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Grout penetration in fractured rock mass using a new developed explicit algorithm

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ABSTRACT

A grout penetrability method based on explicit grout forehead pressure (EGFP) algorithm for joints and cracks in rock mass is developed. This algorithm is more accurate and effective, and demands less computation power and time compared to previously used methods, for almost all types of fluids, under different flow regimes. The pre-existing pore pressure in rock joints is also considered in the present developed algorithm. EGFP does not require a complex program for calculating penetration length, and any simple calculator-based program also could be utilized to implement it. This algorithm is flexible enough to develop to a network of conductors. EGFP divides the conductor to a number of elements and continues the calculations to where the grout forehead gets stopped in the conductor owing to limitation factors. In the present algorithm there is no initial experimental prediction of total penetration length or flow rate of grout fluid that causes increases the accuracy. A series of laboratory tests were conducted and were used to validate and calibrate the numerical results. The results obtained by present algorithm show good agreement with experimental results.

1. Introduction

Joints and cracks in the rock mass often reduce resistance properties and increase the permeability of a fractured rock mass. Since the early nineteenth century, after the grouting technique was invented by Charles Berrgny for improving and sealing rock masses, this method has been faced with ever increasing usage. Nowadays, grout operation is an important part of engineering works in weak rocks, and has a great impact on overall cost and time of project. Therefore, study of the effect of important parameters, such as operational, rheological and geometrical parameters on penetrability of grout fluid, is critical. In this case, the amount of grout uptake and spreading area, which prevents additional time and expense in grouting operation in each borehole, should be evaluated.[1–6] Lombardi developed an equation to determine the penetrability of Bingham grouting fluids. Many other analytical, experimental and numerical research works in this field of study were conducted on his developed equation, and reported in Ref. 1. All of the aforementioned works used the principle of mass conservation and permeability limiting equations to determine the maximum penetration length and grout uptake. Hässler linked grout uptake and penetration length in a single rock fracture. He suggested that in a useful theory for prediction grouting, at least the penetration length of the grouting should be estimated.[2] Although some efforts have been done to highlight the impact of important parameters on groutability in laboratory or field scale,[3–6] those suggested methods do not have sufficient accuracy and it are difficult to generalize in complicated field scales in different locations. Numerical methods offer more accurate and relatively demand less time and cost compared to the experimental works, particularly in the design stage of a project. Gustafsson et al. attempted to predict the permeability of Bingham slurry using numerical modeling, with emphasis on the phenomenon of filtration.[7] Ericsson et al. analyzed the grouting, using a computer program and compared the obtained results with the results of laboratory tests.[8] Shuttle et al. attempted to measure the amount of grout fluid propagation using a computer programming in a three-dimensional network of discrete fractures with constant joints aperture.[9] Rahmani followed the same process in two-dimensional single joint with variable aperture.[10] Similar studies have also been done on two-dimensional fracture networks.[11] Some of the major factors controlling flow through rock joints were extensively studied in the laboratory and simulated by modeling.[12] Barton et al.[13] proposed an empirical equation for the analysis of the relationship between the effective physical aperture and the theoretical aperture, related to the parallel plate analogy (cubic law), using the joint roughness coefficient (JRC).

In general, some limitations could be seen in previous methods, for instance, a number of them uses a general equation (traditionally Lombardi equation) to predict the

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maximum penetration length which is limited by various limiting factors including filtration and pore water pressure which are not accurate methods according to the results provided by other researchers.[1,2,4,5,7–9] Inability to model the joints in vertical section and gravitational effect on the flow of grout fluid,[1,2,4,5,7–9,11] inability to model the pore fluid pressure and its effect on permeability[1,2] and inability to model the different types of grout fluids such as chemical, bacterial and fine grained fluids[1–11] are some of other restrictions. A number of methods ignore the effect of time function hardening of injected grout into the joints during a specified period of time after starting grouting process.[1,2,4,5,7] These shortcomings have been overcome with the developed algorithm in this research work. This method is based on calculation of grout forehead pressure, which suggests more accurate prediction of fluid penetration length into a single joint using the initial grout parameters. A fully explicit algorithm method, which is more flexible to use in computer programming, is facilitated in the present developed numerical code. In this paper firstly, theoretical foundations basic equations of fluid rheology, flow limiting factors on grout forehead pressure and also stopping criterion for computational cycles are expressed. Then the results of the developed algorithm is validated and compared with experimental results in the laboratory and finally discussion and conclusion remarks are drawn.

2. Methodology

What is taken into consideration in this study is utilization of an explicit grout forehead pressure (EGFP) criterion as the core of calculations. It is the main deference between this study and many previous studies that were described above. Using EGFP there is no need to predict maximum penetration length by an experimental equation which causes enhancement in accuracy, as will be explained in the following sections. Also EGFP predicts penetration length without using of a complex software source, in the other word, any simple mathematical based program also could be utilized to implement it.

