CHARACTERIZATION OF EFFECTIVE TRANSMISSIVITY FOR CEMENT GROUT FLOW IN ROCK FRACTURES

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ABSTRACT

Cement grouting has been widely used in rock engineering. Proper characterization of the effective transmissivity for cement grout flow in rock fractures is primarily important for the design of rock grouting. In practice, the hydraulic transmissivity of groundwater flow in rock fractures characterized by hydraulic tests, i.e., pumping or slug test, is often used for the design of rock grouting. However, cement grouts used in rock grouting practice are typical non-Newtonian fluids contain yield stress, which has different effective transmissivity from the Newtonian groundwater. Therefore, using the groundwater transmissivity characterized by hydraulic tests may cause significant uncertainty in modeling and design of cement rock grouting. In this study, we focus on the effective transmissivity of non-Newtonian cement grout flow in a single fracture, aiming to illustrate the difference between the effective transmissivity of non-Newtonian cement grouts and the hydraulic transmissivity of the Newtonian groundwater. The cement grout is assumed as a Bingham fluid. The theoretical solution for the effective transmissivity of Bingham grout for homogeneous fractures is presented. This solution is compared with the theoretical hydraulic transmissivity, i.e., the cubic law. The results generally illustrate the significant differences between the effective transmissivity of non-Newtonian cement grouts and the hydraulic transmissivity of groundwater. The effective transmissivity of non-Newtonian cement grout is nonlinear which a function of injection pressure. Using the hydraulic transmissivity for rock grouting may underestimate the propagation length of the cement grout in rock fractures. The obtained result is helpful for rock grouting design in practice to reduce the potential uncertainties caused by using the hydraulic transmissivity.

KEYWORDS

Cement grouting, Effective transmissivity, Hydraulic aperture, Propagation length

1. INTRODUCTION

Cement grouting has been widely used to reduce groundwater flow and increase the tightness of rock masses in rock engineering projects, such as tunneling, dam foundation and underground structures or construction. Modeling of cement grout flow in rock fractures is important for design and performance of grouting activities in these projects (Stille 2015). Proper characterization of the effective transmissivity for cement grout flow in rock fractures is primarily important for the design of rock grouting, since the effective transmissivity is a key design parameters that controls the propagation of cement grouts in rock fractures. In practice, the hydraulic transmissivity of groundwater flow in rock fractures characterized by hydraulic tests, i.e., pumping or slug test, is often used for the design of rock grouting (Hernqvist et al., 2012; Fransson et al., 2007; 2012; 2016).

In the literature, many models and design methods have been developed to analyze cement grouting in rock fractures (e.g., Lombardi 1985; Hässler 1991; Hässler et al,1992; Eriksson et al. 2000; Gustafson and Stille. 2005; Hernqvist et al., 2012; Funehag and Thörn 2014; Stille 2015; Fransson et al., 2016; Zou et al. 2018a,b; 2019a,b). Notably, Gustafson et al., (2013) developed an analytical solution for the grout penetration with time in a single homogeneous planar fracture, 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 analytical solution provided the theoretical basis for the real time grouting control (RTGC) method (Kobayashi et al., 2008; Stille et al., 2009; 2015). Stille (2015) and Fransson et al., (2016) presented the hydraulic testing and grout selection in Swedish grouting design methods, showing that the prediction of cement grout penetration length and grouting time need to be adopted to the effective hydraulic aperture that is estimated by hydraulic testing. The traditional hydraulic testing, e.g., pumping or slug tests, cannot provide the effective hydraulic aperture for each single fractures. A new hydraulic testing tool, i.e., Posiva flow log (PFL), has been developed to test hydraulic properties of fractured rocks, which is able to quantify the local flowrates of each intersecting fractures with the borehole by setting the supporting distance of packers (e.g., Ohberg and Rouhiainen 2000). This new hydraulic testing tool provides the possibility to estimate effective hydraulic aperture for rock grouting design that is often based on analytical models for a single fracture (e.g., Kobayashi et al., 2008; Stille et al., 2009; 2015).

