Numerical Simulation Investigation on Water-sand Mixture Flow through a Single Fracture

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Abstract

Quicksand is a hazard that water-sand mixture pours into underground space through a pathway and causes financial loss or even casualties. When the fractures connect sand aquifers and underground space, the water and sand will flow into underground space s under hydraulic head and gravity. Numerical simulation of water-sand flow through one single straight fracture is conducted in this paper using DEM-CFD method. The results show that the sand mass flow rate has a positive linear relationship with fracture width and a 1.5 powder relationship with fracture aperture when water-sand mixture transport through a straight flat fracture is in the stable stage.

Keywords: fracture, quicksand, mass flow rate, numerical simulation

Introduction

Quicksand or sand inrush is a hazard which threatens the mining and tunneling. When sand aquifers are connected to underground space by a pathway, the water-sand mixture from the aquifers pours into the underground space through the pathway under the effects of gravity and hydraulic head. For the suddenness and rapidity of occurrence, quicksand is difficult to be predicted timely and is dangerous for production and construction in mining and tunneling. To avoid quicksand hazard, especially in mining, overburden failure were investigated to evaluate the risk of quicksand by scale modeling, empirical approach and numerical simulation (Zhang and Peng, 2005; Yang and Xia et al., 2011; Chen and Zhang et al., 2014). Flow rate of water-sand mixture in quicksand is widely focused in the precious investigations. Liu (2015) experimentally simulated the water-sand mixture flow across the broken zone of rocks. Sui (2017) investigated the speed of sand flow through a fixed porous bed and obtained an equation on calculation of mass flow rate. Zhang (2015) established a calculation model to explain the flow rate of water-sand mixture of quicksand occurring in the Longde coalmine. Liang and Sui (2011) analyzed the relationships among quicksand volume, particle size and diameter of the borehole. Yang et al. (2012) analyzed the relationship between velocity of water-sand mixture and width of fracture pathway, and the relationship between time and quicksand volume. Guo et al. (2013) experimentally studied sand flow through an orifice under variable hydraulic heads on soil-erosion problem. According to the quicksand accidents happened, the types of pathway is various. Drilling boreholes, faults and collapsed columns can all be the pathways. But the common pathway in the quicksand hazard is fractures, which always appears in the form of fracture network. Figure 1 is a diagrammatic sketch of quicksand through fractures. Therefore, the water-sand mixture flow through fractures is an important subject in the research of quicksand. Fracture network is composed by many single fractures and water-sand mixture flow through fracture network is a comprehensive result of water-sand mixture flow through each fracture. Hence, the investigation on water-sand mixture flow through a single fracture is the foundation of the investigation on the water-sand mixture flow through fracture network. Although the phenomenon of water-sand mixture flow through a single fracture is focused, the relationship between mass flow rate of sand in water-sand mixture and the width and aperture of fracture is not investigated sufficiently. Therefore, this paper investigated the relationship between mass flow rate of sand in water-sand mixture and the width and aperture of fracture and the transport process of water-sand mixture through one single straight fracture by using DEM-CFD method.

Methods

DEM (Discrete Element Method) is an approach widely applied in the numerical simulation of granular materials. DEM is more suitable to realize the simulation of discontinuous material compared to the simulation methods based on the continuity hypothesis. EDM approach has an advantage on simulating sand as a kind of discontinuous materials. However, the DEM approach is not suitable for the fluid material. The common method to simulate fluid is calculational fluid dynamics (CFD) which is widely used in the numerical simulation investigation of fluid. But the CFD approach cannot realize the simulation of movement of sand particles. Water-sand mixture is a two-phase material containing solid and liquid phases. Neither DEM approach nor CFD approach can achieve the simulation of water-sand mixture. Therefore, a coupled DEM-CFD approach is carried out to complete the simulation of the movement of water-sand mixture. In coupled CFD-DEM, the movement of particles is obtained by DEM which applies Newton's laws of motion to every particle, while the flow of fluid is solved by CFD approach. The interactions between the fluid and solid phase is modeled by use of Newton's third law.

To investigate the water-sand mixture flow through a single fracture by numerical simulation, a numerical simulation model is established. The numerical simulation model for water-sand mixture transport through a single straight flat fracture is formed by a box and a slant fracture, as shown in Fig. 2. The box is a container of sand particles for modeling the watered sand layer and providing water-sand mixture. The size of the box is 14 cm long, 10 cm wide and 10 cm high. The bottom of the box is connected to the slant fracture. The joint is separated by a small wall which will be removed at the beginning of simulation. When the wall disappears, the sand particles move from the box into the fracture under hydraulic head and gravity. The fracture is a slant straight flat fracture with a 30°dip angle and the section of the fracture is a rectangle. After the sand particles leaving the box and entering the fracture, the sand particles move along the fracture until flowing out of the fracture. The sand particle is regard as a sphere. The diameter, density, Poisson's ratio and shear modulus of the sand sphere is 0.5 mm, 2600 kg/m^3, 0.25 and 1×10^6 Pa respectively. The models of interaction between particle and particle and interaction between particle and wall both are Hertz-Mindlin model. Moreover, the difference of hydraulic head between the top of box and the outlet of the fracture is set as 10 cm. The top of the box is the inlet of water and the outlet of the fracture is the is also the outlet of water.

