第31回岩盤力学に関するシンポジウム講演論文集
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# 変形と表面形状を考慮した
# 単一ジョイント内の水の流れ

## FLUID FLOW IN A SINGLE ROCK JOINT IN CONSIDERATION OF THE ROUGHNESS AND DEFORMATION OF JOINT

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岩盤内の水理問題は、岩盤工学の様々な分野で取り上げられているが、特に最近は核廃棄物の地下処分場の長期安全性評価で注目を集めている。岩盤内の流れの特性は主にジョイントの水理特徴に左右され、ジョイントの透水特性はジョイントの変形（相対変位）とジョイント面の起伏に依存する。掘削影響領域における透水性の変化を考慮するためにはこの影響を評価する事が不可欠である。

本研究では、岩盤内の応力分布の変化によって生じる不連続性岩盤内の水の流れの変化を解析するための基礎として、粗い表面の単一ジョイント内の流れとジョイントの変形に従う透水率の変化、方向依存性について論じた。ジョイント内の流れは Reynolds 方程式を用いて有限要素解析を行い、再現した。

キーワード: 掘削影響領域、透水率、方向依存性、Reynolds 方程式

### 1. INTRODUCTION

Recent concern for the safety of a high-level nuclear waste underground repository has been increasing the importance of research on the hydraulic characteristics of a jointed rock mass. Flow in the jointed rock mass mainly occurs through joints included. For this reason, researchers [Brown, 1987; Zimmerman et al., 1991] have tried to understand the fluid flow through a rock joint and showed that the Reynolds equation could explain the flow in joint with rough surface.

However, when we excavate an underground opening, stress around the opening is redistributed and corresponding changes of hydraulic characteristics of the jointed rock mass are observed [Kelsall, 1984; Pusch, 1989]. These changes result from the opening and shearing of joints due to stress redistribution in surrounding rocks. In addition, hydraulic conductivity or permeability of the joint is known to be highly directional dependent [Lee, 1993] and the direction dependency of fluid flow is expected to increase when joint is sheared.

This paper provides a preliminary evaluation of flow in a single rock joint to understand changes expected to occur in an excavated disturbed zone. Reynolds equation is solved with finite element method to obtain flowing field in the joint and permeability is calculated to compare the difference in flow with regard to flowing direction.

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## 2. REYNOLDS EQUATION FOR FLUID FLOW IN JOINT

Reynolds equation is derived from the Navier-Stokes equation, which is a governing equation of Newtonian fluid flow, by placing some assumptions such as no pressure gradient across fluid height, flow is laminar, inertia effects are negligible, and the aperture is very small compared with the width of flow channel.

$$\nabla \cdot \left( \frac{\rho h(x,y)^3}{12\mu} \nabla p(x,y) \right) = 0$$

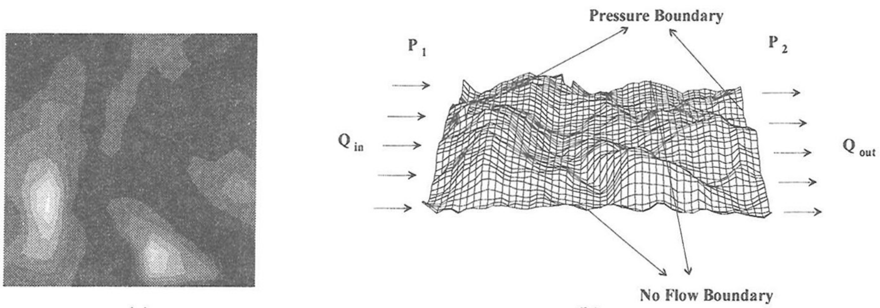
Here, $h(x,y)$ is local aperture, $p(x,y)$ is local fluid pressure, $\rho$ is mass density, and $\mu$ is dynamic viscosity of fluid.

The solution of the Reynolds equation is a pressure distribution of fluid in joint. The pressure field is differentiated and inserted in cubic law ($Q=h^3 \nabla p/12\mu$) to calculate mass flux or volumetric flow rate. The cubic law, which shows that the volumetric flow rate ($Q$) is proportional to the cube of aperture ($h$), is assume to be valid at every local point in the joint.