In addition, natural rock fractures are rough-walled and fracture apertures are spatially variable, which causes important uncertainty for estimating the effective hydraulic apertures. Although many studies have been devoted to quantify the ratio of hydraulic aperture and mechanical aperture in the literature (e.g., Louis 1969; Patir and Cheng 1978; Walsh 1981; Barton et al. 1985; Hakami 1995; Renshaw 1995; Zimmerman and Bodvarsson 1996), quantification of the effective hydraulic aperture remains an open question. Therefore, characterization of the effective hydraulic aperture by hydraulic testing for rock grouting design remains a channeling issue. In particular, cement grouts are typically non-Newtonian fluids with yield stress assumed as Bingham fluids in practice (Håkansson et al., 1992; Håkansson 1993). The Bingham fluid has nonlinear effective transmissivity due to its nonlinear rheological behaviors, which is different from the Newtonian groundwater (Zou et al., 2019b). Therefore, using the groundwater transmissivity characterized by hydraulic tests may cause significant uncertainty in modeling and design of cement rock grouting.

In this study, we aim to demonstrate the importance of properly characterizing the effective transmissivity for rock grouting design with the 1D unidirectional flow configuration. We firstly theoretically analyze the effective transmissivity for the Newtonian groundwater and the non-Newtonian cement grouts as Bingham fluids. Then, illustration examples for cement grout propagation with time using different effective hydraulic apertures are presented. The result is helpful for effective transmissivity characterization for rock grouting design in practice.

2. THEORY AND ANALYTICAL SOLUTIONS

2.1. Fluid flow in rock fractures

The general governing equations based on mass and momentum conservation for incompressible fluid flow can be written as

$$\nabla \cdot \mathrm{u} = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho \mathrm{u}) + \rho\, \mathrm{u} \cdot \nabla \mathrm{u} = -\nabla p \mathrm{I} + \nabla \cdot \tau + \rho \mathrm{g} \tag{2}$$

where $\mathrm{u}\ (m/s)$ is the fluid velocity vector, ρ is fluid density, t is time, P is pressure, I is the identity matrix, g is acceleration of gravity and τ is shear stress.

For groundwater, as a Newtonian fluid, the shear stress is expressed as

$$\tau = \mu\dot{\gamma} \tag{3}$$

where μ is the dynamic viscosity and $\dot{\gamma}$ is the shear strain.

For cement grouts that often assumed as Bingham fluids, the shear stress is expressed as

$$\begin{cases} \tau = \tau_0 + \mu_B\dot{\gamma} & |\tau| > \tau_0 \\ \dot{\gamma} = 0 & otherwise \end{cases} \tag{4}$$

where τ_0 is the yield stress and μ_B is the plastic viscosity.

2.2. Analytical solutions

It is assumed that the fluids, i.e., cement grouts or 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, so that the pressure gradient across the aperture is negligible by adopting the lubrication approximation. The governing equations for the 1D unidirectional flow can be simplified as,

$$\frac{\partial u}{\partial x} = 0 \quad (5)$$

$$-\frac{\partial P}{\partial x} = \frac{\partial \tau}{\partial z} \quad (6)$$

For groundwater flow in a homogenous fracture with a given pressure gradient, its solution is given by the cubic law, expressed as (Snow 1968)

$$Q = -\frac{2B^3}{3\mu_w}\frac{\partial P}{\partial x} \quad (7)$$

where B is half of the aperture, μ_w is the dynamic viscosity of water. For Bingham fluid flow in a homogenous fracture with a given pressure gradient, the simplified governing equations can be analytically solved. The pressure gradient and velocity are given by

$$\frac{\partial P}{\partial x} = \frac{P_1 - P_2}{L} \quad (8)$$

$$u(z) = -\frac{1}{2\mu_B}\frac{dP}{dx}(B^2 - z^2) + \frac{\tau_0}{\mu_B}(B - z) \quad z_p < z \le B \quad (9)$$

$$u(z) = -\frac{1}{2\mu_B}\frac{dP}{dx}\left(B^2 - {z_p}^2\right) + \frac{\tau_0}{\mu_B}\left(B - z_p\right) \quad 0 < z \le z_p \quad (10)$$

where L is the fracture length, P_1 and P_2 are given pressure at the inlet and outlet, respectively, and z_p is half of the plug flow region caused by the yield stress, determined by

$$z_p = \min\left(\frac{\tau_0 L}{P_1 - P_2}, B\right) \quad (11)$$

$$Q = -\frac{B^3}{3\mu_B}\left(1 - \frac{z_p}{B}\right)^2\left(2 + \frac{z_p}{B}\right)\frac{\partial P}{\partial x} \quad (12)$$

2.3. Real time grouting control (RTGC)

Without considering the water phase flow and grout hardening in the grouting process, an analytical solution for Bingham grout penetration with channel flow and radial flow in parallel plates are given by Gustafson et al. (2013). This type of analytical solutions provided the theoretical bases for the real time grouting control (RTGC) approach.

