Evaluation of Geomechanical and Geometrical Parameters' Effects on Hydro-Mechanical Estimation of Water Inflow into Underground Excavations

M. Mazraehli, F. Mehrabani, S. Zare

***Abstract*—**In general, mechanical and hydraulic processes are not independent of each other in jointed rock masses. Therefore, the study on hydro-mechanical coupling of geomaterials should be a center of attention in rock mechanics. Rocks in their nature contain discontinuities whose presence extremely influences mechanical and hydraulic characteristics of the medium. Assuming this effect, experimental investigations on intact rock cannot help to identify jointed rock mass behavior. Hence, numerical methods are being used for this purpose. In this paper, water inflow into a tunnel under significant water table has been estimated using hydro-mechanical discrete element method (HM-DEM). Besides, effects of geomechanical and geometrical parameters including constitutive model, friction angle, joint spacing, dip of joint sets, and stress factor on the estimated inflow rate have been studied. Results demonstrate that inflow rates are not identical for different constitutive models. Also, inflow rate reduces with increased spacing and stress factor.

***Keywords*—**Distinct element method, fluid flow, hydro-mechanical coupling, jointed rock mass, underground excavations.

NOMENCLATURE

q	Passed flow
b	Fracture width
μ	Viscosity
k	Permeability coefficient
Δp	Difference in pressure
e	Mechanical aperture
m	Empirical constant
A	Section area
g	Gravitational acceleration
$i = \Delta H/L$	Hydraulic gradient
v	Flow velocity
τ	Fracture curvature factor
Q	Passed debit
C	Mechanical to hydraulic aperture ratio
ρ	Density

I. INTRODUCTION

DISCONTINUITIES ranging from some millimeters to several kilometers comprise one of the most common ingredients of rock masses. Large scale fractures such as faults and shear zones are formed during geological and geo-structural processes. Small scale fractures including non-persistent joints and discrete fracture networks (DFN), however, are a result of disturbing stress state due to engineering or tectonic activities [1]. Existence of these fractures in rock structure causes a change in its mechanical and hydraulic behavior introducing weak surfaces and fluid flow routes.

Mechanical, hydraulic, and thermal processes in rocks are not independent from each other. This independency implies that there is an interaction between these processes which is called "Thermo-hydro-mechanical coupling" (Fig. 1). It is possible to ignore thermal term when depth of the project is not significant to induce heat transfer. Both mechanical and hydraulic behaviors are largely controlled by morphology of joint surfaces. It is expected that normal and shear stiffness of joint would be related to its hydraulic conductivity. Therefore, hydro-mechanical (HM) term means that there is a coupling relationship between fracture aperture, porosity, permeability, pore pressure, and stresses acting on rock mass [2].

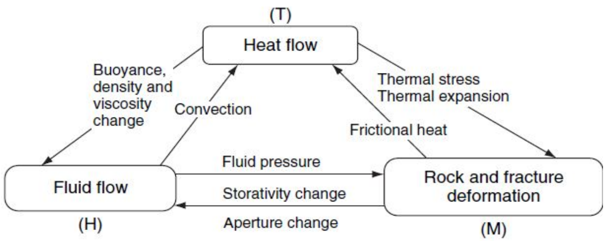

Fig. 1 Thermo-hydro-mechanical process in rock joints [2]

In recent years, study on HM process has been getting more attention setting analysis condition closer to actual case. Hence, investigating HM behavior of rock mass in order to estimate water inflow into underground structures is a matter of great importance. There are two different flow ways in jointed rocks: fluid flow through interconnected network of discontinuities, and diffusion through rock matrix which is considered impermeable for competent rocks (such as granite) in DEM. For most of applications, especially in hard rocks, flow through joints comprises the dominant portion of fluid flow [2].