## 3. CALCULATED JOINT PERMEABILITY

Aperture is first computed from joint surface topographic data acquired by a laser profilometer. The aperture is defined as the difference of heights of upper and lower surfaces. The height distribution of two surfaces is measured by the profilometer in the interval of 3mm for the joint size of 300 mm x 300mm. The average aperture of joint is 1.79mm, when no shear relative displacement is given and normal relative displacement is prescribed so that the contact area ratio (or overlapped area) is 1% of total area. Figure 1 shows one of the aperture distributions and boundary conditions used in the analysis.

Boundary conditions in solving Reynolds equation of rectangular joint surface are two kinds. Along the pressure boundary, fluid pressure is set constant and along the no flow boundary, normal fluid flow does not occur. Pressure gradient is given by setting different pressures on two opposite sides and flow occurs accordingly. The dynamic viscosity and mass density are given as $1.31 \times 10^{-3}$ $Pa \cdot S$ and 999.7 $Kg/m^3$, which are equivalent to water at 10 °C.




(a) (b)

Figure 1. Aperture distribution and boundary conditions used in the analysis. (a) Contour plot of the aperture distribution. Light contour stands for large aperture region (b) The aperture distribution with boundary conditions.

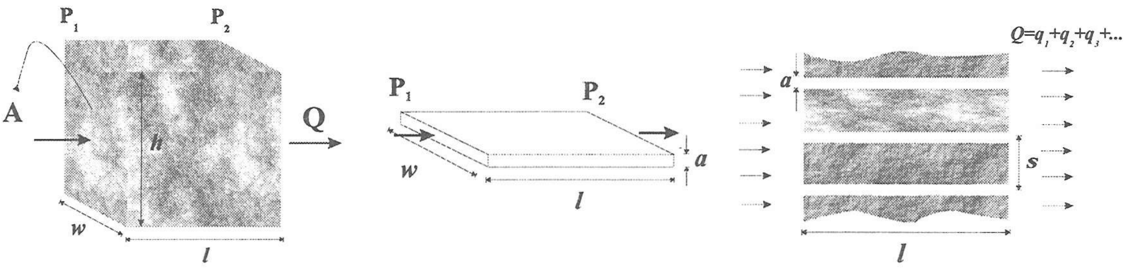
The permeability of materials which follow Darcy's law is characterized by coefficient of permeability, $k$. The relationship between the flow rate ($Q$) of fluid and pressure gradient ($\Delta P = P_1 - P_2$) is formulated using the permeability, $Q/A = k\,\Delta P/l$ (Figure 2a). In this study, the permeability of joints is characterized by joint permeability ($k'$) defined as the relation between the flow rate ($q$) and the pressure gradient ($\Delta P$) in joints and the width ($w$) of joint instead of cross sectional area ($A$) as,

$q/w = k^J \ \Delta P / l$ (Figure 2b). If we assume that the permeable materials are jointed rock masses, which are composed of impermeable rock blocks and a number of parallel joints, the overall permeability ($k$) of the jointed rock mass is expressed by the joint permeability ($k^J$), since the flow rate in permeable material is the sum of flow rate in each joint.

$$Q = \sum_{i=1}^{h/s} q_i \,, \quad \frac{Q}{A} = \frac{k^J}{s}\frac{\Delta P}{l} \quad (A = h \cdot w), \quad k = \frac{k^J}{s}$$

Here, $h/s$ is the number of joint in the material. The joint spacing ($s$) is the inverse number of joint density, which stands for the number of joints per unit length and has the dimension of $[L^{-1}]$ (Figure 2c).

Sometimes, hydraulic conductivity ($K$) is used instead of the permeability ($k$), when water is concerned. The hydraulic conductivity is derived from the permeability by $K = \rho g k / \mu$, where $\rho$ is the specific gravity, $g$ is the gravitational acceleration, and $\mu$ is the dynamic viscosity.

