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Experimental and numerical characterization of hydro-mechanical properties of rock fractures: The effect of the sample size on roughness and hydraulic aperture

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ABSTRACT

This paper investigated fluid flow in low-stress conditions through rock fractures in Kuru granite measuring 25 cm × 25 cm. Physical aperture and roughness were measured using high-precision photogrammetry. Anisotropy in roughness was observed in two perpendicular directions. Physical aperture under normal stresses was measured, and fracture closure was compared with linear variable displacement transducer (LVDT) measurements, showing good agreement. Hydromechanical tests exhibited nonlinear behavior between fluid pressure gradient and flow rate, following the Forchheimer equation. Applying normal stress resulted in decreased hydraulic aperture and increased nonlinearity of fluid flow. Experimental hydromechanical tests also revealed anisotropy in perpendicular directions, aligning with fracture roughness measurements. Photogrammetric models, aided COMSOL simulations, closely matched the experimental results. Increased stress induced channeled flow and greater tortuosity. Validation of the numerical model allowed simulations on larger fractures. A 2 m × 1 m granite fracture studied scale effects, with the rough surface duplicated and shifted by 350 μm to align with initial aperture measurements of 25 cm × 25 cm samples. Fluid flow simulations assessed subsample sizes (5 cm–100 cm), showing size-dependent variations in roughness, hydraulic aperture, and non-Darcy coefficient, stabilizing beyond 30 cm. This underscores sample size's role in parameter stabilization beyond a 30 cm scale.

1. Introduction

Rock engineering projects, such as underground excavations, rock slopes, or mining operations, can disturb the stress distribution in the rock mass. This redistribution can lead to the opening, closing, shearing, or dilation of pre-existing fractures and may also initiate new fractures. These changes can increase the deformability and permeability of the rock mass. The interaction between hydraulic and mechanical processes, known as hydro-mechanical coupling, can further affect effective stress, including fluid pressure and flux. Accurate estimation of hydro-mechanical properties is critical for predicting flow paths and discharge rates in a rock mass.

A fractured rock mass is a complex material composed of intact rock, fracture systems, and possible infillings.[1] The inhomogeneous nature of rock complicates the modeling of hydro-mechanical processes. In crystalline and metamorphic rocks, most water flow occurs through the fracture system, and the permeability of intact rock can be considered negligible.[2–4] The behavior of each fracture is controlled by its geometrical properties (aperture, length, and roughness) and mechanical properties (stiffness and closure), which greatly influence the overall hydro-mechanical properties.[3,5,6] A wide range of factors, such as aperture, roughness, contact area, stress state, matedness, scale effects, and fluid rheology, influence fracture permeability.[7]

Fracture aperture can be described by wall roughness, void spaces, and contact areas.[5] Physical and hydraulic apertures, which describe theoretical and experimental permeability, are usually not identical. Hydraulic aperture is often smaller than physical aperture. Extensive research has established several relationships between hydraulic and physical apertures based on fracture geometries, summarized in prior studies.[8,9]

Fracture aperture can be measured by both contact and non-contact methods. Scanning the fracture surface topography with photogrammetry is one example of a non-contact method.[10,11] Aperture can also be measured by X-ray CT techniques,[12] laser scanning,[13] and

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