Analysis of cement grout propagation in fractured rocks
Analys och simulering av cementinjektering i sprickigt berg

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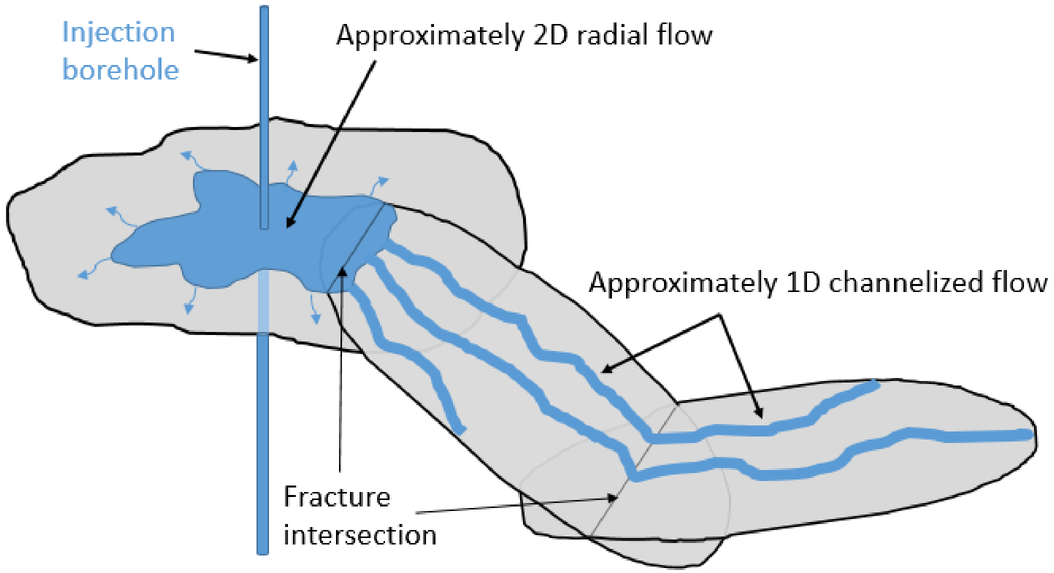
August, 2021

BeFo Rapport 200, 2021

Background

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



Two types of flow configurations are often used to model cement grout flow in fractured rock: radial flow and channelized flow between parallel plates

Open questions:

- There were two solutions for single-phase Bingham grout radial flow in homogeneous fractures in the literature that has caused confusion in the rock grouting research community.
- Most analytical solutions assume that the flow of groundwater is negligible. However, the impact of groundwater flow on grout propagation remains unknown.
- In reality, rock fractures are rough and appears with complex network structures. The impacts of surface roughness, network structures and hydraulic properties on grout propagation remain unknown.
- Grouts are typical non-Newtonian fluids with complex rheology properties. How the complex rheology properties affect grout propagation remains unknown.