In contrast to merely porous media, large-scale fluid flow in many of jointed rocks is established through joints, faults, and other types of fractures. Fluid flow in a single fracture follows

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Navier-Stocks equation in the form of (1) which is called "cubic law".

$$q = \frac{b^3}{12\mu L}\Delta p = \frac{b^3\rho g}{12\mu}\frac{\Delta H}{L} = \frac{b^3\rho g}{12\mu} i \quad (1)$$

Equation (1) is only valid for smooth and slickenside joint surfaces. Cubic law equation might be modified adding two parameters representing fracture curvature and its roughness as below

$$q = \frac{b^3\rho g}{12\mu\tau m} i \quad (2)$$

If joint surfaces are assumed parallel, and fluid flow is considered steady and incompressible, Darcy law can be written as

$$Q = Av = Aki = b.e.\frac{ge^2}{12\mu}.\frac{\Delta H}{L} \quad (3)$$

$$k = \frac{ge^2}{12\mu} \quad (4)$$

Regarding friction of joint surface and its curvature, mechanical aperture is generally different from hydraulic aperture. Zimmerman and Bodvarsson [3] showed that mechanical aperture is larger than hydraulic aperture. According to (5), mechanical/hydraulic aperture ratio is related to average aperture/its standard deviation ratio.

$$C = 1 + m\left(\frac{y}{2e}\right)^{1.5} \quad (5)$$

Hydraulic conductivity of a single fracture is generally determined by its effective aperture which varies during deformation process. In practice, fluid flow problems through porous media are usually analyzed using continuum models with dual porosity and permeability or using multiple continuum methods in FEM and FDM based programs. Fluid flow problems in jointed rocks, however, are discussed utilizing discrete models.

More complicated numerical modeling techniques are being used frequently as a result of computational developments. Applying advanced numerical models involves more aspects of rock mass behavior in research. Studies on mechanical behavior of joints and their modeling procedures have always attracted a considerable attention. Fluid flow and joints deformation modeling technique which is used in this study considers rock blocks impermeable; therefore, there is no interaction between fluid, joints, and pores.

DEM, on the paper, is a more realistic procedure for modeling joints intersections because they are explicitly and intrinsically introduced in DEM. In FEM or FDM, however, numerical difficulties are revealed in simulating interaction between blocks at intersecting points due to their small size comparing to discontinuity elements. Thus, maintaining compatibility of deformation in contact points (without block overlaps) in these intersection points needs specific numerical solutions [2].

Governing equations and solving techniques for fluid flow in 2-dimensional fracture networks in UDEC are essentially identical to those in cubic law. However, some aspects of specific fluid-solid coupling in UDEC flow analysis should be described. For example, fluid pressure is considered steady in a range in which gravity is absent. As gravity is taken into account, fluid pressure would be a linear variable. Variation in hydraulic aperture has been included in the model by mechanical deformation of blocks or elements (Fig. 2). In addition, characteristics of fluid flow are determined with pressure difference between adjacent zones, and flow rate calculation is distinct for different types of joints.

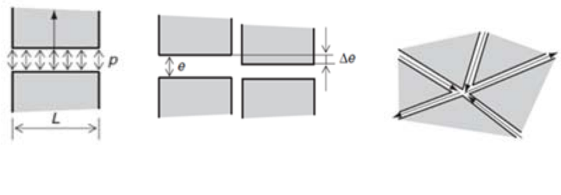


Fig. 2 Rock and fluid interaction in UDEC fractures: (a) fluid pressure; (b) aperture variation; (c) fluid flow ways in an intersection [2]

Interaction between two adjacent blocks is identified with a finite stiffness (spring) in normal direction, and a finite stiffness plus a friction angle (spring and slider in a serie) in tangential direction. Interactional forces developing at contact points are determined by deformation of the springs and the slider (block displacements in contacts) and are decomposed to tangential and normal components. These forces are linearly proportional to relative displacements in the mentioned directions (Fig. 3).

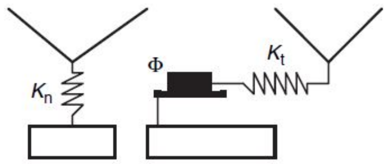


Fig. 3 Mechanical illustration of joints in UDEC using spring-slider in series [2]

