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A simplified model for predicting grout flow in fracture channels

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ABSTRACT

Simulation of rock grouting plays an important role for improving grouting technology and practice. Most of the current models for simulating grouting of fracture channels assume that grout flow between two parallel plates is in a state of static equilibrium, neglecting the influence of inertia forces, thus the average velocity obtained from the governing equation is not simple with nonlinear terms, making it time consuming to simulate grout penetration in a complex fracture network with hundreds of single fractures. However, a simple solution can be derived, if the inertia force is included into the governing equation. Though the process of equation solving is complex, the dimensionless average velocity can be expressed as a constant number finally. Capability of the new model proposed for grouting simulation is studied based on an orthogonal test through comparing with the traditional model. It is found that, the simplified new model can well describe the overall characteristics presented by the traditional model; the accuracy of the new model is high and acceptable, and the relevant computational efficiency is greatly improved.

1. Introduction

Grouting can be used for sealing and stabilising soil, rock and structures, of which the problems to be solved are different (Warner, 2004). According to the way how cement grout fills voids of the potential objects, grouting can be classified into pressure grouting and non-pressure grouting, the latter is becoming less popular nowadays (Ren, 1999). Therefore, the focus now is on pressure grouting. Grouting is a complex process, which includes investigation of geological condition, determination of grouting materials, and operation of grouting equipment (namely, controlling grouting parameters such as injection pressure or flow rate). The latter two should be determined based on analysis of sufficient geological and geophysical data, but this process is done based more on personal experience of onsite engineers. Thus, research should be conducted to provide more guidance for practical grouting operation.

The degree of accuracy in predicting the geophysical and geo-hydraulic conditions depends more on the capability of state of the art technology (Induced Polarization (IP) methods, Direct current (DC) resistivity method, seismic reflection, and ground penetrating radar, and so on), and the ability of specific researchers to carry out backward analysis (Binley and Kemna, 2004; Bowling et al., 2007). Nevertheless, with reasonable assumption of geological conditions, research on the rheological properties of cement grout and influence of grouting parameters can be done in the meanwhile, which are beneficial to practical grouting prediction. Many researchers have contributed to exploration on rheology and application of cement grout, and the influence of additives, they found out that the properties of cement grout varies significantly with different impact factors and different types and percentage of additives mixed in Banfill (1990), Khayat and Yahia (1997), Rosquoët et al. (2003), Eriksson et al. (2004), Güllü (2015) and Güllü (2016).

Moreover, many theoretical models for grout flow are proposed, of which some are valuable for grouting simulation. For ground improvement, jet grouting is generally used, and the rheology of the relevant cement grout used can be described by many models, such as Bingham flow, Herschel-Bulkley flow, Modified Bingham flow, Casson flow, and so on; recently Güllü have derived many different theoretical models concerning relationships between shear stress and shear rate for grout flow with different stabilizer proportions, through a series of experimental data analysis (Güllü, 2016). Regarding grouting of rock masses, where the cement grout used is mainly composed of water and cement, Ruan concluded from experimental study that grout flow cannot be simply treated as only one flow type; moreover, he further derived the formula for different kinds of grout flow based on the relevant water cement ratio (W/C): Newtonian flow with W/C ranging from 2 to 10, Bingham flow with W/C of 0.8–1.0, and the W/C of Herschel-Bulkley flow is within 0.5–0.7 (Ruan, 2005), the classification of Ruan's method is simple and clear, and is used by many researchers thereafter even some potential errors are unavoidable. According to laboratory tests, Håkansson also stated that, it does not have one hundred percent accuracy when using Bingham model to describe the

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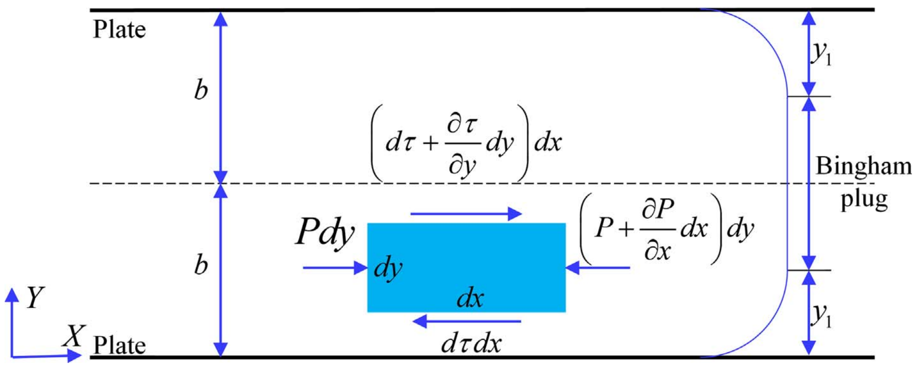

Fig. 1. Force diagram of grout flow in fracture channel (Huilgol, 2015).

characteristics of cementitious grout, but the discrepancy existed is not large (Håkansson, 1993). Therefore, cement slurry for grouting fractured rock masses is normally taken as Bingham flow, where flow will not take place unless the excess pressure is larger than the internal shear stress (Hässler et al., 1992a; Hässler et al., 1992b; Hori and Koyama, 1999; Eriksson et al., 2000; Hernqvist et al., 2008; Fujita et al., 2012; Gustafson et al., 2013).

