Nonlinear Flow and Fractal Properties of Rock Fracture Networks

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Permeability is a crucial hydro-mechanical property of rock masses and is important in many areas of geosciences and geoengineering, including water resources management, contaminant pollution control, and petroleum reservoirs. Fracture network modelling technics that are rapidly developed since 1980s have been adopted as one of the effective methodologies to investigate the permeability of fractured rock masses (i.e., granite and basalt), since fractures play a more significant role in conducting fluid flow and solute transport, comparing with that of the rock matrix. However, there are still many problems that are not solved when calculating the permeability, due to the numerous uncertainties such as fracture geometries, locations, and stress environment in the un-visual underground and the limitation of computing power. This thesis is focused on contributing to two aspects: nonlinear flow and fractal properties of the fractured rock masses, both experimentally and numerically.

First, a review study is presented to introduce previous studies on estimating equivalent permeability of discrete fracture networks (DFNs). Mathematical expressions of the equivalent permeability are summarized with the geometric properties, including (i) fracture length distribution, (ii) aperture distribution, (iii) boundary stress, (iv) fractal dimension, (v) dual-porosity models, (vi) anisotropy, and (vii) model size. The hydraulic properties of 3-D fracture networks are also reviewed, and the results are compared with those of 2-D fracture networks. The results of the previous studies show that (1) the equivalent permeability of fracture networks is strongly correlated to the geometric properties of fractured rock masses. (2) the permeability tensor is utilized to represent the anisotropy of the fractured rock masses, and is affected significantly by the scale effects of the DFN models, and (3) the equivalent permeability of the 2-D DFN models is usually underestimated by a factor of 3 to up to 3 orders of magnitude.

Second, high-precision fluid flow tests and numerical simulations by solving the Navier-Stokes equations are conducted to investigate the nonlinear flow properties of fluid in both intersections and fracture networks. The results of fluid flow at intersections show that with the increment of the hydraulic gradient, the ratio of the flow rate to the hydraulic gradient, Q/J, decreases and the relative deviation rate, δ, increases. When taking account of the fracture surface roughness with JRC = 0 ~ 20, the ratio of the flow rate to the hydraulic gradient would reduce by 0 ~ 26.55%. Here, JRC is the abbreviation of joint roughness coefficient. The influences of the intersecting angle on normalized

flow rate and the ratio of the hydraulic aperture to the mechanical aperture can be negligible when the hydraulic gradient is less than 10^{-3}. An empirical expression is proposed to calculate the hydraulic gradient and its predictions agree well with the numerical simulation results. The results of fluid flow in fracture networks show that the relationship between hydraulic gradient and flow rate can be well quantified by Forchheimer's law; when the hydraulic gradient drops below the critical hydraulic gradient, it reduces to the widely used cubic law. Larger apertures, rougher fracture surfaces, and a greater number of intersections in a DFN would result in the onset of nonlinear flow at a lower critical hydraulic gradient. Mathematical expressions of the critical hydraulic gradient and the coefficients involved in Forchheimer's law were developed based on multi-variable regressions of simulation results, which can help to choose proper governing equations when solving problems associated with fluid flow in fracture networks.

Finally, the fractal properties of rock fracture networks are characterized and a fractal model is proposed to link the fractal characteristics with the equivalent permeability of the fracture networks. The fractal dimension D_T that represents the tortuosity of the fluid flow and another fractal dimension D_f that represents the geometric distribution of fractures in the networks, are introduced into the model. The results indicate that the correlation of fracture number and fracture length agrees well with the results of previous studies, and the calculated fractal dimensions D_f are consistent with their theoretical values, which confirms the reliability of the proposed fractal length distribution and the stochastically generated fracture network models. Using the proposed fractal model, a mathematical expression between the equivalent permeability K and the fractal dimension D_f is proposed for models with large values of D_f. The differences in the calculated flow volumes between the models that consider and those that do not consider the influence of fluid flow tortuosity are as high as 17.64% – 19.51%, which emphasizes that the effects of tortuosity should be included in the fractal model. Based on the new proposed fractal model, a governing equation for fluid flow in fractures that considers the effects of tortuosity and takes into account the out-of-plane geometry of fractures was proposed, and the REV size of DFNs and the effect of random number on equivalent permeability were estimated. The results show that the flow rate in the proposed governing equation for fluid flow in single fractures is proportional to e^{6-D_T}, where D_T ranges [1, 2]. This model fits better with several datasets of in-situ measurements than the cubic law in which the flow rate is proportional to e^3. By taking into account the out-of-plane geometry of fractures, the proposed governing equation incorporated the 3-D geometry of opening-mode fractures into a 2-D framework to facilitate efficient solutions for the fluid flow in DFNs. The REV decreases with increasing D_f, because the flow paths become more homogeneous as increasing number of fractures in a DFN. The random number utilized to generate the fracture length has larger impacts on the calculated equivalent permeability than those for generating the orientation and center point of fractures.