For the 1D unidirectional flow, the solution is written as (Gustafson et al. 2013)

$$t = \frac{6(P_1 - P_2)\mu_B}{{\tau_0}^2}\left\{\frac{I_D}{3(1 - I_D)} + \frac{2}{9}\,ln\left[\frac{2(1 - I_D)}{2 + I_D}\right]\right\} \quad (13)$$

where I_D is the relative penetration length, expressed as

$$I_D = \frac{I}{I_{max}} = \frac{z_p}{B} \quad (14)$$

where I_{max} is the maximum length that the grout can be propagated, determined by (Gustafson et al. 2013)

$$I_{max} = \frac{(P_1 - P_2)B}{\tau_0} \tag{15}$$

In this study, we use this analytical solution to demonstrate the impact of the effective hydraulic aperture on cement grout propagation with time.

3. CHARACTERIZATION OF EFFECTIVE TRANSMISSIVITY

3.1. Effective transmissivity for groundwater

Assuming that the flowrate is measured by a given pressure gradient by hydraulic testing, the effective transmissivity for groundwater 1D flow in a rock fracture can be determined with given pressure gradient and measured flowrate,

$$T_w = -Q/\frac{dp}{dx} = -\frac{2{B_h}^3}{3\mu_w} \tag{16}$$

For homogeneous planar fractures, the hydraulic aperture, B_h, is equal to the mechanical aperture, given by

$$B_h = \sqrt[3]{-\frac{3}{2}\mu_w\, Q/\frac{dp}{dx}} \tag{17}$$

In reality, the natural rock fractures are all rough-walled with variable apertures. Numerous studies have shown that the effective hydraulic aperture for natural rock fractures are less than the mechanical aperture (e.g., Louis 1969; Patir and Cheng 1978; Walsh 1981; Barton et al. 1985; Hakami 1995; Renshaw 1995; Zimmerman and Bodvarsson 1996; Zou et al., 2015; 2017). For instance, Hakami (1995) proposed a simple empirical relationship between the hydraulic aperture B_h and mechanical aperture B_m and suggested the range of its empirical coefficient C for granite rock fractures, expressed as (Hakami 1995)

$$(2B_h)^2 = \frac{(2B_m)^2}{C}, C = 1.1{\sim}1.7 \tag{18}$$

This model and the suggested range of coefficients are adopted in the present study to demonstrate the impact of effective transmissivity on the cement grouts propagation.

3.2. Effective transmissivity for non-Newtonian cement grouts

The effective transmissivity for non-Newtonian grouts is naturally nonlinear and is dependent on the pressure gradient because of the yield stress. According to our previous study on the effective transmissivity for Bingham grouts by direct numerical simulation of cement grouts flow in a single rough-walled rock fracture, the theoretical transmissivity for Bingham grouts based on the analytical solution for idealized homogeneous fracture is valid for rough-walled fractures when Reynolds number (Re) is relatively small, i.e., Re ≤ 10. Therefore, the mechanical aperture can approximate the effective aperture for cement grout flow when Re is relatively small, given by

$$T_B = -Q/\frac{dp}{dx} = -\frac{{B_m}^3}{3\mu_B}\left(1 - \frac{z_p}{B_m}\right)^2\left(2 + \frac{z_p}{B_m}\right) \tag{19}$$

4. ILLUSTRATION EXAMPLE

An example is presented to illustrate the impact of effective transmissivity on the cement grout propagation process. The adopted model geometry and the physical parameters (typically used in rock grouting practice) for the illustration example are summarized in Table 1.

Table 1. Physical parameters adopted for the illustration example.

