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Numerical and analytical analyses of the effects of different joint and grout properties on the rock mass groutability

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ABSTRACT

In this study, an attempt has been made to propose a numerical model to predict grout flow and penetration length into the jointed rock mass using UDEC. The numerical model is adjusted using practical data and presence analytical methods for grouting process. Input data included geomechanical parameters along with grout properties obtained from a case study. The effect of rock mass properties as joint hydraulic aperture, roughness, spacing, trace length, dipping and grout properties as yield value, viscosity and grout pressure was considered on grout flow rate and penetration length. Barton–Bandis joint model has been used to assign joint roughness and strength (*JRC* and *JCS*) in the modeling. The results were in a good agreement with analytical and field database. A general function is defined to demonstrate the effects of rock and grout properties on penetration length of grout.

1. Introduction

Grouting is widely used to reduce water flow through rock masses and, in this regard, various injection techniques have been developed. The groutability is defined as the ability of rock to accept grout (Bruce, 2006). Therefore, groutability of rocks depends on the many factors related to the properties of the joint and the injected grout material. These factors can be divided into two parts: the controllable parameters and uncontrollable parameters. Grout material, pressure, flow and grouting system are controllable parameters. Parameters such as rock mass properties and geological conditions are uncontrollable parameters.

In discussion of the effects of rock mass properties on the grouting process, many researchers have described the rock's behavior with emphasis on its groutability, using the various parameters both practically and theoretically (Ewert, 1985; Houlsby, 1990; Weaver, 1991; Warner, 2004; Lombardi, 1985; Hassler et al., 1988; Gustafson and Stille, 1996, 2005; Eriksson et al., 2000; Foyo et al., 2005; Stille et al., 2012). Rock type itself does not usually affect grouting, but many rock types have special characteristics including jointing system, porosity, and weathering as well as physical and hydraulic properties in which they affect the grouting process, directly. Houlsby (1990) outlined the most effective rock mass properties which influence its groutability including joint spacing, dipping, persistency, filling, aperture and rock soundness, strength and in situ stress.

In addition to rock mass properties, the rheological properties of the grout have important role on the groutability of a rock mass.

One of the most important challenges in penetration grouting is computation of the depth of penetration in the design or analysis. Because of the sophisticated nature of rock mass due to existence of spatial fractures and inhomogeneity, determining the design depth for effective grouting sometimes is impossible using experimental and analytical methods in the field. However, numerical simulations using FEM, DEM and BEM always can resolve the complicated problems concerning rock mass by taking into account some simplifications (Granet et al., 2001; Marmo and Wilson, 2001; Jing et al., 2001; Lorig et al., 1995).

Several researchers, as Herbert (1996), Zhang et al. (1996) and Liao and Hencher (1997), have used UDEC code to investigate fluid flow through jointed rock media. Rock blocks surrounded by discontinuities may be modeled as rigid or deformable material. Fluid flow analysis is performed in which the joint conductivity is directly related to the mechanical deformation associated with the joint (domain) water pressures. Each domain (filled with water) is separated by contact points at which mechanical interaction between blocks is established.

Grouting is mainly utilized to reduce the hydraulic conductivity but also to improve the stiffness of the ground under the dam or foundation. The main objective of this study is to find the effects of both controllable and uncontrollable parameters on the flow

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rate and the penetration length of the grout in rock masses using numerical, analytical and field databases.

In this paper, an attempt has been made to consider the effects of rock joint parameters on rock mass groutability by means of Universal Distinct Element Code (UDEC) software (ITASCA, 2000). Significant parameters in measuring effectiveness of rock grouting during grouting process like flow rate and penetration length into jointed rock mass are discussed. The used models were set up using practical data from grouting information of Bakhtiary dam of Iran. The effects of various features on the grout penetration length have been determined through a parametric study.

2. Flow of grout in jointed rock mass

2.1. General

For a joint to be groutable, the grout must satisfy the conditions of penetrability and flowability. Some researchers use a limit aperture below which cementitious grout cannot penetrate into the joint (Hansson, 1995; Amadei, 2000; Eriksson and Stille, 2004). Many authors have analyzed the gout spread with numerical and analytical models. Hassler et al. (1988) presented some very early model to analyze the flow by numerical methods. Gustafson and Stille (1996) developed a numerical method to estimate grout spread area in the rock joints based on the geomechanical properties of rock and grout specification. Amadei and Savage (2001) presented an analytical solution of the grout flow acting as non-Newtonian/Bingham fluids in rock joints Yang et al. (2002) have carried out a numerical simulation using a stochastic joint network and indicated the effects of the joint properties on grout penetration depth. Their model has related grout properties, mean and standard deviation amounts of joint dipping, aperture, length and joint density to the penetration depth. However, they did not consider the influence of joint roughness and persistency on the grout extension area. The grout material and grouting pressure can be controlled in the operation, and therefore, their effects on the grout depth can be easily taken into account in the design. However, the joint characteristics are not so easy to define. In addition, Analytical solutions have been given by Gustafson and Stille (2005) and El-Tani (2012).

