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Variations of hydraulic properties of granular sandstones during water inrush: Effect of small particle migration

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ABSTRACT

The evaluation of the hydraulic properties evolution of granular sandstones in relation with groundwater inrush within faults is an important issue for mining engineering applications. This paper presents the results of an experimental investigation of small particle migration from granular sandstone samples under different original porosities, particle size compositions and water flow pressures. A new rock testing system has been setup to carry out the tests. Based on the results, it is observed that the overall permeability evolution during the tests can be divided into four different phases, including i) re-arrangement of large rock fragments, ii) water inrush with substantial particle migration, iii) continued moderate particles seepage, and iv) steady state water flow. The crushing of edges and corners of large rock fragments, and the evolution of the fracture network has mainly been observed in the first two phases of the tests. The results indicate that the migration of small particles has an essential effect on permeability and porosity increase during water inrush through fractured sandstone. The samples with higher original porosity, higher percentage of fine particles in their formation and under higher water flow pressures, achieve higher permeability and porosity values when the test is complete. Furthermore, using the measured data, the performances of a number of empirical models, for permeability evolution in fractured porous media, have been studied. The prediction results indicate that not all of the fractures in a sample domain contribute in small particle migration. There are parts of the fracture network that are not effective in particle flow, a sample with less original porosity, more fine particles and under lower water pressure shows less ineffective fractures. Therefore, using the concept of the effective porosity (fracture) is sufficient enough for the flow calculation.

1. Introduction

China, after Russia and the United States, has the largest proven reserves of coal in the world, it is currently the world's largest coal producer (Miao and Qian, 2009). Currently, coal accounts for 70 percent of China's primary energy production; therefore, China's economic development during the foreseeable future will still be highly dependent on coal extraction and production. The extraction of this important resource is often associated with groundwater inrush accidents. Indeed, more than 90% of the casualties in mining work accidents in China are due to water inflow from karst aquifers into the mine through the floor of the coal seam (Li and Zhou, 2006). According to recent statistics (State Administration of Coal Mine Safety, 2014), during the 2000s, groundwater inrush accidents in Chinese mines resulted in the death of several hundred miners each year; although since mid 2000s with increasing application of groundwater inrush prevention systems, the number of related coal mine accidents has shown a clear descending trend (Sun et al., 2016).

Abbreviations: d, particle size [L]; $\overline{d}$, percentage remaining for particles with size 2.5–10 mm [–]; $\overline{\overline{d}}$, percentage remaining for particles with size 2.5–15 mm [–]; h_s, height of the sample before loading [L]; h_0, height of the sample after loading [L]; H_1, height of the cylindrical tube [L]; H_2, pedestal thickness [L]; H_3, porous plate thickness [L]; H_4, filter pad thickness [L]; H_5, water flushing cap thickness [L]; H_6, height of the outflow regulator inside the cylindrical tube [L]; H_7, height of the outflow regulator [L]; H_8, height of the outflow regulator exceeding the cylindrical tube [L]; m_s, mass of the sample [M]; p, water pressure [$ML^{-1}\ T^{-2}$]; p_a, water pressure at the intake boundary [$ML^{-1}\ T^{-2}$]; p_b, water pressure connected with atmosphere [$ML^{-1}\ T^{-2}$]; R^2, coefficient of determination [–]; r, radius of the sample container [L]; t, time [T]; v, water flow velocity [LT^{-1}]; z, vertical axis going through the center of the sample [L]; Δ, partial differential operator [–]; $\Delta()/\Delta z$, Nabla operator [L^{-1}]; μ_w, water kinetic viscosity [$ML^{-1}T^{-1}$]; ϕ, porosity [–]; ϕ_s, porosity of the sample before loading [–]; ϕ_0, porosity of the sample after loading and before water flow initiation [–]; κ, permeability [L^2]; κ_0, permeability of the sample after loading and before water flow initiation [L^2]; ρ_s, mass density [ML^{-3}]; ρ_w, water density [ML^{-3}].

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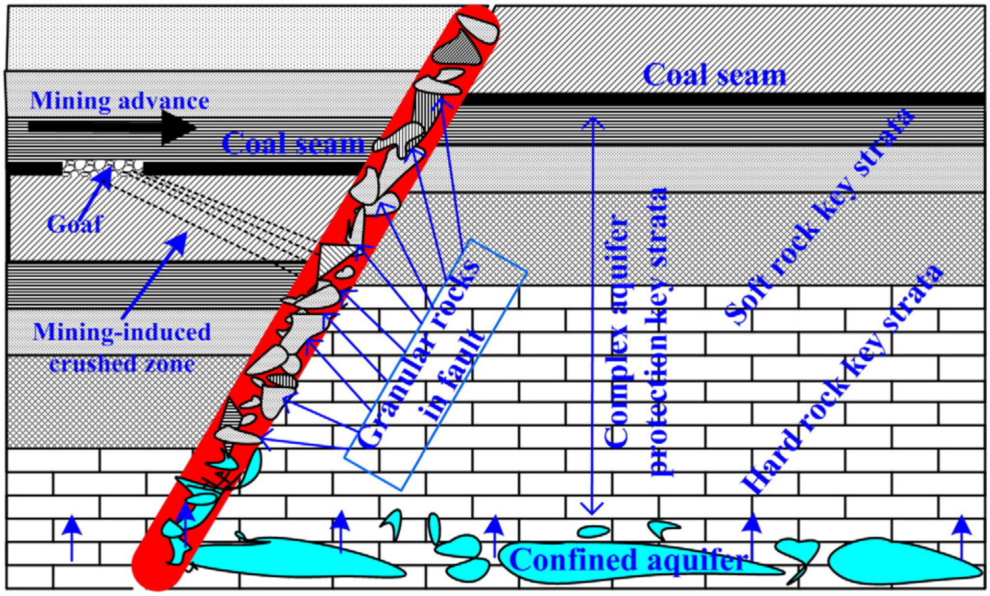