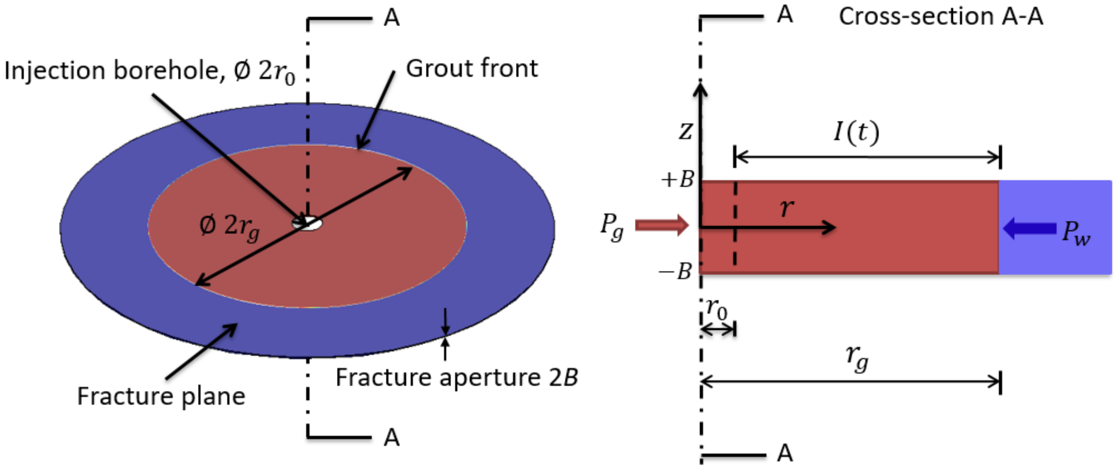
Main objectives

The general objective is to improve predictions, design, and execution of rock grouting, by introducing numerical simulations and possibly new rheological models for cement-based grouts. The main specific objectives are to:

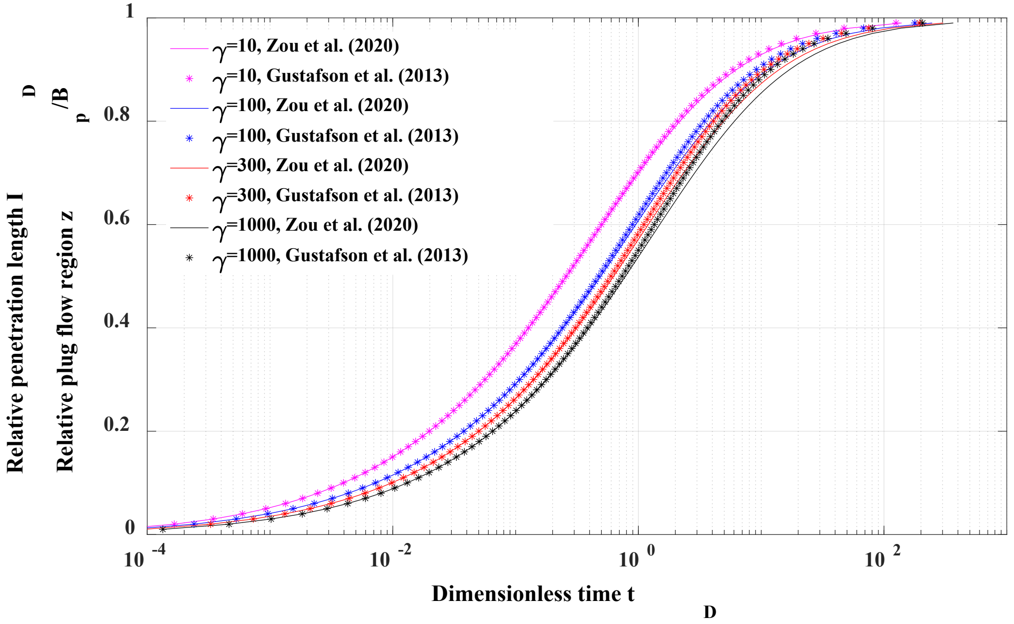
- Clarify the confusion existing in the two solutions regarding the shape of the plug flow region in 2D radial flow of a Bingham fluid for application of the RTGC method.
- Investigate the impact of surface roughness on non-Newtonian cement grout flow in rock fractures by numerical simulations of Bingham grout flow in a single rough-walled fracture.
- Present a two-phase flow model of non-Newtonian cement grout propagation combined with a Reynolds type of equation and investigate the potential impact of water flow on grout propagation for different viscosity ranges.
- Extend the two-phase flow model based on a single fracture for simulating cement grouts (Bingham fluids) propagation in water saturated fracture networks and verify the two-phase fracture network model using the benchmark experimental data by Håkansson (1987).
- Quantify the two-phase propagation processes of cement grouts in saturated fracture networks and investigate the impact of fracture network structure, hydraulic variability, and rheological properties on cement grout propagation in saturated fracture networks.