Brace [4], based on results obtained from his experiments, stated that stress acting parallel to discontinuity surface increases its permeability while stress acting normal to the surface decreases its permeability. Snow [5] proposed an empirical equation relating permeability to normal stress. Walsh [6] presented a relation between confining stress and permeability based on his experimental works. Esaki et al. [7] investigated the effect of shear displacement on hydraulic conductivity of granite samples under different normal stresses, and concluded that conductivity increases with shear displacement. Witherspoon et al. [8], studying axial stress effect on flow through joints, expressed that increasing stress would exponentially decrease fluid conductivity. According to Zimmerman et al. [9], fracture permeability decreases with increasing contact area. Pirak-Nolte et al. [10] conducted many laboratory experiments aimed to evaluate the effect of normal stiffness on fluid flow in samples containing a single joint and stated that fluid flow decreases with increasing normal stiffness. According to Zimmerman [11], apparent fluid conductivity decreases non-linearly with increased Reynolds number exceeding 1. Sharifzadeh et al. [12] applied DEM in order to compare results of HM and hydraulic inflow analyses in a tunnel surrounded by jointed rock mass and concluded that the effect of depth on flow pattern in HM analysis is considerably more obvious than this effect in hydraulic analysis. Mas Ivars [13] conducted a 3D numerical study on HM coupling of fluid flow focusing on the effects of geomechanical parameters such as joints shear and normal stiffness, friction and dilation angle on fluid inflow approximation into wells. Hydraulic parameters disturbance as a result of excavation and stress redistribution around a tunnel was studied by Lin and Lee [14].

In this study, evaluation of the effects of geomechanical and geometrical parameters on tunnel inflow rate is conducted using HM discrete element analysis. Studied parameters include constitutive model, friction angle, joint spacing, angles of joint sets, and stress factor. First, water inflow into a tunnel under significant water table has been estimated using HM-DEM. Then, sensitivity of tunnel inflow rate with respect to the aforementioned characteristics is numerically investigated.

II. Numerical Modeling

Tunnelling and excavation in jointed rock masses under water table makes fluids flow into the underground space in which pressure is lower than joints. Existence of permeable features can considerably affect stability of underground structures. On the other hand, excavating operation disturbs in-situ stress state in the area. Design should be performed considering coupled HM process instead of isolated hydraulic and mechanical analyses, because fluid inflow depends on stress state, physical and mechanical properties of the jointed medium.

Tunnel excavation under substantial amount of reservoir water, and in a rock mass containing two joint sets (J1 and J2) has been concerned. This study aims to estimate water inflow rate in this tunnel during construction phase. Dip angles of joint sets are assumed 60° and −30°, respectively. Tunnel diameter equals to 5 m, and elevation of reservoir water head with respect to the tunnel crown is 300 m. Geometry of numerical model is illustrated in Fig. 4. Geomechanical parameters of rock and joint sets are listed in Tables I and II, respectively. Width and height of the numerical model are set to 25 and 50 meters in order to prevent results being biased by proximity of outer boundary.

TABLE I
GEOMECHANICAL PARAMETERS OF INTACT ROCK

Cohesion (MPa)	Poison ratio	Shear modulus (MPa)	Young's modulus (GPa)
10	0.25	14	35

TABLE II
HYDRAULIC AND MECHANICAL PARAMETERS OF JOINT SETS

Joint set	Dip (°)	Friction angle (°)	Residual aperture (m)	Initial aperture (m)	Tensile strength (MPa)	Cohesion (MPa)	Shear stiffness (GPa/m)	Normal stiffness (GPa/m)
J1	60	35	0.0005	0.001	3	3	12	20

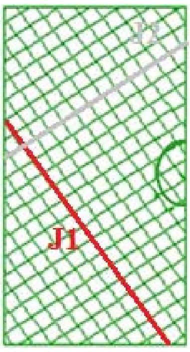


Fig. 4 Model geometry

Boundary stresses are applied in the form of stress gradient, and tunnel depth is assumed to be 50 m where 25 m of overburden is applied as distributed load on upper boundary of the model. Steady fluid flow is applied to left and upper boundaries. Hydraulic head equals to 300 m, and other boundaries are considered impermeable. Horizontal to vertical stress factor, i.e. K, is also assumed to be 1.25.

Computational stages after model construction in UDEC include [15]:

(i) approaching equilibrium state for in-situ stress and joints fluid pressure;
(ii) tunnel excavation (mechanical solving up to second equilibrium state);
(iii) coupled HM solving for fluid flow into the tunnel with atmospheric pressure until the model converges in steady flow state.

Unbalanced forces diagrams after first and third solving stages are presented in Fig. 5. Fluid flow in monitoring points, and, horizontal and vertical stress states around the tunnel are also depicted in Figs. 6 and 7, respectively. Reminding that K is higher than 1, stress distribution patterns illustrate stress concentration at the crown and the invert of the tunnel. Pore pressure and flow condition adjacent to the excavation are also presented in Fig. 8.