Fig. 1. Mining-induced small particle migration in faults above confined aquifer.

In addition to threatening the safety of mining operations, groundwater inrush also causes pollution due to mine spillage (Li and Zhou, 2006; Wu and Zhou, 2008; Zhu and Wei, 2011). Therefore, over the past few years, field and laboratory investigations of the effects of groundwater inrush on hydraulic and mechanical properties of rocks (Bai et al., 2013), and consequently mining environment (Bai and Miao, 2016), have been carried out extensively (e.g., Wu and Zhou, 2008; Ma et al., 2015a). The results from these investigations show that high pressure groundwater can break through the reduced stress zones around the mining face and leak into the working areas which can potentially trigger the hazardous water inrush incident (Li et al., 2011; Miao et al., 2011a). The characteristics of confined aquifer, combined with the mining-induced strata failure (Meng et al., 2016) and the inherent geological structures of the field (Huang et al., 2016), such as water conducting faults, are among the main factors that set off such events (Li and Zhou, 2006; Li et al., 2011; Wu and Zhou, 2008; Zhang et al., 2014; Zhu et al., 2013; Zhu and Wei, 2011). As shown in Fig. 1, the fault fracture zones that contain lots of granular rock fragments can act as effective water inrush channels. It can be argued that the existence of small particles within the faults and voids could be a controlling factor in determining the safety of coal mining activities above confined aquifers (Lu and Wang, 2015; Li et al., 2015; Lu et al., 2015; Ma et al., 2016a).

Up to now, the studies on groundwater inrush mechanism have been mainly concentrated on either the reaction of faults or the damage of floor strata (Caine et al., 1996; Babiker and Gudmundsson, 2004; Zhu and Wei, 2011). Potentially influential aspects, such as the configurational structure of particles within the crushed rock zone and the variations of hydraulic properties have been mainly overlooked in the past studies of the faults (Zhang et al., 2016). A number of researchers

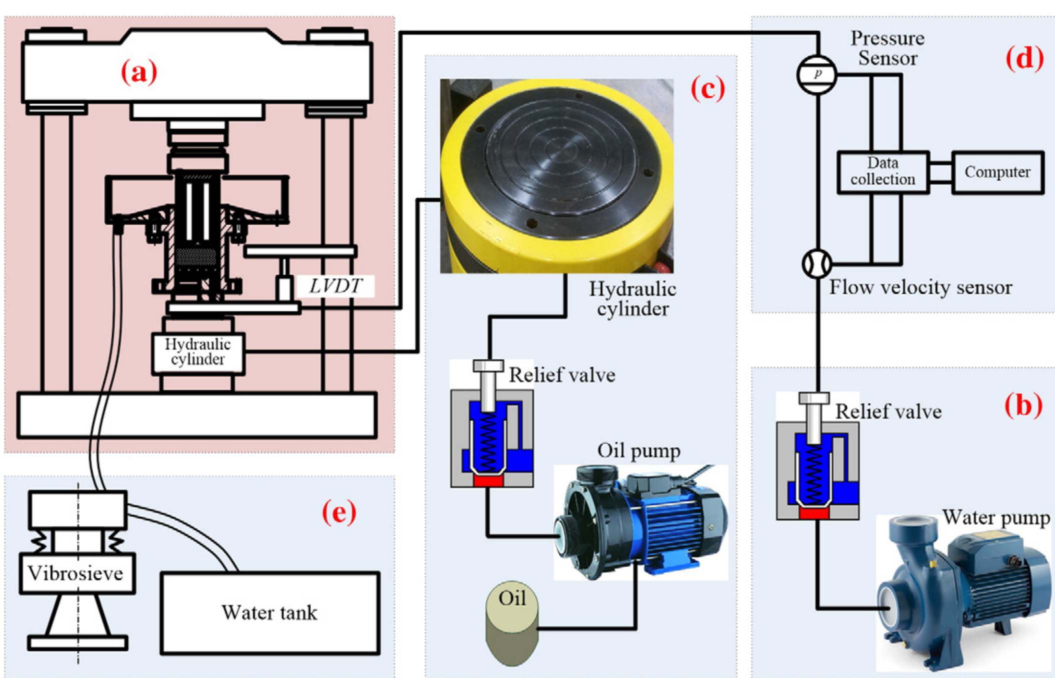

Fig. 2. Schematics of particle migration testing system.