MODELING OF ROCK GROUTING IN SATURATED VARIABLE APERTURE FRACTURES

Injekteringsmodellering av vattenfyllda bergsprickor med varierande apertur

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Abstract
Modeling and analysis of cement grouts flow in rock fractures is important in the design, execution and monitoring of grouting in fractured rocks. At present, modeling of rock grouting mainly relies on analytical models, e.g., the real time grouting control (RTGC) method. In the RTGC method, it is assumed that the rock fractures are consisting of smooth parallel plates or disks and water flow is neglected. However, in reality, the natural rock fractures are commonly consisting of complex rough-walled surfaces and are filled with groundwater; therefore, grouting is actually a multiphase (non-Newtonian grouts and groundwater) flow process in rough-walled rock fractures with variable apertures. In this study, we present an efficient one-dimensional (1D) numerical model for modeling of rock grouting in a single rock fracture with consideration of multiphase flow and variable apertures. It is assumed that the cement grouts are Bingham fluids and that the analytical solution for flowrate with a given pressure gradient in a pair of smooth parallel plates is locally applicable. A time-dependent advection equation is used to describe the interface (between the grout and groundwater) propagation. A finite element method (FEM) code is developed to iteratively solve the mass balance and the interface advection equations. The numerical simulations are compared with the RTGC method. It generally shows that water flow significantly affect grouts penetration in the fracture, especially for the grouts with relatively lower viscosity. The variable aperture significantly postpones the penetration process compared with that of constant aperture. This numerical model is able to describe more realistic physical processes and geometry conditions in rock grouting, which can be readily used in practice to reduce the potential uncertainties in application of simplified analytical models.

Sammanfattning
Modellering och analys av cementbaserade injekteringsmedels strömning är viktiga hjälpmedel för design, utförande och uppföljning av injektering i sprickigt berg. Dagens modeller är ofta baserade på förenklade analytiska lösningar, exempelvis de som ingår i ”Real time grouting control (RTGC)” metoden. För att analytiska lösningar skall kunna användas, antas att sprickorna utgörs av släta, plan-parallella skivor och att dessa inte

innehåller något vatten. I verkligheten är dock sprickorna råa, vattenfyllda och med komplexa geometrier, vilket medför att cementinjektering i sprickigt berg i strikt mening är en multi-fas process i en varierande geometri. I föreliggande studie, presenteras en en-dimesionell numerisk model för injektering i en enskild spricka, under beaktande av multi-fas strömning med varierande spricköppning. En tidsberoende advektionsfunktion används för att beskriva gränsskiktet mellan injekteringsmedel och vatten och dess förflyttning med tiden. Resultaten visar på en betydande påverkan från sprickornas vatteninnehåll, dels på tryckfördelningen men även på injekteringsmedlets inträngning i sprickorna, särskilt vid låg viskositet. Den varierande spricköppningen gör också att inträngningen blir långsammare i förhållande till fallet med en konstant spricköppning, vilket är förväntat. Den numeriska modellen beskriver förhållandena på ett mer realistiskt sätt, både ur fysikalisk och geometrisk synvinkel, vilket kan utnyttjas i praktiken för att reducera potentiella osäkerheter vid användandet av dagens analytiska metoder.

1. Introduction

Modeling of grouting in rock fractures is important for effective design and performance of grouting activities in ever increasing demands of underground rock engineering projects (Stille 2015). In rock grouting practices, cement grouts are often typically non-Newtonian fluids (Håkansson et al. 1992; Håkansson 1993; Rahman et al. 2015), and the grouting process in fractured rocks is commonly idealized as channeling flow between parallel plates. In most underground projects, the fractured rocks are saturated with groundwater and therefore, the grouts spreading in rock fractures is actually a separated immiscible multiphase flow process where the groundwater is driven away by the penetrating grouts (Hässler 1991; Zou et al. 2018).

In past decades, analytical models have been developed to analyze grouting in homogeneous planar rock fractures (e.g., Lombardi 1985; Hässler 1991; Gustafson and Claesson, 2005; Kobayashi et al. 2008; Stille et al. 2009; Gustafson et al. 2013; Funehag and Thörn 2014; Rafi and Stille 2014; Stille 2015). These studies significantly advanced the theoretical development for modeling of rock grouting. However, all the analytical solutions are based on the assumptions that the flow of water phase is negligible and that the fracture is homogeneous with a constant aperture.

