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A study on the hydro-mechanical behavior of jointed rock masses around underground excavation by using a discrete joint network modeling

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Abstract: Discrete joint network approach has widely been used to investigate the hydraulic behavior of jointed rock masses. In general, joints will undergo deformation due to stress redistribution induced by construction of underground openings, hence joint aperture is often assumed to have a probability distribution rather than to be a constant value. In real situations, however, it is more reasonable to take into account the effect of stress change on aperture values by calculating joint deformation. In this report, a mechanical process has been developed to determine the joint opening or closure based on a statistically generated joint network model. By performing numerical analyses, some significant results on the hydro-mechanical behavior of jointed rock masses have been summarized.

1. Introduction

It is well known that the presence of joints in rock masses affects the stability and construction conditions of underground structures, such as road and railway tunnels, gas and oil storage caverns, and waste repositories. This is because rock joints are mechanical defects to weaken the mechanical properties of rock masses, and more importantly joints become flow paths of groundwater to make construction conditions unfavorable. Also, recent interest in the evaluation of contaminant transport in bed rock aquifers and in the need to isolate radioactive waste repositories from the ecosystem have been motivating factors for many studies concerning fluid flow in jointed rock masses. In general, there are two different approaches to modeling the hydraulic behavior of jointed rock masses: continuum analysis and discrete analysis. For both approaches, the major concerns in order to take the effects of rock joints into account lie on the geometrical features of joints. It is also important to consider the change in flow capacity due to mechanical deformation of joints caused by excavation-related stress redistribution (Lee et al., 2002).

There have been considerable attempts to investigate the hydraulic behavior of jointed rock masses by using a joint network analysis (Samaniego, 1985; Billaux et al., 1989; Nordqvist et al., 1992; Song, 1993; Ko and Moon, 2001). Among these, it is interesting to note that Billaux et al. (1989) and Ko and Moon (2001) expended two-dimensional joint network model into three-dimensional joint network model by assuming the rock joints to be circular discs. Norqvist et al. (1992) used a joint network model with variable aperture distributions in order for more realistic modeling for flow and transport in jointed rock masses. In this report, a discrete joint network approach has been used in order for modeling fluid flow in jointed rock masses and normal deformation of rock joints has been considered. As the hydraulic behavior of jointed rock masses depends on the joint geometry and its connectivity, it needs to identify the connected flow paths based on the statistically generated joint networks. From the determined joint networks, normal deformation of joints has been calculated by determining the change in normal stress acting on each joint before and after the excavation. Numerical investigation of the effect of joint deformation on hydraulic behavior of rock masses shows that joint geometry and stress condition are equally important to estimate the hydraulic behavior of underground excavations in jointed rock masses. Also, according to three-dimensional numerical analyses, it is observed that the water inflow of underground openings is influenced by the excavation stage and sequence as well as joint geometry and stress conditions.

2. Hydro-mechanical Discrete Joint Network Model

As rock masses contains several to many joint sets with various orientations, jointed rock masses tend to be of complex geometric structure. The characteristics of rock joints can be approximated by probability distributions, and hence the statistical methods for generating a joint network are valid. When the suitable probability distributions are determined based on field measurement and statistical processes, the generated joint models will be more realistic than continuum or deterministic models.

Generation of discrete joint network

In this study, both the two-dimensional and three-dimensional joint network have been adopted assuming that joints are planar, thin circular discs, and randomly distributed with specific probability distributions in space. Fisher distribution has been used for joint orientation, and joint size is inferred from trace length data and stereological principle (Lee, 1992; Ko and Moon, 2001). In order to obtain a joint network for fluid flow analysis, unnecessary connections of joints have been removed through a series of checking modules for the connectivity of joints. The checking modules include joint identification, boundary identification, opening identification, construction stage identification, and so on.