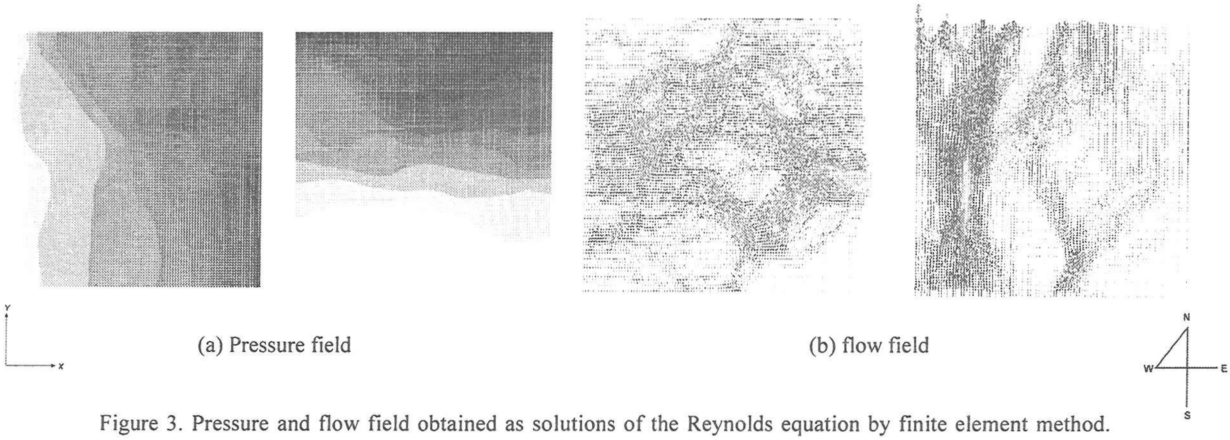



(a) General permeable material (b) Single joint (c) Jointed rock

Figure 2. The calculation of joint permeability

### *3.1 Initial joint permeability*

The numerical solution of fluid flow in a joint with no shear displacement and 1% contact area is presented in Figure 3. The aperture distribution is the same, but the direction of pressure gradient is different. Computed joint permeabilities are $4.76 \times 10^{-7}$ $[m^2]$ and $6.58 \times 10^{-7} [m^2]$, respectively and it is shown that the flow pattern and computed joint permeability depend on the flowing direction.

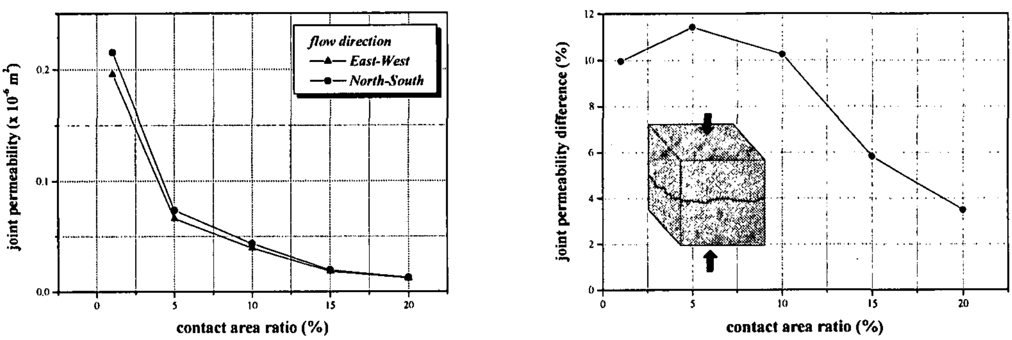



(a) Pressure field (b) flow field

Figure 3. Pressure and flow field obtained as solutions of the Reynolds equation by finite element method. Pressure gradient is set from West to East in left figures, and from South to North in right ones. (a) Light color contour stands for high-pressure zone. (b) Each vector stands for flow direction and flow rate at each point in joint surface. High flow rate region appears with deep color. It is seen that tortuous and channeled flow is formed and its pattern is different with different flow direction.

### *3.2 The effect of normal closure*

When high normal stress is applied, joint gets closed and contact area of two opposite joint surfaces increases. In the present study, the deformation of asperity of joint is not considered. Relative normal displacement is given and the overlapped area is treated as closed. At five stages (1%, 5%, 10%, 15%, and 20%) of contact area ratio, joint permeability was calculated and plotted in Figure 4 to show the difference between flowing directions at each stage. It could be seen that dependent on the flow direction, since two surfaces match well in the condition of high normal stress. The increase of anisotropy in permeability at the beginning of closure in Figure 4b might be explained by the fact that the permeability in completely opened joint is close to that in parallel plate model, in which permeability is independent of flow direction.




(a) (b)

Figure 4. The variation of joint permeability and its difference with regard to contact area ratio. At each stage of the contact area ratio, flows from West to East and from South to North were created. The joint permeability in each flow direction was computed (a) and the permeability difference ($k_{S\text{-}N} - k_{W\text{-}E}$) was normalized by the permeability ($k_{W\text{-}E}$) of West-East flow (b).

