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A tensorial representation of the hydraulic aperture of rough fractures under compressive and shearing stresses

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The interplay between fracture roughness, topology, and permeability is of major interest in hydrogeology, and models that account for the roughness and tortuosity of fractures to upscale hydraulic apertures that represent the microscale aperture distribution have been the focus of many studies in the past decades (He et al., 2021). However, these models often overlook the tensorial aspects of hydraulic aperture, focusing instead on scalar aperture models (Smith & Freeze, 1979; Neuzil & Tracy, 1981; Schrauf & Evans, 1986; Nick & Bisdom, 2018), which do not fully capture the anisotropy that may be observed in the fluid flow in fractures (Nick & Bisdom, 2018). To address this gap, our study introduces a method for upscaling microscale aperture distributions into equivalent hydraulic aperture tensors.

Constraints in experimental designs limit hydraulic aperture measurements in fractured media to a single direction (Xing et al., 2021; Phillips et al., 2021), preventing the direct verification of hydraulic aperture tensors in the lab. To overcome this challenge, we test our method through numerical experiments. Our approach involves creating synthetic fracture walls using fractional Brownian motion (Mandelbrot & Van Ness, 1968) with varying joint roughness coefficients (Barton et al., 1985). We then use fluid flow simulations to explore the effects impacts of compressive and shear stresses, translated into contact area and shear displacement, on the hydraulic aperture tensors.

Our findings indicate that highly anisotropic fluid flow patterns might emerge due to changes in the contact area between fracture walls, which scalar aperture models cannot capture. In addition, no clear correlation between the JRC values and the anisotropy change with contact area was observed, meaning that more information is necessary for characterizing the flow properties of rough fractures. The flow model used in this research has been previously verified through laboratory tests (Konzuk & Kueper, 2004) and numerical experiments (Rybak & Metzger, 2020), and the upscaling methodology has been validated using analytical solutions (Ferreira et al., 2022). This supports the reliability of the present study, thus suggesting the necessity of a tensorial representation for hydraulic apertures. This work provides a basis for developing a rigorous upscaling methodology utilizing a tensorial representation for the hydraulic aperture.

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