At an early stage, Hässler (1991) and Eriksson et al. (2000) firstly developed numerical models to calculate the flow velocity in a structured network of planar fractures, filled with both water and a Bingham fluid (grout). Their results demonstrated the penetration behaviors of the grouting process with consideration of the water phase flow and the variable aperture in regular fracture networks. The impact of these assumptions, i.e. neglecting the water flow and internal variable apertures adopted in analytical models, has not been comprehensively studied in these previous works.

In this study, a two-phase (i.e. cement grout as a Bingham fluid and groundwater as Newtonian fluid) flow model is developed to simulate cement grouts penetration in single water-saturated fractures with internal variable apertures. The main objective of this study is to investigate the impact of water flow and variable aperture on the rock grouting process.

2. Cement grout penetration models

2.1 Physical system

We consider an immiscible two-phase flow process in a single fracture with variable aperture. Figure 1 presents the conceptual model of grouting with immiscible multiphase flow in a water-filled fracture, as the basic element of fracture networks in rock masses. Similar to the local cubic law, used for modeling of water flow in rough-walled fractures, we assume that the solution for the Bingham grout flow between parallel plates can be applied locally. For each local segment, the fracture is approximated as a pair of smooth parallel plates. The local aperture is $2B_{ij}$. The pressure at the left-hand-side and the right-hand side is P_i and P_2 , respectively, and the length of the fracture is L_{ij}. In the grouting process, the grout displaces the groundwater in the fracture. The distance between the inlet surface 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.

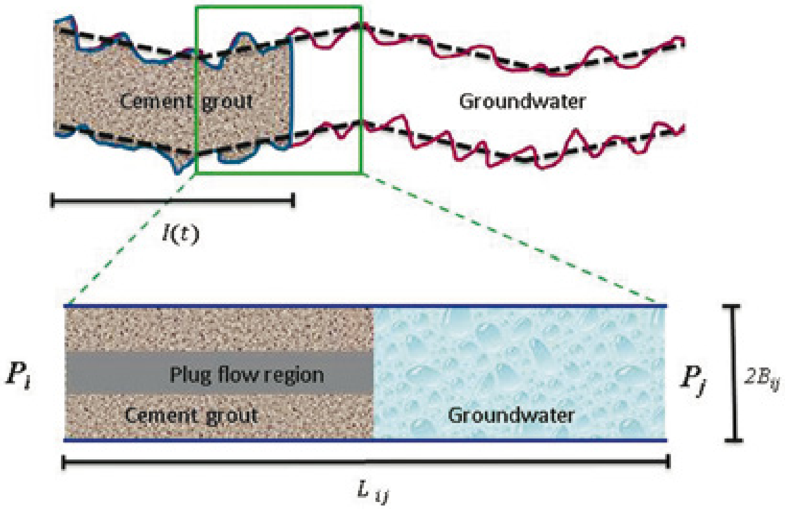

Figure 1Illustration of cement grout penetration in a single fracture.

2.2 Two-phase flow model

Similar to the Reynolds equation for modeling of water flow in fractures, the grouting process of immiscible two-phase flow in the fracture can be described by a set of the following equations (Zou et al. 2018)

$$\frac{\partial}{\partial x}\rho(C)T(C)\frac{\partial P}{\partial x} = 0 \quad (1)$$

$$u = \frac{T(C)}{2B}\frac{\partial P}{\partial x} \quad (2)$$

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} = 0 \quad (3)$$

where B is the half of local aperture and $T(C)$ is the local transmissivity which is a function of the phase function. The local transmissivity for the Bingham grout can be written as (Zou et al 2018)

$$T(C = 1) = -\frac{B^3}{3\mu_g}\left(1 - \frac{z_p'}{B}\right)^2\left(2 + \frac{z_p'}{B}\right) \quad (4)$$

where μ_g is the viscosity of grout, z_p' is half of the plug flow region, determined by the yield stress and the pressure gradient between the injection surface and grout penetration front I(t),

$$z_p' = min\left(\frac{\tau_0 I(t)}{P_i - P_{I(t)}}, B\right) \quad (5)$$

where $P_{I(t)}$ is the pressure at the interface. For the groundwater, the local transmissivity is given by the cubic law, expressed by

$$T(C = 0) = -\frac{2B^3}{3\mu_w} \quad (6)$$

where μ_w is the viscosity of groundwater.

Initially, the fracture is filled with water and the grout is injected into the fracture through the inlet boundary, under a constant pressure. A Galerkin finite element method (FEM) code using the Picard iterative method is developed to solve the governing equations. A Lagrangian interface tracking method was adopted to explicitly track the grout penetration, expressed as

$$I^{n+1} = I^n + u(I^n)\Delta t \quad (7)$$

where I is the position of the interface and Δt is the time step.