Stresses acting on a discontinuity

According to conventional joint network analyses, the aperture of generated joints is assumed to be a constant value or of probability distribution. In real situations, however, it seems to be more reasonable to take the stress redistribution due to the excavated openings into account so that opening and closure of joints can be modeled. A simple way of obtaining the stress state, $[\sigma_K]$, induced by a circular opening will be the use of Kirsch solution. When a non-circular opening is modeled, the stress state can be determined from numerical methods, such as a finite element method. If there is single joint around the opening (Fig. 1), the stress acting on the joint can be calculated as

$$[\sigma^*] = [R][\sigma_K][R]^T = \begin{bmatrix} \sigma_{mm} & \sigma_{mn} \\ \sigma_{mn} & \sigma_{nn} \end{bmatrix}, \tag{1}$$

where $[R]$ is the rotation matrix for the m-n system relative to the r-θ system. From the induced stress due to excavation, the aperture change, Δe, can be calculated from the change in stress, $\Delta\sigma$, before and after the excavation as (Ouyang and Elsworkth, 1993)

$$\Delta e = \frac{\Delta\sigma}{K_J}, \tag{2}$$

where K_J is the normal stiffness of joints. From equation (2), the aperture values can be determined by adding the aperture change to the initial aperture. As the joint roughness can significantly influence the fluid flow through a joint (Zimmerman and Bodvarsson, 1996; Lee, 2002), the hydraulic aperture has been calculated from the relation between the mechanical aperture and hydraulic aperture in terms of joint roughness coefficient, JRC (Barton et al., 1985).

Fig. 2 shows an example of joint networks without and with mechanical process described above, and the width of lines indicates the aperture size. As can be seen, the openings of joints induced by the circular opening is highlighted, whereas joints have the identical line width in case of non-mechanical process, indicating the potential qualitative influence of aperture change on fluid flow into the opening.

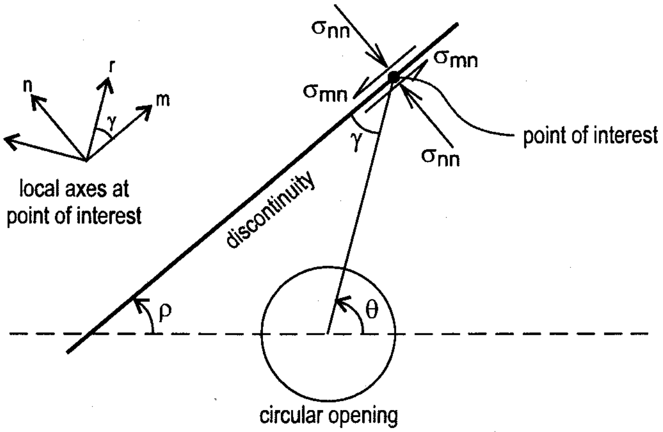
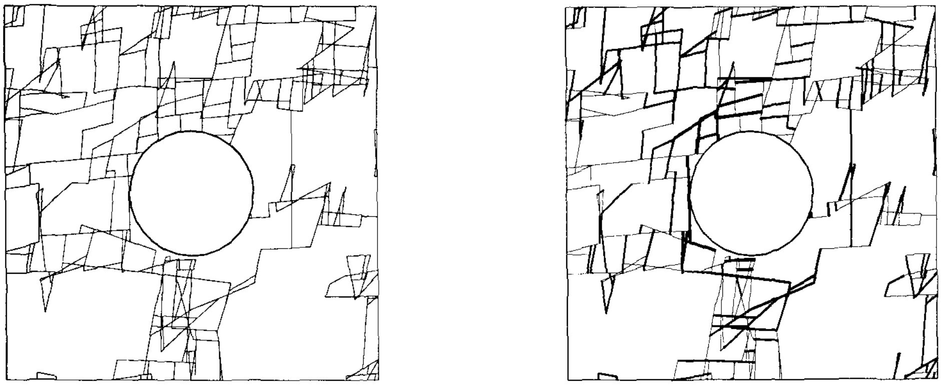


Fig. 1. Stresses acting on a discontinuity plane adjacent to a circular opening in a biaxial stress field.



(a) Joint network without mechanical process (b) Joint network with mechanical process

Fig. 2. Comparison of joint networks without mechanical process and with mechanical process.