The factors influencing the water-sand mixture flow are various and complex. The fracture width and fracture aperture are two important factors in the water-sand mixture flow. To investigate the relationship between mass flow rate of sand in water-sand mixture and the width and aperture of fracture, the transport of water-sand mixture through a single straight flat fracture under different fracture apertures and fracture widths are simulated. Tab. 1 shows the numerical simulation scheme. There are 9 trials which

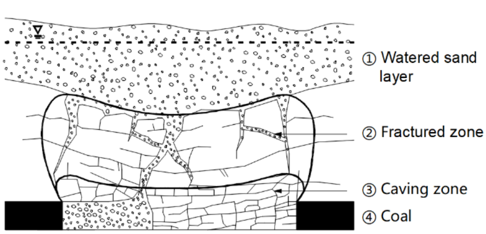

Figure 1 Diagrammatic sketch of quicksand through fractures

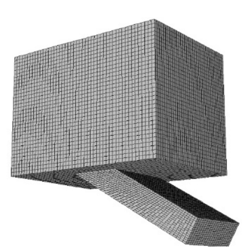

Figure 2 Numerical simulation model

can be divided into to two groups. One group contains No.1, 2, 3, 4 and 5 trials, which have different fracture apertures, the other contains No.6, 7, 3, 8 and 9 trials, which have different fracture widths.

Results

Fig. 3 shows the process of numerical simulation of water-sand mixture transport through a single straight flat fracture. When the straight fracture is connected with the sand box, the sand particles fall into the fracture under water flow and gravity. The sand particles accelerate and flow along the fracture dip. After entering the fracture, the sand particles concentrate in the bottom of fracture and the stratification of sand particles strengthen with the increment of transport distance. The stratification is caused by the density difference of water and sand. The density of sand is higher than that of water, thus the sand particles sink and concentrate in the bottom of fracture. Transport distance, the velocity of sand, the velocity of water and density of sand particle all influences the degree of stratification. Generally, the long transport distance and high density of sand particles strengthen the degree of stratification while the high velocity of sand and water weaken the degree of stratification.

***Table 1** Numerical simulation scheme*

Trial	Fracture aperture (mm)	Fracture width (mm)
No.1	1	6
No.2	1.5	6
No.3	2	6
No.4	2.5	6
No.5	3	6
No.6	2	4
No.7	2	5
No.8	2	7
No.9	2	8

Fig. 4 shows the curve of accumulative mass of sand versus time. During the transport of water-sand mixture the sand flow comes into a stable state rapidly after a short initial state. The stable state maintains with a decrease of the height of sand layer. On the top of sand layer, a funnel forms and develops. When the height of sand layer is thin, the mass flow rate of sand begins to decrease gradually until the sand flow out entirely. Therefore, the transport process of water-sand mixture through a straight flat fracture can be divided into three stages: initial, stable and end stages. In the stable stage, the mass flow rate of sand keeps constant. The mass flow rate of the stable stage represents the maximum ability of the fracture to transport

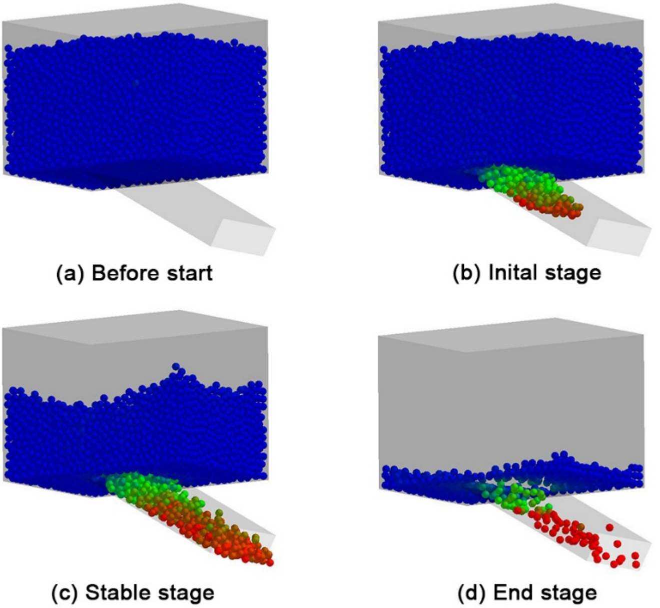

***Figure 3** Numerical simulation of water-sand mixture transport*

the sand in water-sand mixture under the same condition. Therefore, the mass flow rate of sand in water-sand mixture investigated in this paper is focused on that in the stable stage.