Fluid inflow rates obtained from numerical modeling in the points intersecting the tunnel are presented in Table III.

Aggregate amount of these values represents total fluid inflow into the excavation through joint sets.

III. Evaluation of Geomechanical and Geometrical Parameters Effects on Inflow Rate

In this section, effects of different geomechanical and geometrical parameters including constitutive model, friction angle of joints, their spacing and dip, and stress factor on tunnel inflow rate are evaluated.

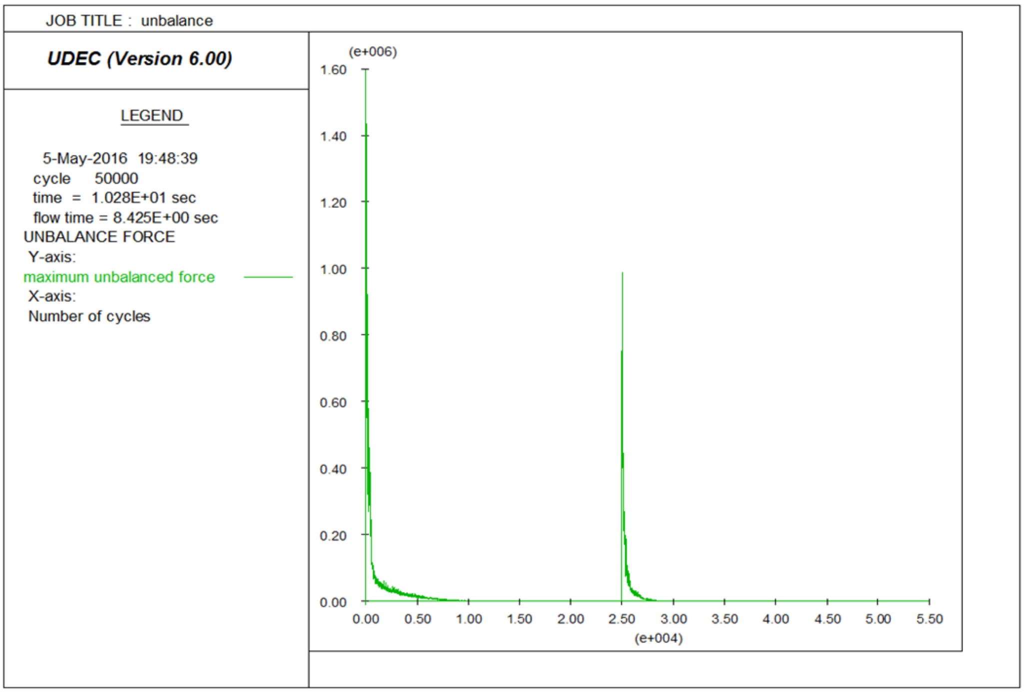


Fig. 5 Unbalanced forces

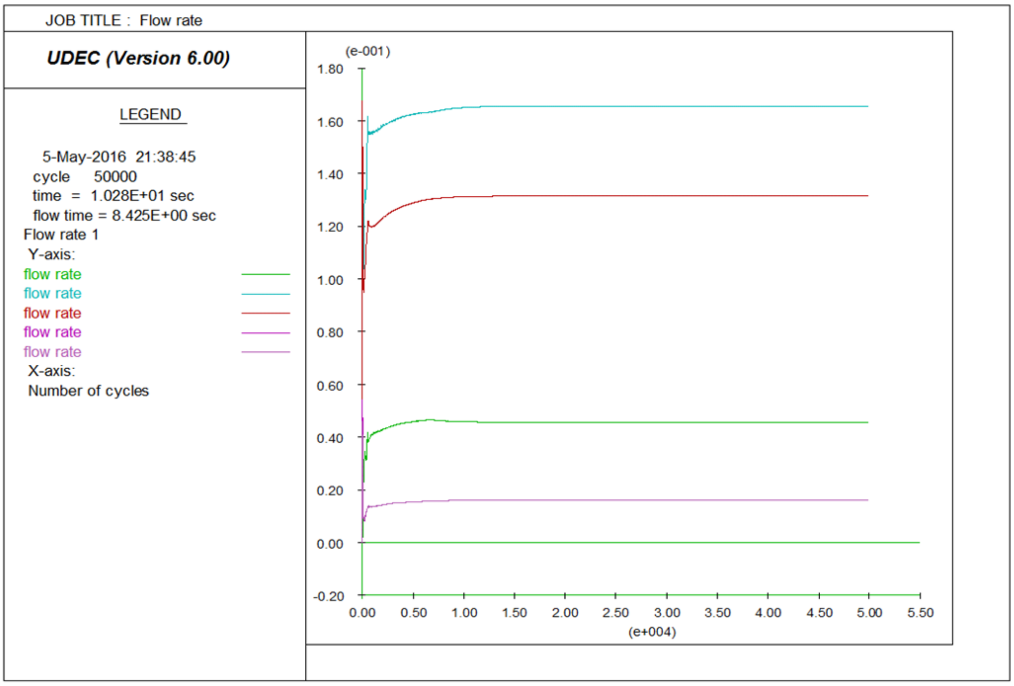
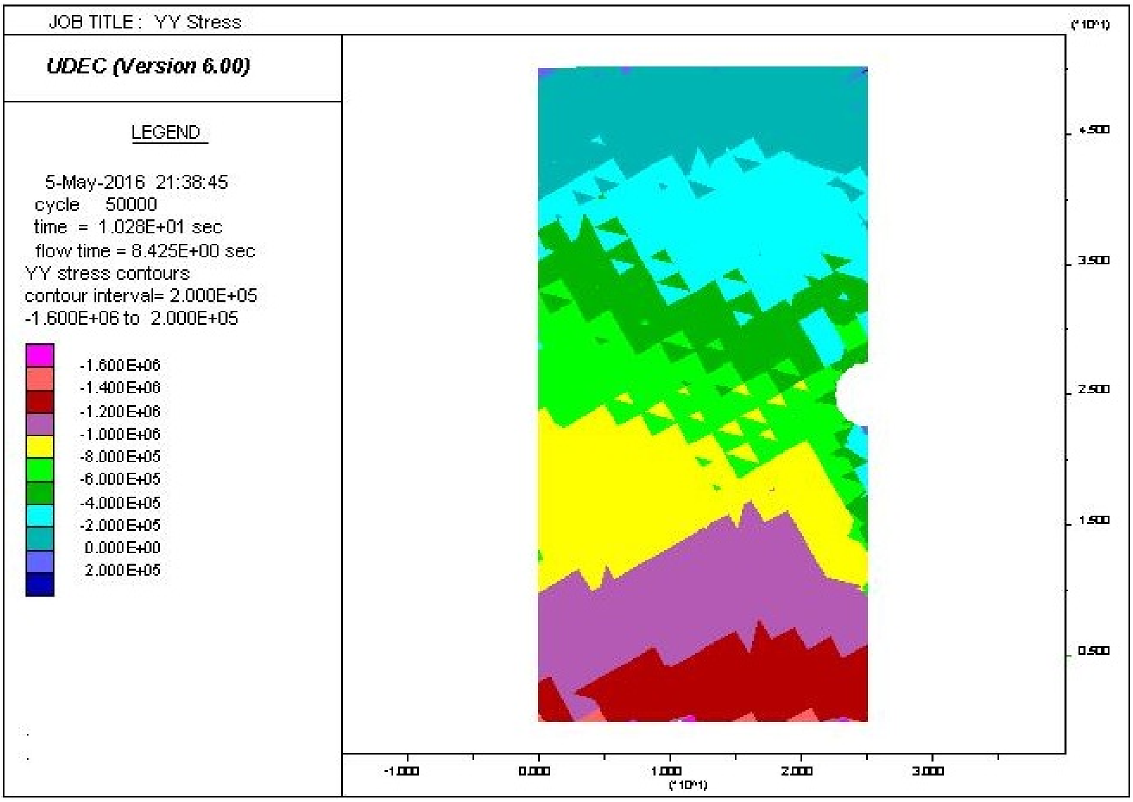
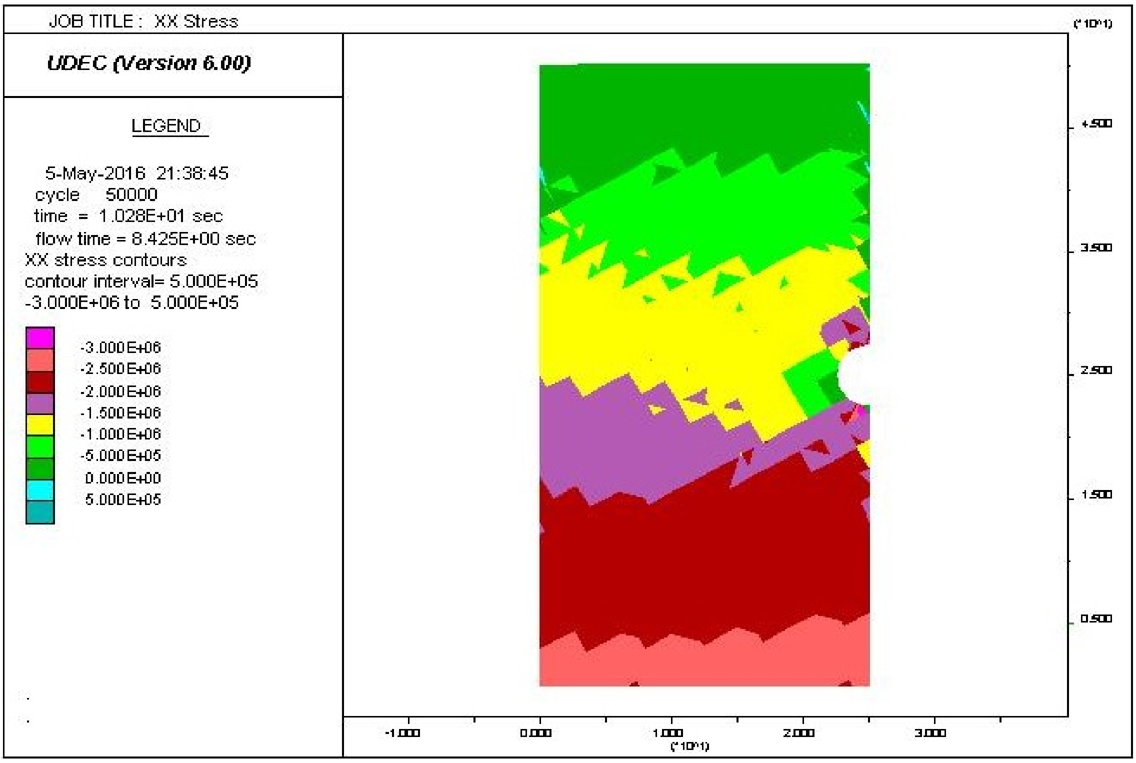