Fluid flow in discrete joint network model

In jointed rock masses of low permeability, such as crystalline and tight sedimentary rocks in which the flow capacity of the intact rock material is much lower than that of rock joints, the transport of fluid through discontinuity planes is of great interest in engineering rock mechanics. In this case, fluid will flow along the least resistant flow paths, or connected joint network. Assuming that fluid flows through the void space comprising two parallel plates, the Navier-Stokes equations reduce to the cubic law, in which the flow rate is proportional to the cube of the distance between the two plates (Zimmerman and Bodvarsson, 1996). Hence, the distribution of hydraulic head within a joint network can be calculated by adopting a finite difference method by solving the following equation

$$H_j = \frac{\sum C_{ij} H_i}{\sum C_{ij}}, \tag{3}$$

where H_i and H_j are hydraulic head at node i and j, respectively, and C_{ij} is the conductance from node i to j, given by

$$C = \frac{g e^3 \lambda}{12 \nu l}, \tag{4}$$

where g is the acceleration due to gravity, e is the hydraulic aperture of joints, ν is the kinematic viscosity, λ is the joint width, and l is the joint length. Tsang and Tsang (1987) suggested that the joint width is proportional to the joint length, such as

$$\lambda = 0.2\, l. \tag{5}$$

Finally, the fluid flow into the underground opening can be determined by the summation of flow rate of joints on the opening boundary, in which the flow rate, Q, is function of the hydraulic conductance and head difference, given by

$$Q = C \Delta H. \tag{6}$$

3. Numerical Analyses

As the stress redistribution is influenced by the initial stress state, the ratio of the vertical stress and the horizontal stress, K, becomes the important factor controlling the mechanical process discussed previously. In the two-dimensional condition, as the joint strikes are generally assumed to be parallel to the tunnel axis, the effect of the value of K on the mechanical process will be very critical. In three-dimensional analysis, however, the excavation stage seems to be even more important because the stress redistribution along the tunnel axis will affect the mechanical process of joints whose strikes are not parallel to the tunnel axis.

Parameters for joint network generation

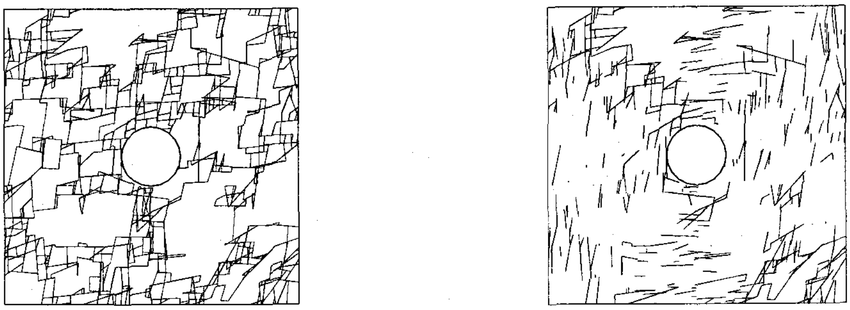
The domain of numerical analyses for two-dimensional case and three-dimensional case are 50m by 50m and 50m by 50m with 100m of tunnel axis, respectively. For both cases, a circular opening with a diameter of 10m is assumed to locate 200m below the ground surface, and three joint sets are assumed in order for joint network generation (Table 1), the initial mechanical aperture of 300μm. For two-dimensional analysis, K values are 0.5, 1.0, and 2.0 in order to investigate the effect of the initial stress condition, with JRC values of 10, 12, and 14. In three-dimensional case, 80m of excavation is assumed to be constructed in steps of 20m with K of 1.0 and JRC of 10.

Table 1. Input parameters for joint network generation.

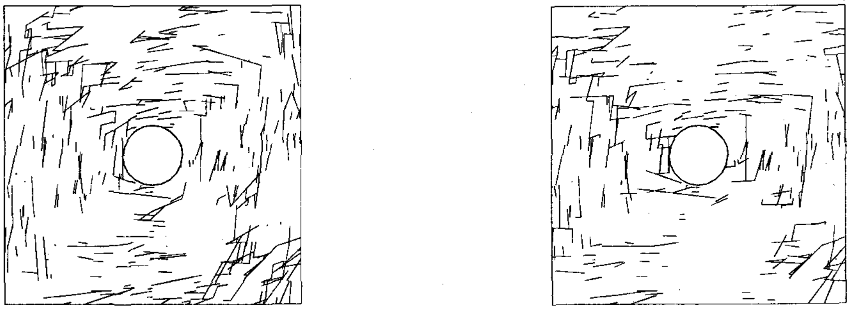
Items		Set 1	Set 2	Set 3
Orientation	Dip direction (degree)	90	180	270
	Dip angle (degree)	5	50	85
	Fisher K	50	50	50
Spacing	Mean (m)	2.45	6.75	1.55
	STD (m)	2	2	2
Trace length	Mean (m)	5	5	5
	STD (m)	2	2	2
Fracture density (EA/m^2)		0.112	0.04	0.172