Fig. 5 shows the flow rates of sand in the stable stage under different fracture apertures. The mass flow rate of sand increases with the increment of fracture width. Data fit shows that the relationship between the sand mass flow rate and fracture width satisfies the positive linear correlation.

The mass flow rates of sand in the stable stage under different fracture apertures are represented in fig. 6. Similar to the relationship between the sand mass flow rate and fracture width, the fracture aperture also increases the sand mass flow rate. But the relationship between the sand mass flow rate and fracture aperture does not satisfy the linear relationship. Data fit shows that the relationship between the sand mass flow rate and fracture aperture is positive correlated by 1.5 power.

According to the results of data fit, the sand mass flow rate has a linear relationship with fracture width and a 1.5 powder relationship with fracture aperture when water-sand mixture transport through a straight flat fracture is in the stable stage.

Discussions and limitation

Water-sand mixture is a two-phase material containing sand and water. During the transport of water-sand mixture, the sand particles and water interact with each other. The transport of water-sand mixture is a comprehensive representation of interactions.

The mass flow rate of sand in water-sand mixture is different with the mass flow rate of pure water flowing through a single straight fracture. The mass flow rate of water only fits for the cubic law. The sand mass flow rate of water-sand mixture has a linear relationship with fracture width and a 1.5 powder relationship with fracture aperture. The relationships with fracture width are both linear relationships. The difference of them is the relationship with fracture aperture. This means that the mechanism of sand in water-sand mixture transport is different with that of water only.

The transport of water-sand mixture through a single straight flat fracture is affected by many factors. However, this paper only investigates the effect of fracture width and fracture aperture on the mass flow rate of sand in water-sand mixture. The effects of other factors such as fracture dip angle, particle diameter and friction coefficient are not studied. Therefore, these factors are needed to be investigated in the future work. Furthermore, a straight flat fracture is a

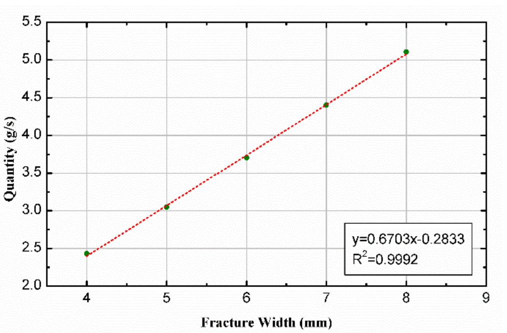

Figure 5 *Mass flow rates of sand under different fracture apertures*

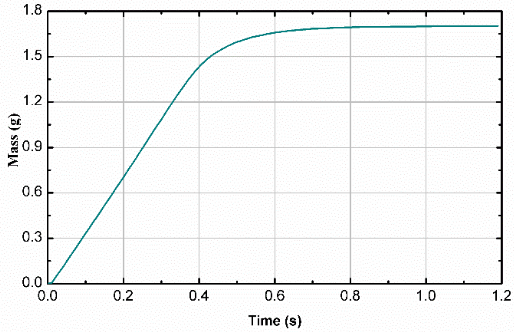

Figure 4 *Curve of accumulative mass of sand versus time*

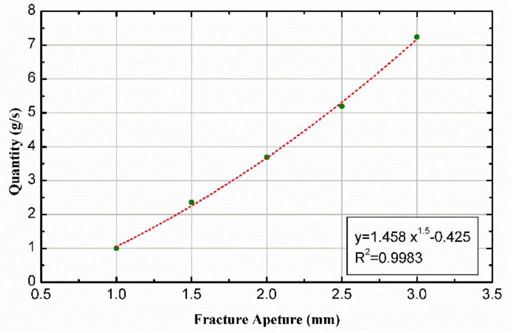

Figure 6 *Mass flow rates of sand under different fracture apertures*

simplified fracture and has a difference with the natural fracture. Therefore, the complex fracture should be investigated based on the investigation of one single straight fracture in the future.

Conclusions

This paper investigates transport of water-sand mixture through one single straight fracture and the relationship between mass flow rate of sand in water-sand mixture and the width and aperture of fracture by numerical simulation. By changing the fracture width and fracture aperture, the relationships between sand mass flow rate and fracture width and the relationships between sand mass flow rate and fracture aperture are observed and analyzed. The main conclusions are as follows:

(1) The sand particles concentrate in the bottom of fracture and the stratification of sand particles strengthen with the increment of transport distance.
(2) The transport process of water-sand mixture through a straight flat fracture can be divided into three stages: initial, stable and end stages.
(3) The sand mass flow rate increases with the increment of the fracture width and fracture aperture. The sand mass flow rate has a positive linear relationship with fracture width and a 1.5 powder relationship with fracture aperture when water-sand mixture transport through a straight flat fracture is in the stable stage.

Acknowledgements

The authors thank.

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