3. Result and discussion

3.1 Simulation scenarios

A series of numerical simulations were conducted to illustrate the grouting process and investigate the impact of water flow and variable aperture. We use a sine function to represent the variable apertures, as a simple illustration. The selected sine function for the aperture is

$$e = 2B + a\sin(\pi x) \quad (8)$$

where 2B is the mean aperture and $a < B$ is the amplitude that represents the variation of the aperture. The adopted geometrial model and the physical parameters (typically used in rock grouting practice) for the simulation are summarized in Table 1.

Table 1 Geometrical and physical parameters adopted for the numerical simulation.

Parameters	Units	Values
Fracture length, L	[m]	10
Mean aperture, $2B$	[m]	5e-4
Aperture variation amplitude, a	[m]	0, 2e-5 and 4e-5
Grouting pressure, $P_1 - P_2$	[kPa]	500
Viscosity of grout, μ_g	[Pa·s]	0.005, 0.01 and 0.1
Yield stress of grout, τ_0	[Pa]	2
Density of grout, ρ_g	[kg/m^3]	1500
Viscosity of groundwater, μ_w	[Pa·s]	0.001
Density of groundwater, ρ_w	[kg/m^3]	1000

3.2 Impact of water flow

Figure 2 presents the simulation results of the penetration curves for the case of constant aperture, i.e. a = 0, with different grout viscosity ($\mu_g = 0.005$ Pa · s, 0.01 Pa · s and 0.1Pa · s). Without considering the water phase flow and the variable aperture of the fractures, an analytical solution for Bingham grout penetration into 1D planar fractures are given by Gustafson and Claesson (2005), Gustafson et al. (2013), written as

$$t = \frac{6(P_1 - P_2)\mu_g}{{\tau_0}^2} \left\{ \frac{I_D}{3(1 - I_D)} + \frac{2}{9} \, ln \left[\frac{2(1 - I_D)}{2 + I_D} \right] \right\} \quad (9)$$

where I_D is the relative penetration length. This analytical solution builds the theory basics for the real time grouting control (RTGC) method. The penetration curves calculated by the RTGC method are also presented in Figure 2, for comparison.

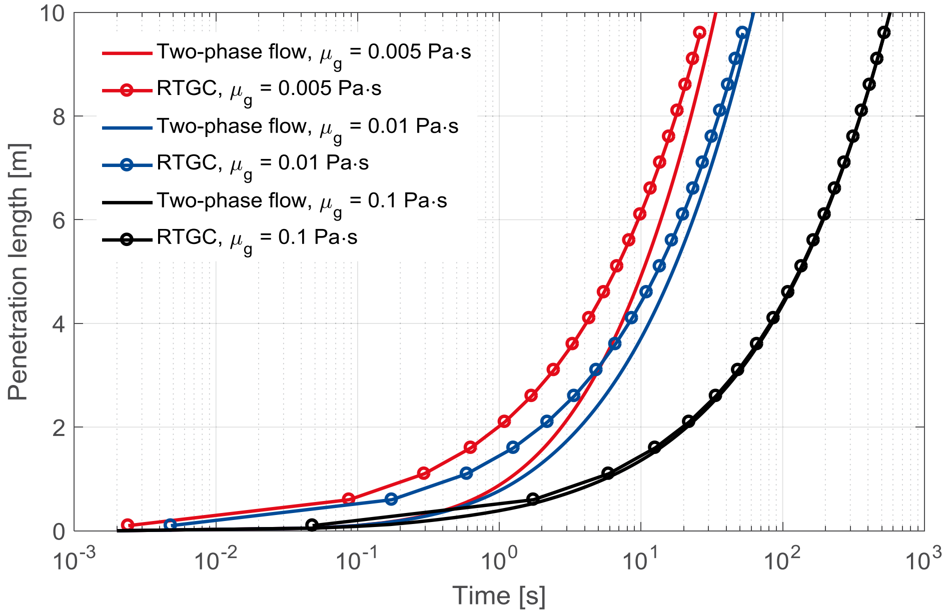

Figure 2 Penetration curves for different grout viscosity.

In general, the penetration rate reduces with the increase of grout viscosity. The results from numerical modeling and RTGC match well when the grout viscosity is relatively large, e.g. $\mu_g \geq 0.1$ Pa · s. In contrast, when the grout viscosity is relatively small, e.g. $\mu_g < 0.01$ Pa · s, the penetration curves from the RTGC method are much larger than the results given by the numerical simulation with consideration of the two-phase flow, especially at the early stage of injection. This difference is caused by neglecting water flow in the RTGC method, which highlights that it is important to consider the water phase flow in the modeling of rock grouting, using the two-phase flow model. This result also indicates that the analytical model, i.e. RTGC method, may only be applicable for the cases when grout viscosity is much larger than that of groundwater, i.e. $\mu_g \geq 0.1$Pa · s.