Two-dimensional analysis

Fig. 3a shows the joint network, which is generated based on the condition mentioned above and the connected joints are plotted, and Fig. 3b-d are the joint networks with mechanical process with respect to K value in which only the opened joints are plotted. It is important to notice that joint opening is influenced by the stress state indicating that joints perpendicular to the direction of larger initial stress tend to open because of stress release due to opening.



(a) Joint network without mechanical process (b) Joint network with mechanical process for $K = 0.5$



(c) Joint network without mechanical process for $K = 1.0$ (d) Joint network with mechanical process for $K = 2.0$

Fig. 3. Two-dimensional joint networks for different K values.

In order to examine the effect of K and JRC values together with the mechanical process on the hydraulic behavior of jointed rock masses, the flow rate into the circular opening is plotted in terms of K and JRC values (Fig. 4). First of all, it is clearly observed that with increasing the joint roughness the flow rate decreases and this is more significant at lower JRC values. Also, the flow rate is higher at K value of 2.0 for all JRC values, when the mechanical process is considered. It is because the stress level at K value of 2.0 is higher than K value of 0.5, although they are reciprocal each other in K value.

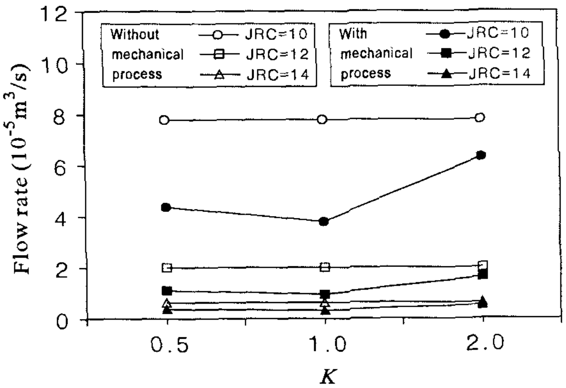
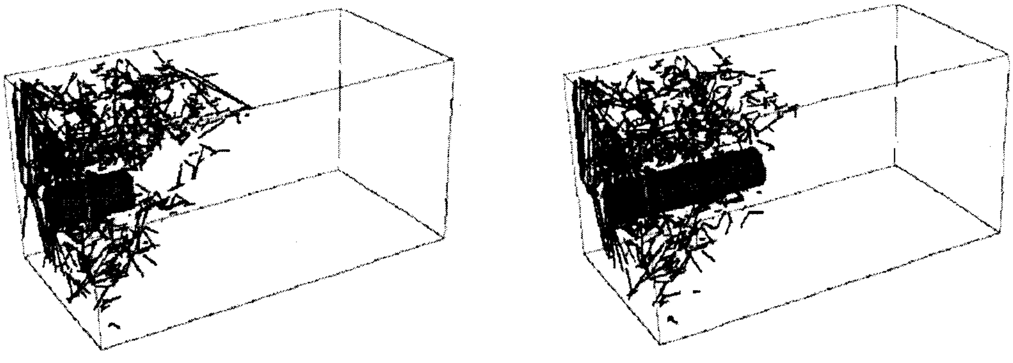
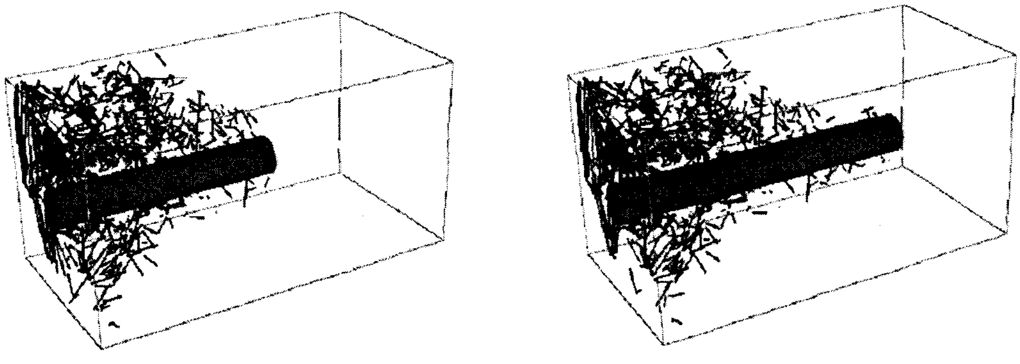


Fig. 4. Effects of K values on flow rate with different joint roughness coefficients.