Main results: analysis of the two existing solutions

Schematic of grouting with 2D radial flow



Comparison between the two solutions



Model I by Dai and Bird (1981) considers the vertical velocity component:

$$\frac{\partial v_r}{\partial r} + \frac{v_r}{r} + \frac{\partial v_z}{\partial z} = 0$$

$$\frac{\partial P}{\partial r} + \frac{\partial \tau_{zr}}{\partial z} = 0$$

Model II presented in this report, also in El Tani (2012), assumes that the vertical velocity component is negligible $\frac{\partial v_z}{\partial z}$ = 0:

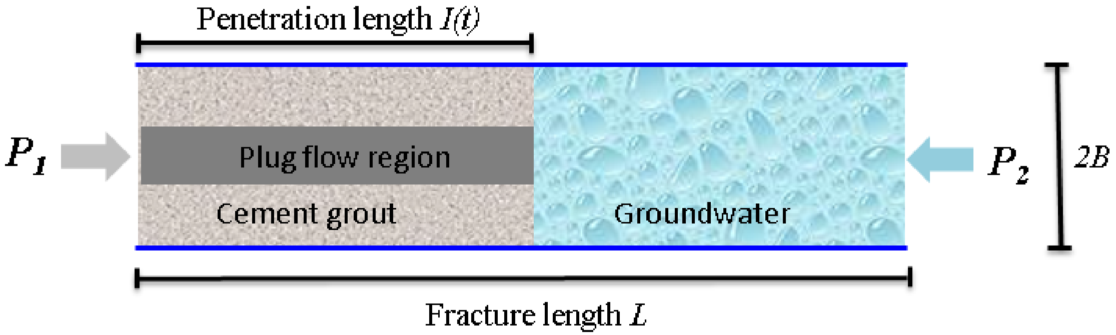
$$\frac{\partial v_r}{\partial r} + \frac{v_r}{r} = 0$$

$$\frac{\partial P}{\partial r} + \frac{\partial \tau_{zr}}{\partial z} = 0$$

- The two solutions based on different assumptions.
- The difference between the two solutions for grouting analysis is negligible.
- The expressions of model II presented in this report is much simpler that can be eazily used in practice.

Main results: two-phase flow model

Illustration of cement grout penetration into a single water-saturated fracture:



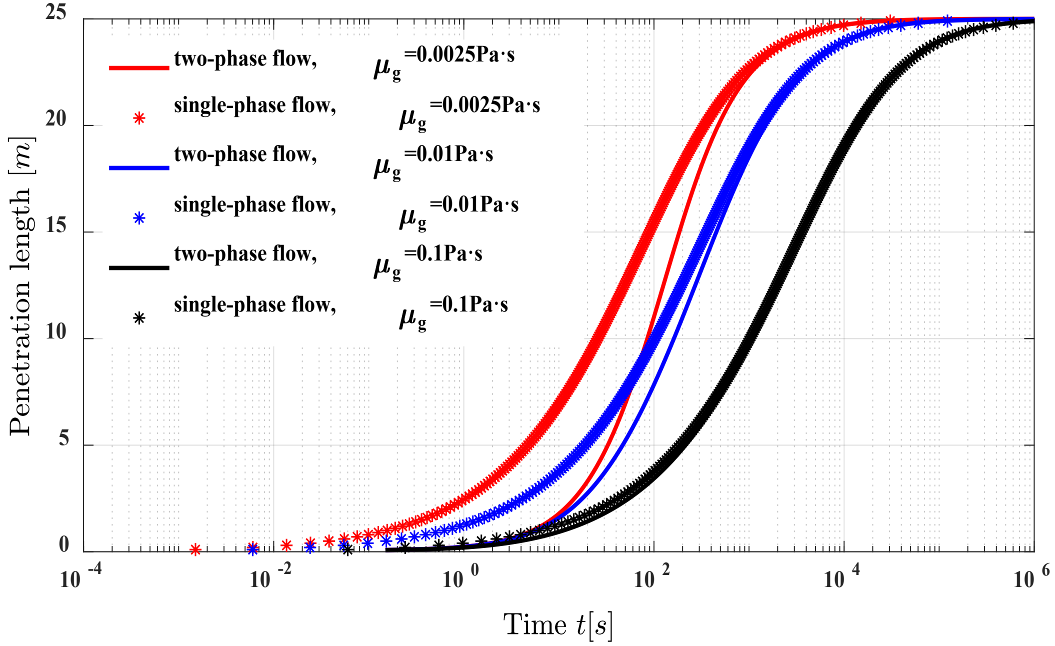
Two-phase flow model:

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

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

$$\frac{\partial C}{\partial t}+u\frac{\partial C}{\partial x}=0$$

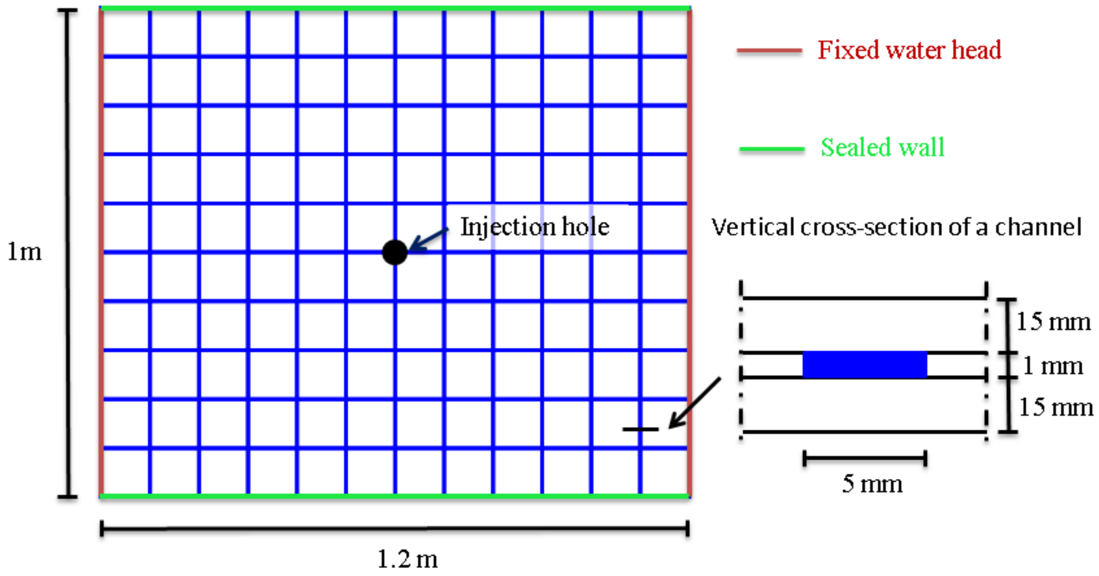
Impact of two-phase flow



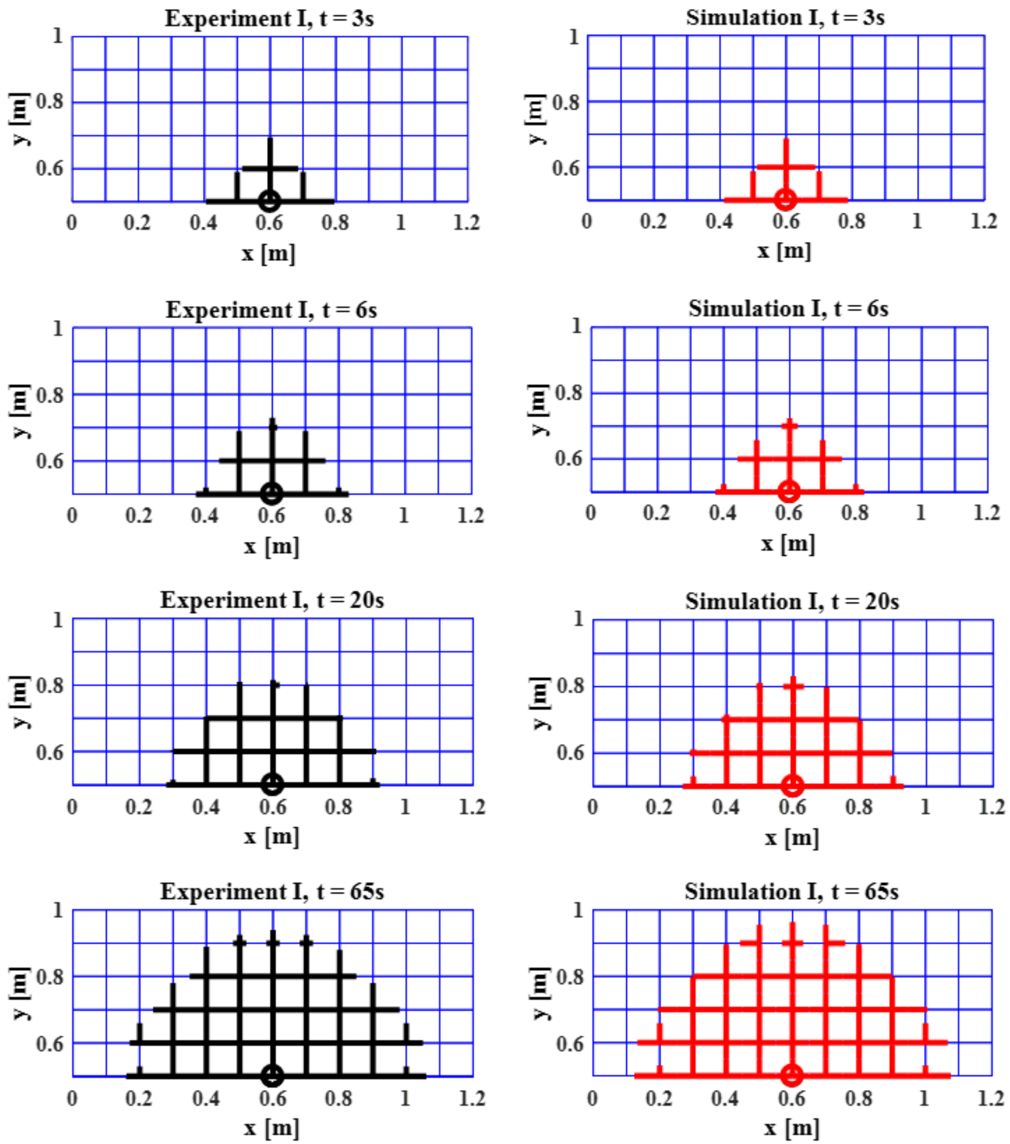
- The water phase flow may significantly affect the grout penetration process especially when the viscosity of grout is relatively small compared to the viscosity of groundwater.

Main results: grout propagation in fracture networks I

Validation by experimental data from Håkansson (1987)