As increasing number of public facilities are to be constructed underground, rock excavation is becoming inevitable. Unfortunately, due to poor rock mass quality, rock excavation is often accompanied by water inflow or rock collapse, which may lead to large economic loss or casualties. In practice, grouting is generally accepted as an economic and environmentally friendly method to improve the rock mass quality and reduce water inflow. However, the efficiency of the rock grouting is quite poor due to insufficient information on detailed geological conditions and lack of theoretical knowledge on grouting mechanism. Grouting simulation is an effective way to improve the design of rock grouting and guide grouting practice (Eriksson et al., 2000), so as to optimize the grouting processes.

Practical rock fractures are in three-dimensional (3D) fracture system, which are composed of many two-dimensional (2D) fractures, thus grout flow in fracture system is 3D if without any simplification (Butron, 2012). Nevertheless, grout flow is of 2D radial penetration in rock fractures intersected by grouting hole before it touches the boundary of width, and it becomes 1D channel flow thereafter. The first theoretical model for grout flow in fracture channel was proposed by Waller based on Bingham flow (Wallner, 1976), and it is used for describing grout flow between two parallel plates (Hässler et al., 1992a). Waller's model has been adopted as the theoretical basis for 1D grouting simulation with tiny change since then (Hässler et al., 1992a; Hässler et al., 1992b; Gustafson and Stille, 1996; Eriksson et al., 2000; Yang et al., 2002; Gustafson and Stille, 2005; Stille et al., 2009; Saeidi et al., 2012; Saeidi et al., 2013), except that the relevant grout penetration and grout volume were nondimensionalized (Gustafson and Stille, 2005). The accuracy of this model is considered to be high, and can describe experimental data fairly well (Gustafson et al., 2013).

However, being critical for grouting simulation, the average velocity derived from the traditional model is not simple due to the existence of nonlinear terms, leading to the fact that it takes quite long time to simulate grout penetration in a complex fracture network with hundreds of single fractures. Therefore, the present work aims at deriving an explicit and simple expression for the average velocity of 1D channel flow, which can clearly show the variation of grout flow velocity during the grouting process. The inertia term was included into the governing equation concerning grout flow within two parallel plates, and parameters involved were all nondimensionalized. Then, the nondimensionalized equation was solved using separation of variables, hence the succinct form of average velocity was obtained based on assumptions and simplifications. Feasibility analysis for the derived new model is conducted based on orthogonal test, where grout penetration between two parallel plates was simulated by both the traditional and simplified new models.

2. Theoretical model

2.1. Rheology of cement grout

Cement grout is a viscoplastic material, which has various rheological properties with varying water cement ratio or additives. Therefore, many experiments were done, with many fluid models being proposed to describe its rheology, like Bingham flow, Herschel-Bulkley flow, Modified Bingham flow, Casson flow, and so on (Banfill, 1990; Khayat and Yahia, 1997; Guan, 2001; Yahia and Khayat, 2001; Rosquoët et al., 2003; Eriksson et al., 2004; Schwarz and Krizek, 2010; Celik and Canakci, 2015; Rahman, 2015; Güllü, 2016). As for grouting of fractured rock masses, grout flow is commonly taken as Bingham fluid, not because it is of one hundred percent accuracy, but it is linear and simple with acceptable precision, especially for mostly used cement grout with W/C ratio ranging from 0.8 to 1 in practical engineering project (Eriksson et al., 2004). Therefore, grout flow is taken as Bingham fluid in the present work, the relationship between shear stress τ and shear rate is as follows (here the velocity gradient is in the vertical direction),

$$\begin{cases} \frac{\partial u}{\partial y}=0, & \tau<\tau_0 \\ \tau=\tau_0-\mu\frac{\partial u}{\partial y}, & \tau\geqslant\tau_0 \end{cases} \tag{1}$$

where u is velocity of grout flow at location y as shown in Fig. 1, τ_0 and μ are yield stress and viscosity of Bingham flow, respectively.

Here, τ_0 is the shear stress at the height of y_1, which is the height of the boundary of Bingham plug measured from the nearest boundary plate, and the width of Bingham plug is $2(b-y_1)$ (Huilgol, 2015). Within the Bingham plug, all the shear stress is less than the yield stress, thus the whole area is moving forward as a plug with the same velocity, as shown in Fig. 1.

As can be known from Eq. (1), the relationship between shear stress and shear rate can be represented by a linear curve, with the viscosity of Bingham flow μ as the slope and the relevant yield stress τ_0 as the intercept.

Experiments have been done by Rosquoët to describe the rheology of cement grout with varying W/C ratio, where no additives were added, and the cement used is CEM I 52.5 PM ES CP2 from Teil (France) (Rosquoët et al., 2003). For detailed components of this cement, please refer to Rosquoët's work. Cement grout with six different W/C ratios are tested, and the results are presented in Fig. 2.

It can be seen from Fig. 2 that it is approximately a linear curve for cement grout with W/C ratio ranging from 0.6 to 1.0, indicating that it can be described by Bingham model with high degree of accuracy. While the curve become nonlinear for other larger W/C ratios, which can no longer be represented by Bingham model.