(a) Stage 1 (20m of excavation)

(b) Stage 2 (40m of excavation)



(c) Stage 3 (60m of excavation)

(d) Stage 4 (80m of excavation)

Fig. 5. Joint networks of opened joints with respect to the excavation stage.

Three-dimensional analysis

Three-dimensional analysis has been performed, and Fig. 5 shows the joint networks with mechanical process with respect to the excavation stage in which only the opened joints are plotted. Here, the stress state at each excavation stage is determined by performing three-dimensional finite element analysis for the given conditions mentioned before. It is interesting to note that joint opening is mainly occurred at the initial stage of excavation. Although this result indicates that the relation between the excavation stage, joint geometry, and stress conditions, it suggest the need of more comprehensive numerical investigation in order for obtaining quantitative results. Also, it should be noted that the graphical presentation is difficult to implemented, and hence understanding the three-dimensional situation is not straightforward.

Fig. 6 shows the flow rate into the circular opening with respect to the excavation stage. When the mechanical process is not taken into account, the increase in flow rate into the circular opening is almost linear as the volume of excavation increases. When the mechanical process is taken into account, however, the increase in flow rate is non-linear as the volume of excavation increases, indicating the significance of the interaction between the stress state and joint opening and closure. It is also observed that the flow rate is higher at the initial stage with mechanical process, and it becomes lower comparing that without mechanical process. The results shown here emphasize the effect of stress state on the hydraulic behavior of jointed rock masses.

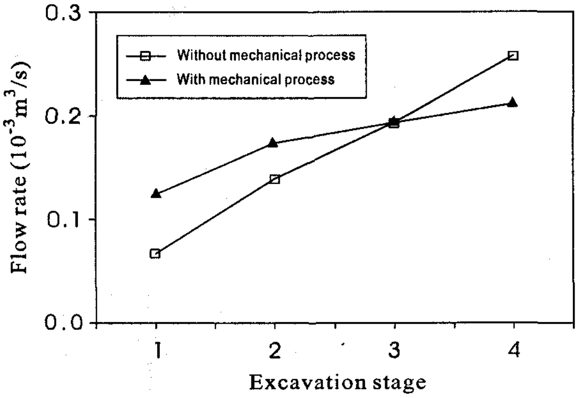


Fig. 6. Changes in flow rate with respect to the excavation stage.

4. Conclusions

This study focuses on the effect of mechanical deformation of joints on the hydraulic analysis using a discrete joint network model. The stress state around an underground opening has been used to determine the joint opening and closure (mechanical process in a discrete joint network model). By performing two- and three-dimensional numerical analyses, significant findings are summarized as follows.

First of all, joint opening, which seems to be more significant than joint closure because the flow rate is generally proportional to the cube of aperture size, is influenced by the stress change between the initial stress state and induced stress due to excavation so that joints perpendicular to the direction of larger initial stress tend to open.

The influence of K and JRC values are also important when it comes to the flow rate into the opening, showing that the increase in JRC gives rise to the decrease in the flow rate and that with increasing the K value the flow rate tends to increase when the vertical stress is a function of the depth.

According to three-dimensional analysis, it is observed that the increase in flow rate is non-linear as the volume of excavation increases, whereas the increase in flow rate is almost linear for convention joint network analysis. This seems to be related to the joint geometry and stress condition, which tend to control the joint opening with respect to the excavation stage. These results indicate that there is qualitative or quantitative relationship between the underground excavation and the hydraulic behavior together with geometric and stress conditions.

Consequently, it is shown that the need of mechanical process for more realistic numerical analysis in a joint network model. In this study, however, normal deformation of joints has been formulated, and it should be noted that shearing of rock joint also plays important role in the hydraulic behavior of jointed rock masses which needs to be implemented within the mechanical joint network model presented here.

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