Fig. 6 Flow rate convergence after model solving



(a)



(b)

Fig. 7 (a) Vertical; and (b) horizontal stress states after excavation

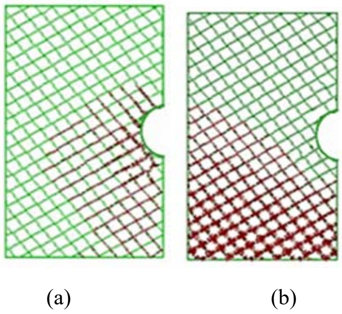


Fig. 8 (a) Flow pattern; and (b) pore pressures adjacent to the tunnel

A. Joints Friction Angle

To compare inflow rates in different friction angles, two constitutive models, i.e. Mohr-Coulomb and continuous yielding models are used. As it is shown in Fig. 9, friction angle variation when using Mohr-Coulomb constitutive model has no considerable effect on tunnel inflow rate. In continuous yielding model, however, increase in friction angle makes inflow rate reduce.

TABLE III
INFLOW RATES FOR SINGLE JOINTS INTERSECTING THE TUNNEL AND TOTAL INFLOW RATE CALCULATION

Monitoring point No.	Inflow rate (m^3/s)	Inflow rates (lit/s)
1	1.32×10^{-1}	132
2	1.63×10^{-1}	163
3	0.67×10^{-1}	67
4	0.43×10^{-1}	43
5	0.18×10^{-1}	18
6	0.147×10^{-1}	14.7
total	4.37×10^{-1}	437.7

