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Two-phase cement grout propagation in homogeneous water-saturated rock fractures

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ABSTRACT

Modeling of cement grout flow in rock fractures is important for the design, monitoring and execution of rock grouting that is widely used in a variety of rock engineering applications. This study presents a mathematical model based on the Reynolds flow equation for cement grout flow in a homogeneous water-saturated rock fracture. The model is based on two-phase flow, i.e. grout as a Bingham fluid and groundwater as a Newtonian fluid, and is used for investigating the importance of the water phase in rock grouting. The modeling results for the two-phase flow generally show the importance of the water phase that can significantly affect the pressure distribution and grout penetration in the fracture, especially under the condition of grout hardening. Such effects depend on the viscosity ratio between the grout and groundwater, which becomes increasingly important for cases with smaller values of the viscosity ratio. The grout density also affects the grout penetration length. Applying an analytical solution based on single-phase flow, i.e. neglecting the impact of groundwater flow, for modeling grout injection, will generally overestimate the penetration length.

1. Introduction

Grouting is widely used in rock engineering to reduce groundwater flow and increase the tightness of rock masses. Modeling of grouting in rock fractures is important for effective design and execution of grouting activities, driven by more stringent demands for controlling groundwater flow affected by underground structures or construction.[1]

In engineering practice, cement grouts are typically assumed to be Bingham fluids and their rheological properties are time-dependent.[2–4] Cement grouts are typically injected through boreholes with a constant pressure.[1] Two types of flow configurations are often used to model cement grout flow in fractured rock: radial flow and channelized flow between parallel plates.[1] Fig. 1 illustrates the relevance of both flow configurations when considering multiple fractures. Approximately radial flow may occur in the fracture intersecting the injection borehole, while channelized flow can take place through connecting fractures (Fig. 1). The present study focuses on channelized flow in a single homogeneous fracture as a basic component of grout propagation in fracture networks.

In most underground projects, fractured rock is saturated with groundwater and therefore, grouts spreading in rock fractures are actually an immiscible two-phase flow process, where the groundwater is displaced by the penetrating grouts.[5–7] In the past decades, analytical models have been developed to analyze grouting in homogeneous planar rock fractures.[e.g., 1, 8–20] For instance, Gustafson and Claesson[9] developed an analytical solution for the grout penetration with time, by assuming that both the pumping pressure and in situ groundwater pressure are constant (i.e. the flow of groundwater is neglected) and the grout properties are time-independent. This type of analytical solutions provided the theoretical basis for the real time grouting control (RTGC) method.[10,12,13] Mohajerani et al.,[19] developed a grout penetrability method based on an explicit grout pressure algorithm for homogeneous fractures in rock masses. Lavrov[21,22] and Bao et al.,[23] simulated non-Newtonian fluids (including power-law, truncated power-law and Bingham fluids) flow in 2D rock fractures. However, these analytical methods and numerical studies are based on the assumption that the flow of water phase is negligible or without consideration of two-phase flow in the rock fractures. Hässler[5,6] and Eriksson et al.[7] developed a numerical model to simulate the grout penetration in single fractures as well as regular fracture networks[5–7] that accounted for the presence of water but did not explicitly reveal its impact for different grout properties. As noted above, the effect of water is typically neglected in

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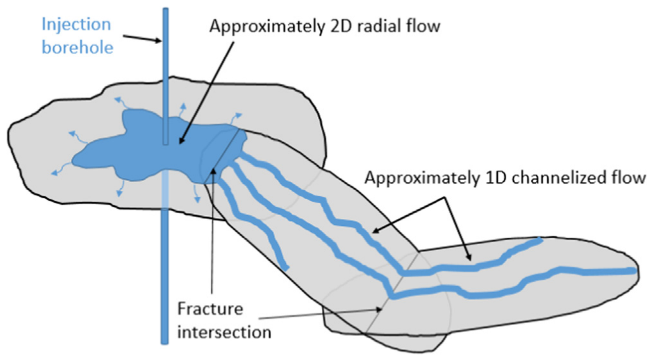

Fig. 1. Schematic diagram of the radial and channel representation of cement grout flow in multiple-fracture network.

analytical solutions that have been used in grouting practice.[1,9–20] It is therefore of interest to systematically elucidate the impact of water but also to provide a more general multi-phase formulation of grout flow that can be used for further studies of alternative boundary conditions relevant for practical applications.

In this work we consider grout flow in single water-saturated rock fractures based on an analogous configuration as studied previously.[5–7] The objectives of our work are: i) to present a two-phase flow model of non-Newtonian cement grout propagation combined with a Reynolds type of equation, and show that the results are identical to the flowrate based formulation considered by Hässler[5]; ii) to investigate the potential impact of water flow on grout propagation for different viscosity and density ranges; iii) to illustrate the combined effect of the water phase and grout hardening process for different parameter ranges.

2. Problem formulation

We consider an immiscible two-phase flow process in a single fracture defined by two smooth parallel plates. Surface roughness or aperture variability are clearly present in natural rock fractures however these are not considered in the present study in order to focus on the effect of water flow.