If joints are considered as conductors in an electrical field, the differential pressure required to inject grout into the joints can be simulated by electrical potential difference. Therefore the grout pressure drop and calculations of pressure changes in multi-ways can be simulated using the laws govern the flow of electricity in series or parallel circuits.[14] If multiple grouting paths are connected in parallel position, the pressure difference at the two ends of each path is equal to the pressure difference between the ends of all paths, while if we have conductors in series, the pressure difference between two ends of general direction is a summation of total pressure difference in individual paths.

Analogously to most of the previous reported research works, in this study a joint is considered to be a pair of parallel plates with unit width.[15–18] Another advantage of using EGFP is possibility of modeling with different types of grout fluids such as cement-based, chemical and fine-grained grouts which follow Bingham, power-law and Newtonian rheological models respectively.[19,20]

2.1. Theoretical foundations

Rheology is the science of deformability and flow of material. To simulate the state of flow, the rheology or structural relationships of fluid must be known. In most cases, the material behavior can be described with various rheological models.[21] In general, rheological models of fluid flow behavior are divided into two general categories: Newtonian and non-Newtonian. Newtonian rheological model is satisfied in the case of fluids in which relationship between shear stress (τ) and velocity gradient (dv/dy) is linear (Fig. 1).

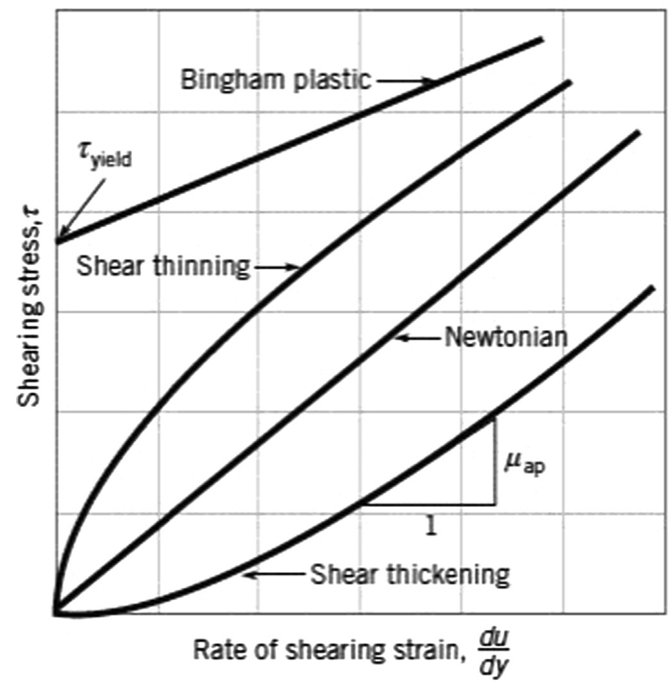

Fig. 1. Variation of shearing stress with rate of shearing strain for several types of fluids, including common non-Newtonian fluids.[22]

$$\tau = \mu(dv/dy) \quad (1)$$

where μ is the dynamic viscosity.[21]

A common example of a Newtonian fluid is water. Fluids such as very fine-grained cement-based grouts (silicasol) and also bacterial grouts (MICP) are described by this model. A Bingham fluid is a viscoplastic fluid which behaves as a rigid material at low shear stresses and as a viscous fluid at high shear stresses. This rheological model is used most often as the main rheological model for cement-based grouts, in which relationship between shear stress and velocity gradient is of the form of (Fig. 1)

$$\tau = \mu(dv/dy) + \tau_O \quad (2)$$

where τ_O is the shear stress required to initiate flow.[22]

Fig. 1 also shows a power-law fluid, which is a kind of generalized Newtonian fluid. The relationship between shear stress and velocity gradient in the power-law fluid is in the following form:

$$\tau = k(dv/dy)^n \quad (3)$$

where k is the flow consistency index and n is the flow behavior index.[22]

Power-law fluids can be divided into three subcategories according to the flow behavior index. As shown in Fig. 1, if the flow behavior index is smaller than 1, the power-law fluid is pseudoplastic. In pseudoplastic fluids, viscosity decreases consistently with increasing shear rate. The more chemical and polymeric fluids are some common examples. If the flow behavior index is 1, the power-law fluid becomes Newtonian and if the flow behavior index is greater than 1, the power-law fluid is dilatant in which with increasing shear rate, the viscosity increases.

According to mentioned contents, because the Newtonian rheological model is obtained from both Bingham and power-law rheological models (τ_O=0 in the Bingham model and n=1 in the power-law model), in this study, only the calculations for Bingham