In both the analytical solutions and the numerical models, the flow is assumed to occur in channel or disc with a constant aperture. Therefore, joint aperture is an important parameter to be considered. This aperture must reflect the physical aperture in order to correctly calculate the penetration. However, it is not possible at least in practical sense to directly measure the physical aperture. Indirectly the water flow for given pressure can be measured and the corresponding hydraulic aperture can be calculated by the cubic law. The physical aperture has been found to be larger about 1.2–3 times according to Zimmerman and Bodvarsson (1996).

The water-bearing capacity of the rock mass can be described by the hydraulic conductivity or the transmissivity of the jointed rock. A rock joint is a 2-D structure with an aperture, a, that varies over the joint surface (Stille et al., 2012). The ability of the fracture to let through a flow of water is characterized by the fracture transmissivity, T in m^2/s:

$$T = \frac{\rho_w g a^3}{12\mu_w} \tag{1}$$

where ρ_w is the water density in kg/m^3, g is the gravity acceleration in m^2/s and μ_w is the water viscosity in Pa s. The transmissivity T is evaluated from hydraulic tests of boreholes. Boreholes are tested in sections and the evaluation results in a section transmissivity T_L, where L is the length of the tested section. The transmissivity of boreholes and borehole sections may be determined by water pressure tests (WPTs) and evaluated by Moye's formula (Moye, 1967). The statistical distribution of the fracture transmissivity in a borehole based on WPTs was investigated by Gustafson and Fransson (2000). They found that the transmissivity of a borehole in fractured crystalline hard rock roughly followed a power law distribution. Using the cubic law, Eq. (2), the hydraulic aperture can be evaluated:

$$a = \sqrt[3]{\frac{12\mu_w}{\rho_w g} T} \tag{2}$$

Gustafson and Stille (1996) calculated the maximum grout penetration for a Bingham fluid flow using a shear force balance. They obtained that at the point of grout full stop inside a fracture the injection pressure is balanced by the shear stress towards the joint walls (Fig. 1).

Assuming a single joint to have parallel walls (Fig. 1) with an effective hydraulic aperture a the grout penetration, $I_{\max}$ is defined as in:

$$I_{\max} = \frac{(P_g - P_w)}{2\tau_0} a \tag{3}$$

where $I_{\max}$ is the maximum penetration length at infinite time, P_g applied pressure on grout, P_w is the water pressure inside the joint and τ_0 is the yield value of grout. In this study because the grouting was carried out in dry area, P_w was neglected. The model by Gustafson and Stille (1996, 2005) was developed to one and two-dimensional flows in rock joints with mean and standard deviation of apertures in a network of joints.

The effective hydraulic aperture strongly depends on joint surface roughness of rocks. Barton et al. (1985) proposed an empirical relation (Eq. (4)) to relate joint hydraulic aperture and physical aperture with joint roughness coefficient (JRC) as

$$E = \sqrt{a \times JRC^{2.5}} \tag{4}$$

where JRC is the joint roughness coefficient, E is the physical or mechanical aperture in micron and a is the effective hydraulic aperture in micron. The JRC an index from 0 to 20, proposed by Barton and Choubey (1977) for description of the shear strength of rock joints is the most used now for normal deformation and shearing analysis of rock joints (Barton, 1982; Bandis et al., 1983). The JRC is determined by corresponding joint surface roughness with Barton's profiles. Effective hydraulic joint aperture, a is obtained from borehole water pressure tests (WPTs). Substituting Eq. (4) into Eq. (3), it can be rewritten as follow

$$I_{\max} = \frac{(P_g - P_w)}{2\tau_0} \frac{E^2}{JRC^{2.5}} \tag{5}$$

Most of the previous studies indicate that the grout flow is governed by Bingham fluid equations (Hassler et al., 1992; Fransson, 1999; Shuttle and Glynn, 2003). Bingham fluids can be simulated using a viscosity and yield value approximation.

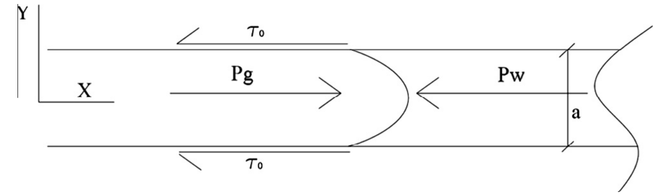

Fig. 1. Grout flow through a rock joint.