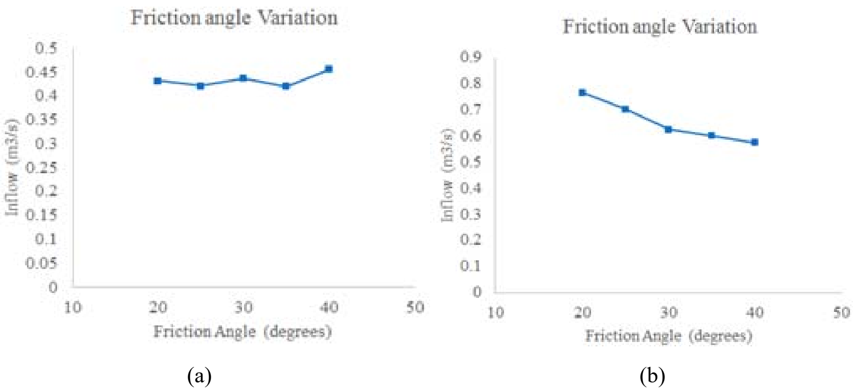


Fig. 9 Inflow rates versus friction angle for: (a) Mohr-Coulomb; and (b) continuous yielding models

B. Spacing of Join Sets

In the case of evaluating J1 spacing effects on water inflow rate, four different values, i.e. 2, 4, 6, and 8 meters are considered for this parameter, while J2 spacing is constant and equals to 2 meters (and vice versa). As it is shown in Fig. 10, tunnel inflow rate reduces with spacing of discontinuities. Considering increase in joint spacing, block dimensions in unit area increase, and frequency of joints intersecting the tunnel wall decreases. According to Fig. 10, J1 spacing variation has more effect on inflow rate in comparison with J2 spacing.

C. Dip Angles of Joint Sets

In order to investigate effects of joint sets configuration on tunnel inflow rate, it is considered that J1 dip angle varies $\pm 10°$ while J2 dip angle is assumed to be constant (and vice versa). Fig. 11 presents inflow rate versus dip angle of joint sets. According to Fig. 11, J1 dip angle has a bit more effect on inflow rate comparing to J2 dip angle.

D. Stress Factor

It was mentioned in the past sections that stress acting on joints is one of the parameters influencing HM behavior of rock masses. Three different values are assigned to stress factor (K), i.e. 1, 1.25, and 1.5, to numerically evaluate effect of stress on inflow rate. Fig. 12 shows inflow rate variation diagram with stress factor. As it is seen, increase in K reduces inflow which can be related to effect of horizontal stresses on closure of J1 surfaces.

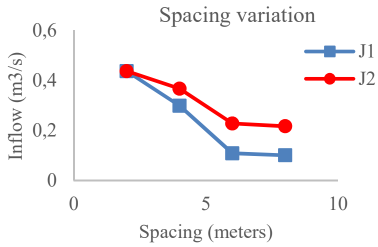


Fig. 10 Water inflow rate versus joints spacing

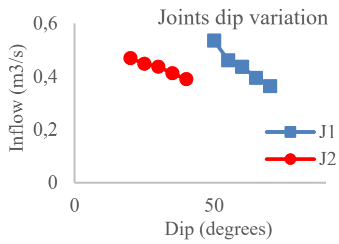


Fig. 11 Water inflow rate versus joint dip angle

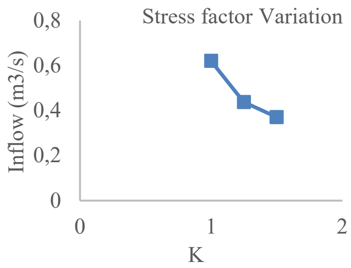


Fig. 12 Inflow rate versus stress factor

IV. Conclusions

HM coupling implies hydro-mechanical behavior of geomaterials and their interactive effects on each other. Hydro-mechanical behavior of tunnels located under substantial water pressure is affected by various parameters such as surrounding medium, tunnel lining, water level, internal water pressure, etc. In the case of design for excavation, however, surrounding rock mass and water head comparing to the other parameters are the matter of great importance. Characteristics of discontinuities along with stress state control hydro-mechanical behavior of rock masses. In this paper, effects of these controlling parameters on fluid inflow rate into a tunnel were investigated using discrete element modeling. Results show that friction angle variation applying Mohr-Coulomb constitutive model has no considerable effect on inflow rate into the tunnel. Utilizing continuous yielding model, however, reveals the effect on inflow rate. According to the results, inflow rate decreases with friction angle in the latter constitutive model. In addition, increase in spacing and stress factor, K, decreases tunnel inflow rate. Besides, tunnel inflow rate shows more sensitivity to dip angle and spacing of the dipper joint set than that of the other.

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