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Numerical simulation of particle migration from crushed sandstones during groundwater inrush

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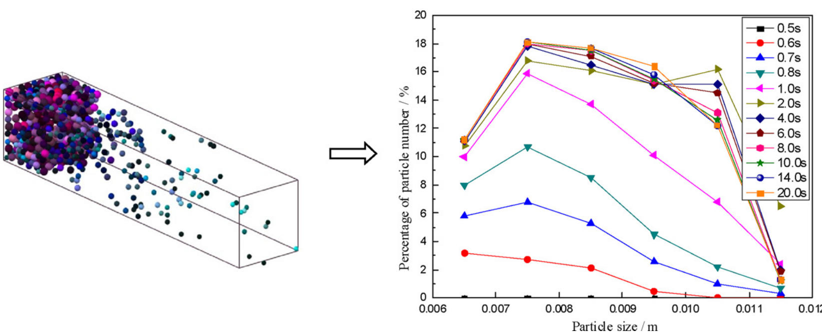
GRAPHICAL ABSTRACT



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ABSTRACT

Groundwater inrush through fault fracture zones is caused by small particle migration from fractured rocks of the faults. To investigate particle migration with the water flow, a 3D model was established for the solid-water two-phase flow. First, the simulated crushed sandstone was represented by certain different-sized particles with a novel cohesive force. The discrete element method (DEM) was applied for particles considering the cohesive force, the collisions, the friction, and other conventional forces. Second, the process of particle migrating from the crushed sandstone was simulated under multiple effects accompanied by some experiments. The results indicate that the migration characteristics vary with different-sized particles, and the mass loss for different-sized particles are high at the beginning leading to stabilized conditions at different times. It can be also found that the total mass loss rate and the final mass loss all increase with the increases of initial water velocity, while the final mass loss decrease with the increases of the axial force. Moreover, selected stimulation results were compared with the experimental results and the previous simulated results, and reasonable agreements could be obtained, which would provide consults for particle migration during groundwater inrush through fault fracture zones in underground engineering.

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Nomenclature

C_d	drag coefficient (dimensionless)
d_p	particle diameter(m)
$\boldsymbol{f}_a$	axial force(N)
$\boldsymbol{f}_b$	buoyant force(N)
$\boldsymbol{f}_c$	I nter-particle collision force (N)
$\boldsymbol{f}_d$	drag force (N)
$\boldsymbol{f}_g$	gravity force(N)
I	rotational inertia (kg·m^2)
k	elasticity coefficient (dimensionless)
m	particle mass (kg)
$\boldsymbol{n}$	normal unit vector (dimensionless)
St	axial force per kilogram(N/kg)
$\boldsymbol{T}$	resultant moment(N·m)
t	time (s)
$\boldsymbol{u}$	velocity (m/s)
$\boldsymbol{v}_n$	normal component of relative velocity(m/s)
$\boldsymbol{v}_t$	tangential component of relative velocity(m/s)
$\boldsymbol{v}_r$	relative speed of particle i and particle j (m/s)

Greek letters

μ_f	Friction coefficient (dimensionless)
ω	rotational velocity (radians/s)
η	damping coefficients (dimensionless)
δ	the displacement (m)
ρ	density(kg/m^3)

Subscripts

i	particle i
j	particle j
n	normal component
p	particle phase
t	tangential component
w	water phase

1. Introduction

Groundwater inrush is a serious hazard in underground engineering [1–3]. Groundwater inrush has resulted in several hundred deaths of miners each year in China, which also causes pollution due to mine spillage [4,5]. Considerable efforts have been made to prevent the disaster [6–8], and numerous researches have been carried out, not only on the mechanical properties of rocks [9,10], but also on mining environment [11]. The results from the previous investigations indicate that the disaster is so complicated that can not be solved easily, since the occurrence is determined by multiple complex factors, including the mining-induced rock fractures, water pressure, water-resisting ability of floor aquifuge, and inherent geological structures of the field [12–15]. The previous results also show that high-pressure groundwater can permeate through the reduced stress zones around the working face and leak into the working areas, which can potentially trigger the hazardous water inrush incident [6].

In recent years, groundwater inrush caused by the fault reactivation from coal seam floors has been increasing in China [16]. During the mining process, rock mass deformation and failure in the working face can lead to mining-induced fractures, which are the source of a series of mine disasters. The fault fracture zones contain lots of granular rock fragments. Once a fault fracture zone meets the groundwater resource, the water will permeate it under certain pressure. Meanwhile, the small particles within the faults can be dragged away under the continuous action of groundwater, and a small amount of the granular material will pour out before the water breaks into the fault fracture zone, which directly leads to effective channels for water inrush. Groundwater inrush then occurs accompanied by a large volume of groundwater gushing [5,6]. The gushing of the granular material means the migration and mass loss of solid particles. The configurational structure of particles within the crushed rock zone is regarded as a potentially influential aspect on determining the safety of underground activities near confined aquifers, which have been mainly overlooked in the past studies of the faults [6]. It can be argued that groundwater inrush within fault fracture zones is closely related to small particle migration from granular rocks of the faults. Therefore, the evaluation of the dynamic properties of particle migration through the fault fracture zones is an important issue for groundwater inrush in tunneling and mining engineering [6].

Particle migration in water flow is commonly found in many industrial processes, including chemical, pharmaceutical, mineral and tunneling [17,18]. Particle migration process directly determines the microstructure or the micro-properties of rocks, which then affect the rock strengths and their deformation behaviors. However, there are no many reported field measurements for permeability evolution and particle migration through granular rocks deep under the ground, since it is inaccessible to carry out direct measurements to detect the variations of microstructure of rocks [6,19]. Fortunately, numerical simulation has been validated as a powerful tool to further understand the complex processes that available experimental techniques can not achieve. The most commonly applied numerical methods for rock mechanics are the continuum methods, the discontinuum methods and the hybrid continuum/discontinuum models. Compared to the continuum methods, numerical modeling based on the discontinuum or the hybrid methods are easily to simulate rock fracturing under loading. The fracturing process in rock-like material can be explicitly accomplished by the direct representation of cracks in the models formulated based on the Discrete Element Method (DEM) [20,21]. DEM has been widely accepted as an effective method of addressing engineering problems in granular and discontinuous materials, especially in granular flows and rock mechanics [22–27].

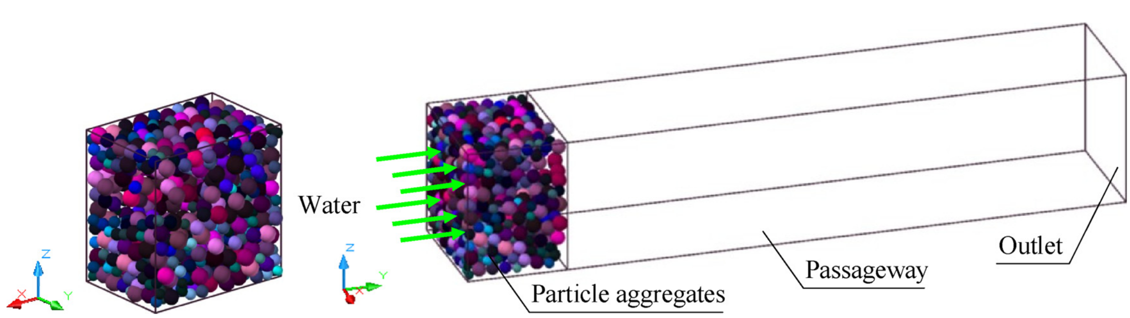

Fig. 1. Simulated model of the crushed sandstone and the flow channel.