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Experimental investigation on chemical grouting of inclined fracture to control sand and water flow

Yankun Liang[a,b], Wanghua Sui[a,*], Jianfeng Qi[c]

[a] School of Resources and Geosciences, Institute of Mine Water Hazards Prevention and Controlling Technology, China University of Mining and Technology, Xuzhou, Jiangsu, China
[b] Henan Province Key Laboratory of Rock and Soil Mechanics and Structural Engineering, North China University of Water Resources and Electric Power, Zhengzhou, China
[c] Wuhan Metro Group Co Ltd, Wuhan, Hubei, China

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ABSTRACT

This paper presents an experimental investigation of the propagation of chemical grout in an inclined fracture model to control sand and water flow. The experimental grouting setup for an inclined fracture examines the propagation of chemical grout in water and sand flows by considering the different inclination angles of the fracture. The results show that grouting effectively reduces the discharge of the sand and water mixture. Moreover, the total volume of discharged sand and water is reduced when the fracture has a smaller inclination angle. Further analyses show that there is a critical inclination angle that differentiates two types of grout patterns: the "gel deposition grout pattern" and "erosion dispersion grout pattern". The former is when the inclination angle of the fracture is less than the critical inclination angle, which is 12.4° in this study, and the water and sand flow can be stopped with grouting. The latter is when the inclination angle is greater than the critical inclination angle, so that grouting will not be able to stop the water and sand flow. The mechanisms of the sealing of inclined fractures are discussed from the perspective of a two-phase flow. It is found that the key to sealing fractures is the formation of a stable sand layer. The grout viscosity and the tendency of the grout to gel not only can reduce the speed of the water flow, but also increase the stability of the deposition of the sand particles, which explains for their improved settlement and the subsequent formation of a porous layer. Finally, the grouting becomes permeation grouting after the formation of the porous layer.

1. Introduction

One of the major challenges that underground engineers need to address is the inrush of water along with a large volume of sand into tunnels or panels which could take place through geological fractures or faults (Sui et al., 2008; Islam et al., 2009; Chen et al., 2014). This is especially problematic in China as more than 200 water and sand inrush incidents have been observed just in the last few decades (Zhao et al., 2013), and have consequently caused serious financial losses or even casualties. To control such inrush events, one of the most common methods to date is grouting the fractured rock mass. Therefore, considerable efforts in the literature have been made to study the theories and techniques involved as well as the materials used (Zhao et al., 2013; Li et al., 2016; Wang et al., 2016). However, due to the uncertainties in predicting the actual geological conditions and geotechnical behavior of rock masses, determining the grouting parameters and process design is still an empirical process and grout spread in flowing water and sand needs to be further elucidated, which will be addressed in this study.

Practical methods for grouting and sealing mechanisms in fractured rock mass to date are theoretical analyses, numerical simulations, and in-situ and laboratory tests. However, theoretical analyses are largely based on assumptions and approximations. For instance, radial flow equations for parallel fractures have been developed by considering grout as a Newtonian or Binghamian fluid (Dai and Bird, 1981; Amadei and Savage, 2001; Gustafson et al., 2013; Xiao et al., 2017). Theoretical modeling of grout flow is helpful to simulate grouting, but is not entirely accurate when used to describe the grouting and sealing mechanisms of fractures (Håkansson, 1993; Ruan, 2005). Furthermore, numerical simulations based on such approximated models cannot well simulate the real conditions of grouting in fractures. That is because the accuracy of in-situ tests in practice mainly depends on details of the geological characteristics. However, it has been challenging for academics in underground engineering to determine the grouting

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* Corresponding author.
E-mail address: suiwanghua@cumt.edu.cn (W. Sui).

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parameters with in-situ tests and thus study the grouting mechanisms in fractures. Therefore, laboratory testing is a good alternative for investigating factors that cannot be controlled in the field (Sharpe, 1990; Fransson, 2001; Mohammed et al., 2015; Cheng et al., 2018). With the development of digital photography and image processing technologies, laboratory tests are now extensively used to obtain further insights into the process of grouting in fractures (Cunningham et al., 2009; Minto et al., 2016; Funehag and Thörn, 2018).

High levels of water inflow are one of the main causes of sand and water inrushes (Hunt and Daniel, 1952; Castro et al., 2017; Vallejos et al., 2017), which also add to the difficulties of grouting (Mao et al., 2016). The experimental results in Sui et al. (2015) showed that the initial speed of the water flow contributes the most to the sealing efficiency of grouting compared to the width of the fracture aperture, grout take, and gelling time. Furthermore, the propagation of grout changes from a circular to an elliptic shape (Zhan et al., 2011; Zhang et al., 2011). However, layers in a U-shape were found during grouting of fractures with cement to inhibit water flow in a study by Li et al. (2011). The test results in Yang et al. (2016) showed that when carbon fibers are added to cement grout, the length of the propagation of the grout increases with increased water flow speed, grouting pressure and grouting time as well as a higher joint roughness coefficient, but decreases with increased plastic viscosity of the cement grout due to the incorporation of the carbon fibers. These studies emphasize the propagation of grout in flowing water. However, sand is also prevalently found in the mixed water and sand inrushes, which means that the findings in the extant literature which have not taken this into consideration are not applicable for cases that involve flowing water mixed with large quantities of sand.