Parameters	Units	Values
Hydraulic aperture, 2B	[μm]	100
Viscosity of grout, μ	[Pa·s]	0.025
Yield stress of grout, τ_0	[Pa]	5
Grouting pressure, $P_1 - P_2$	[MPa]	1
Coefficient, C	[-]	1, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6 and 1.7

By given a hydraulic aperture from hydraulic testing, the mechanical apertures are estimated by using Hakami's model. The estimated mechanical apertures are used to parameterize the RTGC grouting model. Figure 1 shows the effective transmissivity for cement grouts flow in the injection process for different values of the coefficient C in Hakami's model. Since the transmissivity is dependent on the pressure gradient that reduces with the increasing propagation length, the effective transmissivity for cement grouts flow is nonlinear and it reduces with the increasing propagation length to zero until the grout propagate to the maximum propagation length. The case when C = 1 represents that the fracture is homogeneous with constant aperture, where the hydraulic aperture is valid for calculating the effective transmissivity for cement grout propagation. When C > 1, the mechanical apertures are larger than the hydraulic aperture obtained from hydraulic testing. For instance, at the early stage of propagation, the effective transmissivity for the case C = 1.7 is more than two times of that for the case when C = 1. Such difference gradually reduces with the increasing propagation length. This result indicates that direct using the hydraulic aperture from hydraulic testing will underestimate the effective transmissivity for cement grout propagation.

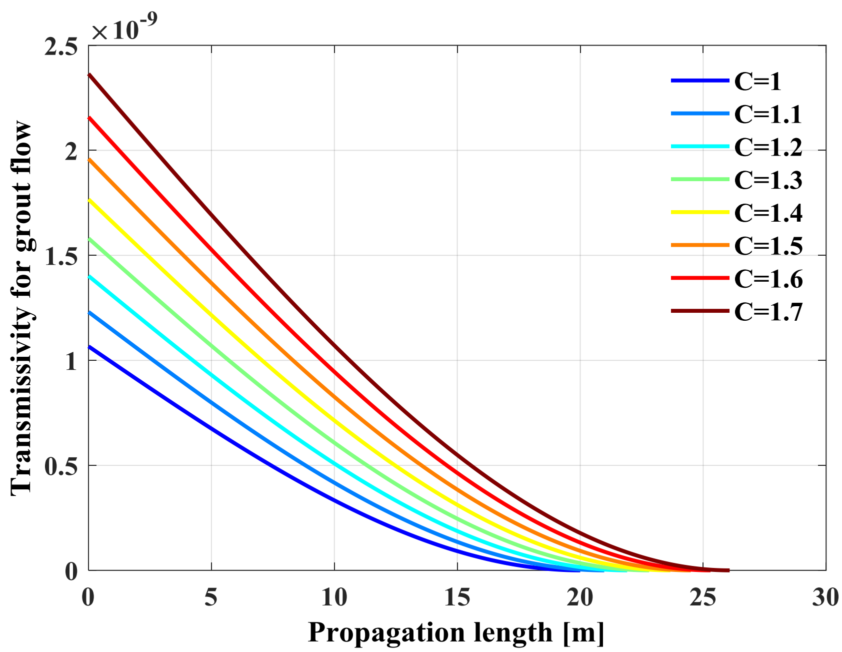

Figure 1. Illustration of the effective transmissivity for cement grouts flow in the injection process for different values of the coefficient C in Hakami's model.

Figure 2 presents the increasing propagation length with the injection time for different values of the coefficient C in Hakami's model using the RTGC method. The absolute values of propagation length and injection time rather than the normalized propagation curve are presented in this example to show the variation of predicted propagation length in practice. Generally, the propagation lengths for the cases when C > 1 are larger than that for the case when C = 1. The differences between the propagation lengths for the cases when C > 1 and C = 1 gradually increase with the injection time. In particular, when C = 1.7, the maximum of propagation length is around 26m, which is more than 30% larger than that of the case when C = 1 where the maximum of propagation length is around 20m. This result indicates that direct using the hydraulic aperture from hydraulic testing for rock grouting design will underestimate the propagation length in practice.

