocks under hydro-mechanical conditions [15]. Tang et al. [16] originally proposed a flow–stress–damage (FSD) coupling model for heterogeneous rocks. This model was implemented within a previously developed code for rock failure process analysis (RFPA) [17] and was used to investigate the mining-induced strata failure and water inrushes [7,18,19]. Such a modeling approach is successful in capturing several features of water inrush phenomenology both in time and in space, but its capacities are limited by the oversimplified phenomenological laws of damage evolution and permeability changes which are not clearly connected to the physical mechanisms. Experiments indicate that there can be significant changes in both the mechanical and hydraulic properties of rocks (*e.g.*, the elastic modulus, Biot effective stress coefficients and permeability) with microcracking [20,21]. Thus, the microscopic kinetics of microcrack growth are of particular importance for modeling the fundamental characteristics of coupled damage growth and fluid flow in rock and should be incorporated into the numerical models that intend to accurately reproduce the fracture process and water inrushes induced by mining [4,22,23]. In view of this, we have recently developed a microcrack-based coupled damage and flow modeling approach to follow the fracturing evolution coupled by fluid flow in rocks [24]. This numerical approach combines a microcrack-based continuous damage model with generalized Biot poroelasticity, in which the tensors of macroscopic elastic stiffness, Biot effective stress coefficients and overall permeability are directly related to microcrack propagation. This allows for replicating the evolution of fracturing and fluid flow in rocks during processes of hydro-mechanical interaction, including key processes at the microscale, in a physically realistic and visual manner.

In general, water inrushes from underlying aquifers can be classified into two types: geologic structures-controlled water inrush and damage-induced water inrush [25]. The former is directly related to the presence of faults [2,19], karst collapse columns [4,26] and pre-existing macro-fractures [27–30] in the floor strata, whereas the later is mainly caused by the mining-induced failure of 'intact' floor strata (usually containing randomly distributed natural small-scale cracks) [3,7,9]. In this work, the proposed micromechanics-based numerical approach is employed for the study of damage-induced water inrush during coal mining above a confined aquifer. The water inrushes controlled by macroscopic geologic structures will be addressed in a future investigation. The present study is conducted to provide a thorough understanding of mining-induced fracturing characteristics and associated hydraulic conductivity variations in the floor strata without macroscopic geologic structures subjected to the influences of the mining process, strata heterogeneity and confined hydraulic pressure as well as to provide deeper insight into the physical mechanisms responsible for damage-induced water inrushes from underlying confined aquifers.

2. Outline of the micromechanics-based modeling approach

In this section, the main features and principles of our previously developed microcrack-based coupled damage and flow modeling approach are briefly summarized, and more details about this approach can be find in Lu et al. [24]. Furthermore, the basic theoretical framework of this approach is a combination of several previous works by [23,31–34]. The reader is advised to consult these earlier studies for more detailed derivations and model validations.

2.1. Basic assumptions

We consider a dual-scale conceptual model for the representation of a realistic rock medium containing micro-fractures (see Fig. 1). A series of regularly arranged, uniform and square mesoscopic elements, *i.e.*, representative elemental volumes (REVs), are used to divide the rock medium at the macro-scale, and each of the REVs at the meso-scale is made of a homogenized porous medium with embedded random microcracks. In principle, the size of the REV should satisfy two requirements: (i) from the macroscopic point of view, the REV should be sufficiently small so that it can be regarded as a component particle of the global material and (ii) from the microscopic point of view, the REV should be