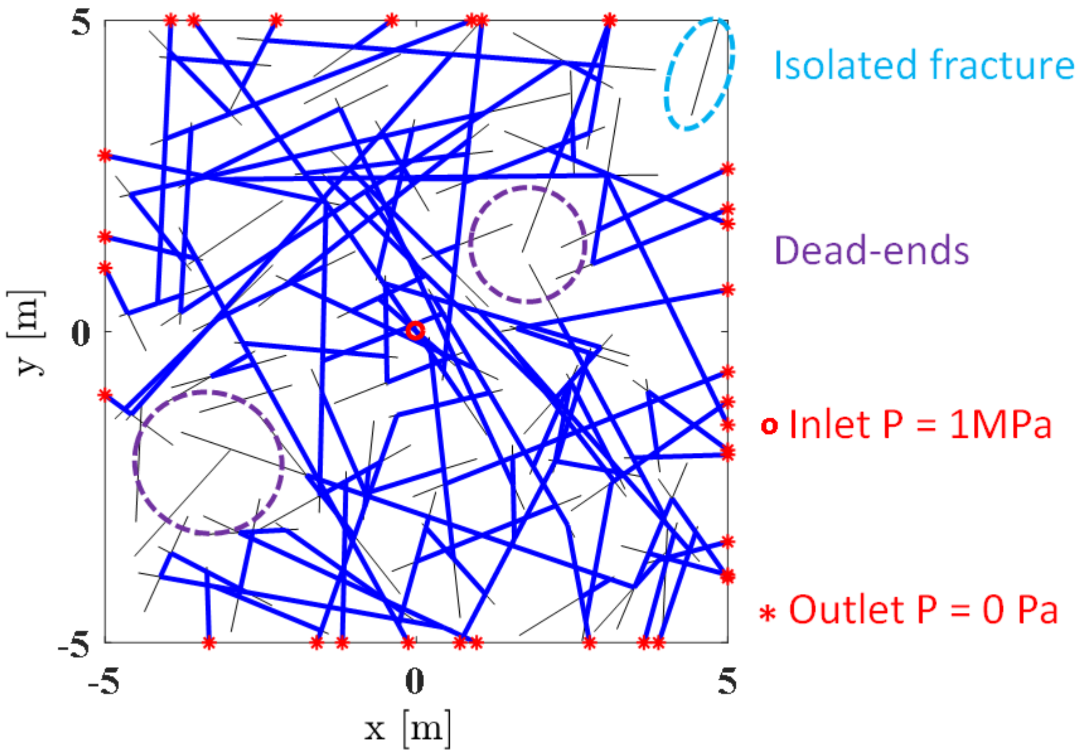


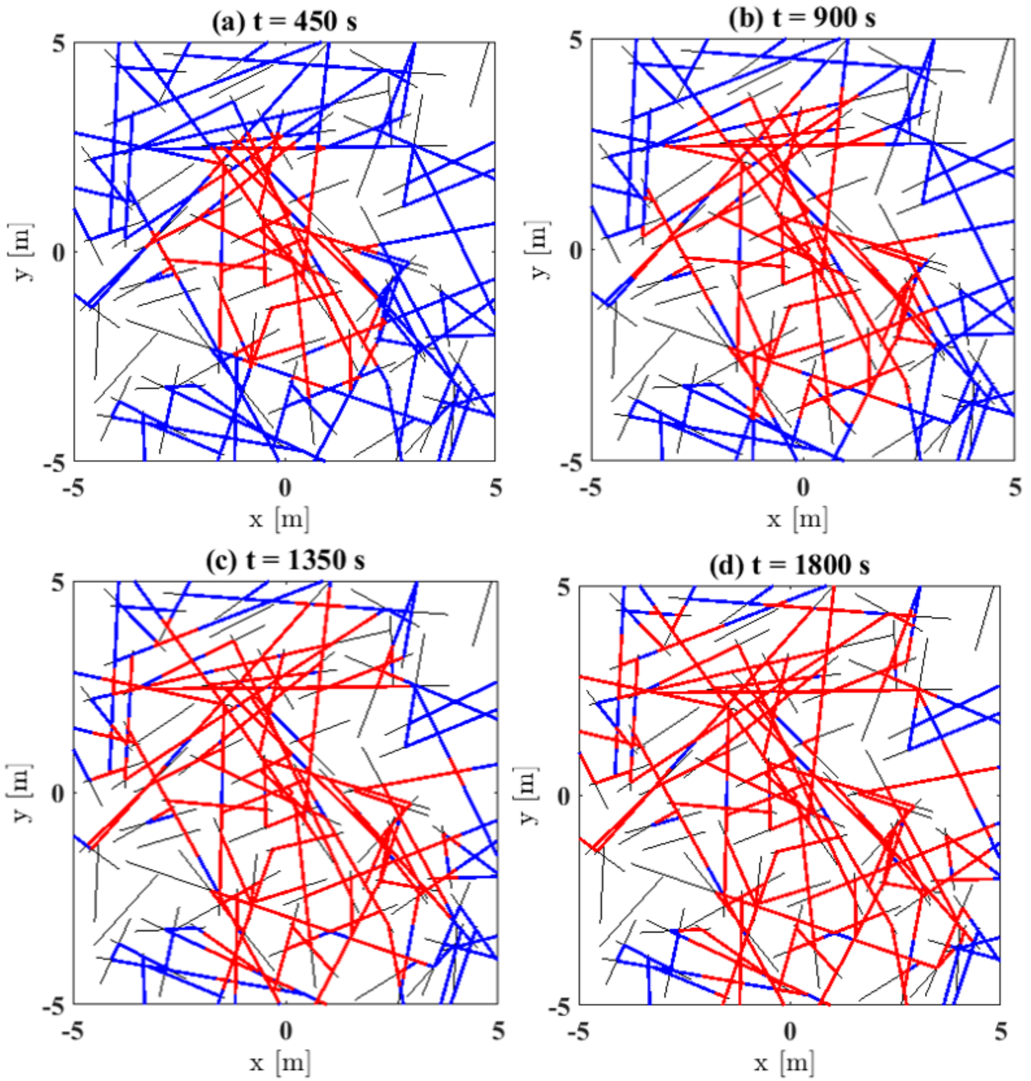
- The simulation results calculated by using the extended two-phase flow model match well with the experimental results.