Fig. 2 presents the conceptual model of grouting with immiscible multiphase flow in a water-filled idealized planar fracture, as the basic element of the fracture networks in rock masses. The fracture aperture is 2*B*. The cement grout is considered as a Bingham fluid, injected from the left-hand-side of the fracture (i.e. inlet) with a constant pumping pressure P_1, which follows the previous studies and the condition used in the RTGC approach.[5–13,19] The length of the fracture is *L*. The pressure on the right-hand side of the fracture (i.e. outlet) is P_2. In the grouting process, the grout displaces the groundwater in the fracture. The distance between the inlet and the grout front, i.e. the interface between grout and water, represents the grout penetration length *I(t)*, which is a function of the grouting time.

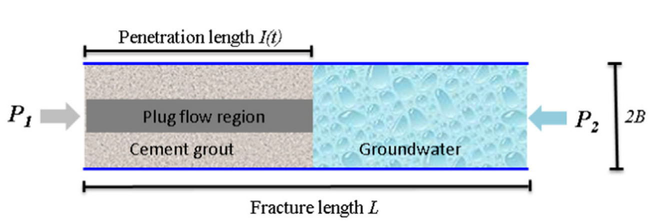

Fig. 2. Illustration of cement grout penetration into a single water-saturated fracture.

3. Mathematical models and solution strategy

3.1. Bingham fluid flow

The general fluid flow process is governed by the mass and momentum balance equations. The governing equations for a single-phase flow problem can be written as

$$\frac{\partial \rho}{\partial t}+\nabla\bullet\rho\boldsymbol{u}=0 \tag{1}$$

$$\frac{\partial \rho\boldsymbol{u}}{\partial t}+\boldsymbol{u}\nabla\bullet\rho\boldsymbol{u}=-\nabla \mathrm{P}-\nabla\bullet\tau+\rho\boldsymbol{g} \tag{2}$$

where ρ is the fluid density, t is the time, P is the pressure, $\boldsymbol{u}$ is the velocity, $\boldsymbol{g}$ is gravitational acceleration and τ is the shear stress. For Bingham fluids, the shear stress is given by

$$\begin{cases}\tau_{ij}=\left(\dfrac{\tau_0}{\left|\dot{\gamma}_{ij}\right|}+\mu_g\right)\dot{\gamma}_{ij}, & |\tau_{ij}|>\tau_0\\ \dot{\gamma}_{ij}=0 & otherwise\end{cases} \tag{3}$$

where τ_0 is the yield stress, μ_g is the plastic viscosity, τ_{ij} is the shear stress tensor and $\dot{\gamma}_{ij}$ is the shear rate tensor, which is given by

$$\dot{\gamma}_{ij}=\nabla u_{ij}+\nabla u_{ij}{}^T \tag{4}$$

$$|\dot{\gamma}_{ij}|=\sqrt{\frac{1}{2}(\dot{\gamma}_{ij}:\dot{\gamma}_{ij})} \tag{5}$$

Under the condition of grout hardening, the yield stress and the viscosity are both an increasing function of time.[2]

It is assumed that the grout and groundwater are incompressible, the gravitational forces and inertial effects are negligible (the flow is laminar) and the fracture aperture is much smaller than the lateral dimensions (i.e. the pressure gradient across the aperture is negligible by adopting the lubrication approximation).

According to these assumptions, the governing equations for the single-phase of a Bingham fluid flow in a homogenous fracture can be simplified as,

$$\frac{\partial \mathrm{u}}{\partial \mathrm{x}}=0 \tag{6}$$

$$-\frac{\partial \mathrm{P}}{\partial \mathrm{x}}=\frac{\partial \tau}{\partial y} \tag{7}$$

$$\begin{cases}\tau=\tau_0+\mu_g\frac{\partial u}{\partial y}, & |\tau|>\tau_0\\ \frac{\partial u}{\partial y}=0 & otherwise\end{cases} \tag{8}$$

For Bingham fluid flow in a homogenous fracture with a given pressure gradient and no-slip boundary condition on the fracture surfaces, the simplified governing equations can be analytically solved by integration.[24] The pressure gradient and flowrate are given by

$$\frac{\partial P}{\partial \mathrm{x}}=\frac{P_2-P_1}{L} \tag{9}$$

$$Q=-\frac{B^3}{3\mu_g}\left(1-\frac{z_p}{B}\right)^2\left(2+\frac{z_p}{B}\right)\frac{\partial P}{\partial x} \tag{10}$$

$$u=\frac{Q}{2B}=-\frac{B^2}{6\mu_g}\left(1-\frac{z_p}{B}\right)^2\left(2+\frac{z_p}{B}\right)\frac{\partial P}{\partial x} \tag{11}$$

where B is half of the aperture, z_p is half of the plug flow region caused by the yield stress, determined by

$$z_p=min\left(\frac{\tau_0 L}{P_1-P_2},\ B\right) \tag{12}$$