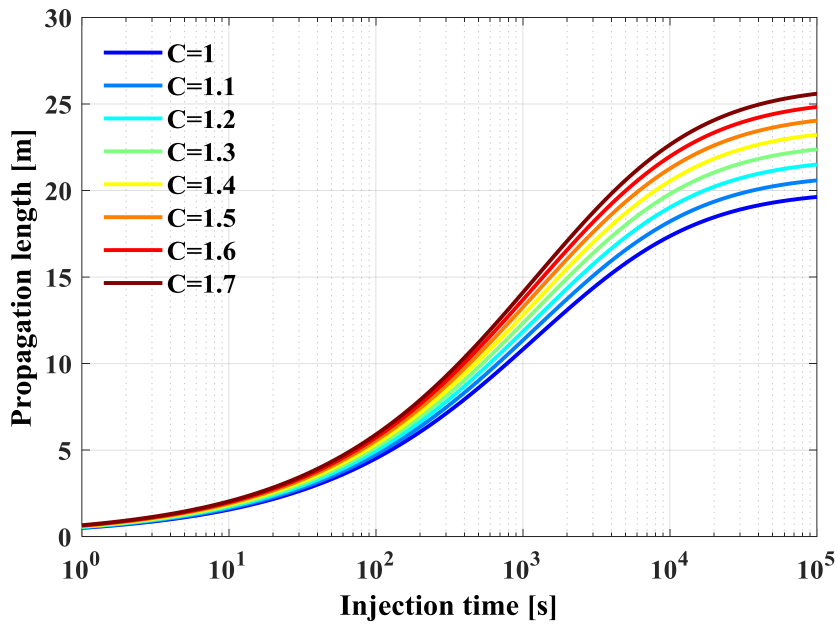

Figure 2. Illustration of the cement grout propagation with injection time for different values of the coefficient C in Hakami's model.

5. CONCLUDING REMARKS

In this study, we demonstrated the impact of effective transmissivity on the cement grout propagation for rock grouting design. The effective hydraulic aperture obtained from hydraulic testing is one of the key information for rock grouting design. The cement grouts are typically non-Newtonian fluids that have nonlinear effective transmissivity depending on the pressure gradient. Previous study show that when the Reynolds number is relatively small, i.e., Re <10, the cement grout flow is dominated by the plug-flow, so that the fracture surface roughness has limited impact on the effective transmissivity. Therefore, the effective transmissivity for cement grouts can be estimated by the mechanical aperture. However, direct measuring fracture mechanical aperture in the field remains a challenge. It is, therefore, impossible to directly take the mechanical aperture as input design parameter.

In practice, the hydraulic aperture obtained from hydraulic testing remains an important input design parameter, but it should not be directly used to calculate the effective transmissivity for cement grouts flow, since the measured hydraulic aperture is often smaller than the effective aperture for cement grouts flow due to different significances for the impact of fracture surface roughness for the Newtonian groundwater and the non-Newtonian cement grouts. The results demonstrate that direct using the effective hydraulic aperture will underestimate the effective transmissivity for cement grouts flow and consequently underestimate the propagation length.

We adopted the Hakami's model to estimate the mechanical aperture (i.e., the effective aperture for cement grouts flow) for the demonstration. At present, the relationship between the mechanical aperture and effective hydraulic aperture remains a challenging issue because of complex geometrical and hydraulic conditions for fluid flow in natural rough rock fractures. The empirical coefficient C in Hakami's model directly affect the prediction result of the effective transmissivity and propagation length. The value of the coefficient C was suggested ranging from 1.1

to 1.7, which may contains uncertainty in practice. However, the suggested range of the coefficient C can be used to show the variation range of the predicted propagation length in rock grout design, which is helpful for quantifying the uncertainty of propagation lengths.

We only considered the case when the Reynolds number is relatively small, i.e., Re < 10, where the cement grout flow is dominated by the plug-flow. However, the Reynolds number is infinitely large at the initial stage of injection and reduces with the increasing propagation length. At the initial stage of injection, the effective transmissivity will be smaller than that estimated from the mechanical aperture, since the flow of cement grout is dominated by the viscous flow that is similar to the Newtonian groundwater. The effective transmissivity for cement grouts flow when Reynolds number is relatively high when Re > 10 at the initial stage of injection and its impact on the cement grout propagation remain open topics for the future study.

ACKNOWLEDGEMENT

The funding for this work is provided by BeFo, Rock Engineering Research Foundation, which is gratefully acknowledged.

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