### *3.3 The effect of shear*

To investigate the effect of shearing of joint, relative shear and normal displacement are given. To see the characteristic effect of dilation in shear of rough joint, results with and without dilation were compared in Table 1. The normal displacement is either kept zero (without dilation) or controlled so that the contact area is kept constant (with dilation). It is seen that aperture increases with increasing shear displacement due to the dilation of joint.

Figure 5a shows the relation between the shear displacement and flow directions. Solid symbols stand for the computed permeability in South-North flow, and open symbols are West-East flow, respectively. The flow from West to East, for example, is parallel to the direction of shear along $x$ direction, but perpendicular along $y$ direction. The permeability perpendicular to the direction of shear has little been known for the difficulty in experiments except for Yeo (1998).

If we simplify the rock joint as saw-tooth model (Figure 5b), it is expected that the change of flow perpendicular to the direction of shear is far bigger than that of parallel when the joint is sheared. Note that the calculated permeability perpendicular to the direction of shear is slightly greater in both shear directions in Figure 5a.

| Shear displacement [x $10^{-2}$ m] | 0 | 0.3 | 0.6 | 0.9 | 1.2 |
|---|---|---|---|---|---|
| With dilation [x $10^{-3}$ m] | 1.79 | 1.68 | 2.56 | 3.01 | 3.09 |
| Without dilation [x $10^{-3}$ m] | 1.79 | 1.81 | 1.83 | 1.85 | 1.88 |

Table 1. Comparison of aperture changes in shear with dilation and without dilation.

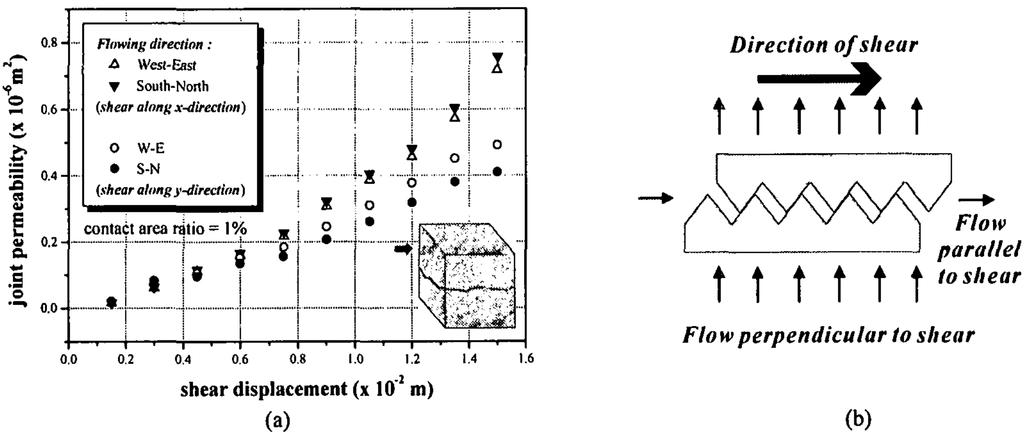



Figure 5. (a) The variation of joint permeability in two different shear directions, and (b) Saw-tooth model and flow directions in shear

## 4. SUMMARY AND CONCLUSION

Flow in a single rock joint was examined by solving Reynolds equation with finite element method. The effect of deformation of joints and the difference with regard to flowing direction were examined.

Plastic deformation and infillings of rough joints were not considered in this study, and an average aperture was used to capture the joint dilatancy. These kinds of problems could be overcome by using a discrete joint element model (interface element) to simulate the deformation of joint.

### References


1) Brown, S., "Fluid flow through rock joints; the effect of surface roughness", *Journal of Geophysical Research*, Vol. 92, No. B2, pp. 1337-1347, 1987

2) Zimmerman, R., Kumar, S., and Bodvarsson, G., "Lubrication theory analysis of the permeability of rough-walled fractures", *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.* Vol. 28, No. 4, pp. 325-331, 1991

3) Kesall, P., Case, J., and Chabannes, C., "Evaluation of excavation-induced changes in rock permeability", *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.* Vol. 21, No. 3, pp. 123-135, 1984

4) Pusch, R., "Alteration o the hydraulic conductivity of rock by tunnel excavation", *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.* Vol. 26, No. 1, pp. 79-83, 1989

5) Yeo, I., Freitas, M., and Zimmerman, R., "Effect of shear displacement on the aperture and permeability of a rock fracture", *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.* Vol. 35, No. 8, pp. 1051-1070, 1998

6) Lee, C., and Farmer, I., "Fluid flow in discontinuous rocks", Chapman & Hall, 1993