Main results: grout propagation in fracture networks II

Random 2D discrete fracture network (DFN)





- The network structures and hydraulic properties affect the propagation rate of grouts in fracture networks .

Main conclusions: I

- For 2D radial flow of a Bingham fluid, the theoretical solution presented in this report and the solution by Dai and Bird (1981) are based on different assumptions. Dai and Bird (1981) considered the vertical velocity component in the continuity equation, and we assumed that vertical velocity is negligible. This difference leads to two different approximation models for rock grouting analysis, i.e., one is presented in this report and the other one is derived by Gustafson and Claesson (2005).
- The differences in the results of grout penetration length and flowrate evolution with respect to the grouting time between the two solutions are negligible within the full range of grouting time.

Main conclusions: II

- The water flow significantly affects the pressure distribution in the fracture and delays grout penetration.
- Analytical solutions or numerical models for rock grouting that ignore water phase flow, e.g., RTGC method, may only be applicable for cases where the grout viscosity is much higher than that of groundwater and the density is close to that of groundwater.
- Neglecting groundwater in grout flow modeling overestimates the penetration length, i.e., the errors can be over 20% of the maximum penetration length for the cases with low viscosity ratios.

Main conclusions: III

- The two-phase flow model for a single fracture can be extended for modeling of cement grouts as Bingham fluids propagation in 2D water saturated, randomized discrete fracture network (DFN).
- The network structures, distribution of apertures, correlation of aperture to the fracture length, and rheological properties of the cement grout (yield stress and plastic viscosity), can significantly affect the propagation process of cement grout in DFN.

Publications from this project

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3) Zou L, Håkansson U, Cvetkovic V, Analysis of Bingham fluid radial flow in smooth fractures, *Journal of Rock Mechanics and Geotechnical Engineering*, Volume 12, Issue 5, October 2020, Pages 1112-1118. https://doi.org/10.1016/j.jrmge.2019.12.021
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5) Zou L, Håkansson U, Cvetkovic V, Yield-power-law fluid propagation in water-saturated fracture networks with application to rock grouting, *Tunnelling and Underground Space Technology*, Volume 95, 2020, 103170. https://doi.org/10.1016/j.tust.2019.103170
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7) Zou L, Håkansson U, Cvetkovic V, Characterization of effective transmissivity for cement grout flow in rock fractures, the 9th Nordic Grouting Symposium, September 2-3, 2019, Helsinki, Finland.
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9) Zou L, Håkansson U, Cvetkovic V, Non-Newtonian grout flow in single rough-walled rock fractures, Bergdagarna 2019. March 19, 2019, Stockholm.
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11) Zou L, Håkansson U, Cvetkovic V. Modeling of rock grouting in saturated variable aperture fractures. Bergdagarna 2018. March 20, 2018, Stockholm.
12) Zou L, Håkansson U, Cvetkovic V. Non-Newtonian fluid flow in 2D fracture networks. AGU Fall Meeting 2017. 11-15 Dec. 2017, New Orleans.