The important influence of fracture aperture on the grouting of fractures has been acknowledged by many researchers (see for example, Houlsby, 1990; Eriksson, 2002; Rafi and Stille, 2015). Aside from fracture aperture, other parameters that characterize the fracture geometry, such as fracture roughness, stiffness, tortuosity, and inclination, also impact the fluid flow through fractures to different degrees (Hakami, 1995; Dalmalm, 2004). Cochard and Ancey (2009), Haza et al. (2013) and Qian et al. (2018) showed that the inclination of fractures is an important factor that influences sand and mud flow. However, there are few publications that have examined the influence of the inclination of fractures on fracture grouting. One of the few is Luo et al. (2009), who concluded theoretically that the flow speed of grout according to the Bingham model is not dependent on the inclination of fractures. In contrast, the experimental results in Yu et al. (2014) showed that the rate of grouting increases with higher inclination angles, and the shape of the grout spread changes from a U-shape in horizontal fractures to a comet shape in inclined fractures.

The purpose of this paper is to provide further insights into the mechanism of grouting in inclined fractures with a continuous mixed sand and water flow through an experimental investigation, in which a single fracture is examined in a transparent model. This fracture is assumed to be the simplest representation of a fractured rock mass at the laboratory scale with the following advantages: the boundary conditions can be controlled and most of the flow patterns can be determined by using an image acquisition system. Then a series of experiments are performed to examine fractures with different inclination angles and determine the effects of the inclination angles on the grouting pattern.

2. Materials and method

This paper aims to provide insight into the grouting propagation in an idealized inclined fracture with continuous sand and water flow. Fundamentally, we found that grouting when used to control water and sand flows is somewhat similar to that used to control water inrush. Thus, the laboratory experimental setup in this study is modified based on that used to study grouting in flowing water in Sui et al. (2015) and Li et al. (2016), but the water supply at the entry of the fracture has been changed to a water and sand supply system.

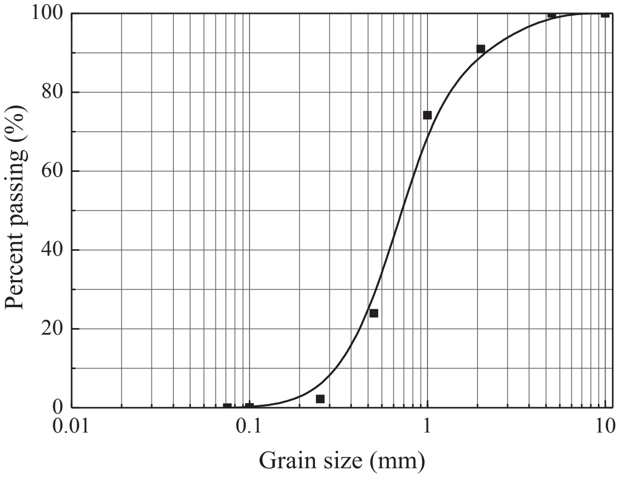

Fig. 1. Grain size distribution of sand.

2.1. Materials

Aeolian sand aquifers have been reported to contribute to water and sand inrushes in western China (Miao et al., 2010). The particle size of aeolian sand ranges from 0.1 to 2 mm, and the coefficient of uniformity (C_u) is about 2.3–3.2, which is generally regarded as poorly graded sand (Yuan and Wang, 2007). Fig. 1 shows the grain size distribution of the sand used in this study. The particle size distribution (d_{50}) is 0.8 mm, and the C_u is 2.42 which means that the sand is poorly graded.

The grouting solutions selected for the experiments consist of a mixture of a modified urea–formaldehyde (UF) resin and an oxalic acid solution, hereinafter Liquids A and B. This type of chemical grout is widely used to control groundwater inrush in China as there are fewer chemical reactions with rocks, minimal changes to the volume and cause little pollution to the environment. The viscosity and gelling strength of this hybrid grouting material remains almost constant before curing, and quickly increases after gelling starts. Additionally, the gelling time can be adjusted from a few seconds to a few hours depending on the concentration of oxalic acid in Liquid B. Fig. 2 shows the changes in gelling time for different concentrations of oxalic acid in Liquid B. Measurements of the gelling time were conducted with a 1:1 vol ratio of Liquids A and B. The results show that the gelling time ranges from 22.6 s to 161.8 s, which is inversely proportional to the concentration of oxalic acid in Liquid B. Fig. 3 shows the corresponding

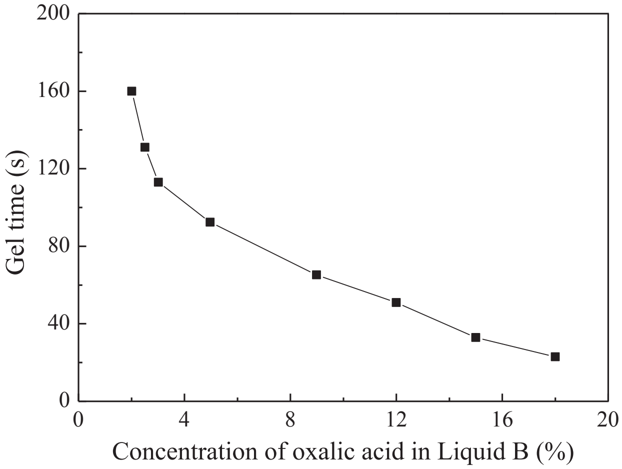

Fig. 2. Results of test on gelling time.