3.3 Impact of variable apertures

Figure 3 shows numerical modeling results of the penetration lengths for the rough fractures with different variation amplitudes, i.e. a = 1e-5 m and 2e-5 m.

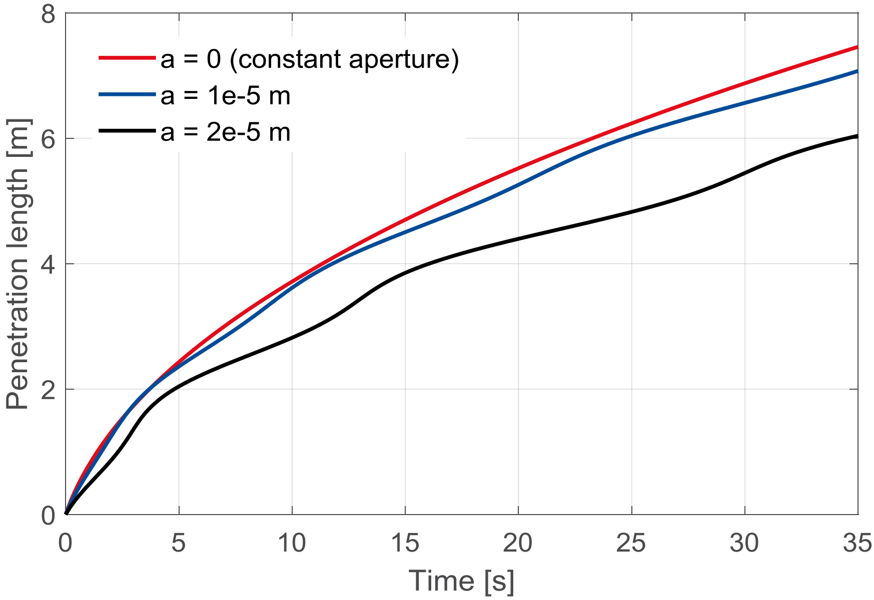

Figure 3 Penetration curves for variable fractures with different variation amplitudes.

Comparing with the result of a homogenous fracture, with constant aperture, i.e. a = 0 (the red line in Figure 3), the penetration lengths for the rough fractures (the blue and black lines in Figure 3) are smaller at the same point of time. The penetration rate reduces dramatically with the increases of the aperture variation amplitude. Such difference increases with the penetration length or the grouting time. These results indicate that the variable aperture of fractures significantly affects the grout penetration length by reducing the penetration rate. Ignoring the fracture apertures may overestimate the penetration length in practice. Note that the simple sine curve is used to represent the feature of internal variable apertures in this work, as an illustration only. Real apertures in natural rock fractures are far more complicated than the regular sine curve, and therefore, the overestimation by using simplified analytical models will become more significant in reality.

4. Concluding remarks

In this work, we developed an efficient two-phase flow model for the modeling of cement grout penetration in single rough rock fractures. Using this two-phase flow model, we investigated the impact of water phase flow and variable fracture apertures on the grout penetration length. The simulation results were compared both with the RTGC method and the case with a homogenous fracture with constant aperture, where the water flow and variable apertures are neglected. Such comparison generally illustrated the significant impacts of the water phase flow and the variable fracture apertures.

In rock grouting applications, the cement grout viscosity is commonly less than 0.1Pa·s and the rock fractures are naturally rough-walled with variable apertures. Therefore, applying such analytical solutions like the RTGC method without consideration of the water flow and fracture variable apertures will overestimate the penetration length in most cases in practice. In order to precisely model the grouts penetration in the rock grouting, it is therefore important to use the two-phase flow model and consider the variable apertures of the rock fracture.

The two-phase flow model presented in this study is based on an important assumption that the transmissivity based on the analytical for Bingham fluids flow in parallel plates are applicable locally. Many studies showed that such local approximation of the transmissivity contains important uncertainty even for the modeling of Newtonian fluids, i.e. groundwater, flow in rough-walled fractures (e.g. Zou et al. 2015; Zou et al. 2017). The validity of such approximation and the uncertainties of the transmissivity for the Bingham fluids flow in natural rock fractures remain important topics for the future studies.

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