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# Permeability of displaced fractures

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## Abstract

Flow along fractures becomes increasingly important in the context of geo-engineering applications. Commonly, the permeability of fractures is approximated using the cubic law assumption. However, fracture flow is influenced by the surface roughness and the relative shear displacement. A numerical approach was used which calculates the flow pattern within a rough fracture. Therefore, fracture surfaces are generated using a power spectral density function and fracture flow is simulated under the incompressible Navier Stokes approximation. It is shown that the cubic law solution overestimates the permeability as modeled by the 3D numerical simulation of flow in fractures.

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*Keywords:* fracture permeability; flow in fractures; fracture roughness; cubic law

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## 1. Introduction

Flow along fractures or in fissured systems becomes increasingly important in the context of Enhanced Geothermal Systems (EGS), shale gas recovery or nuclear waste disposal. Fault zones and natural fracture networks are more and more considered as main reservoir targets, for example the geothermal exploitation in the Southern German Molasse Basin [1]. An approximation of the potential of fracture transmissivity is therefore an important topic. In reservoir simulations, commonly, a constant fracture aperture is used to describe permeability in a fracture or in fracture networks. The permeability of fractures is approximated using the Hagen-Poiseuille solution of the Navier Stokes equation. Flow in fractures is assumed to be laminar between two parallel plates separated by a constant distance $a$, such that the fracture permeability $k_f$ can be derived from the cubic law approximation [2]:

$$k_{f,cubic} = \frac{a^2}{12} \tag{1}$$

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However, it is a well-known fact, that fracture flow is strongly influenced by the fracture surface roughness and the shear displacement along the fracture planes [3, 4, 5]. Furthermore, the orientation of the pressure gradient in respect to the aperture field is causing a strong variability of the hydraulic behaviour of a rough fracture [6]. Correction factors for the aperture to calculate the cubic law permeability were therefore introduced by several authors. Méheust and Schmittbuhl [7] studied the deviation of the cubic law for a natural fracture surface and plexiglas, observing higher deviations from the cubic law for small apertures, which are correlating to the same trend in experimental investigations. Zimmerman & Bodvarsson [3] corrected the aperture $a$, considering the mean aperture, ⟨a⟩, a surface roughness factor, $C_r$, and a tortuosity factor, $C_t$, that was later modified by Walsh et al. [4]:

$$a = \langle a \rangle \cdot C_r \cdot C_t \tag{2}$$

Jin et al. [5] introduced a semi-empirical function using fitted parameters depending on the surface geometry accounting for the surface roughness, as well as for the hydraulic and surface tortuosity effect. We are providing a fracture flow simulation considering 3D Navier Stokes flow for rough and displaced fractures. We further provide a quantification of the deviation from the cubic law permeability. The controlling parameters on fracture permeability of rough and displaced fractures are discussed.

## 2. Methods

The workflow for the fracture flow simulation in a 3D fracture comprises three main steps: (1) generating fracture topographic surfaces with varying roughness and displacement, (2) generating a finite element mesh to produce a 3D model of a fracture, (3) perform fracture flow simulations using Navier Stokes flow in the finite element software Comsol Multiphysics (www.comsol.de), to derive fracture permeability from the pressure and velocity field using Darcy's law.

### 2.1. Fracture topography generation

Rock fracture surface anisotropy can be captured by power spectral density formulations [8]. The following simplified equations were used to generate fracture topographies following a power law with a uniform random signal:

$$h = P_0^{0.5} \cdot \frac{h_0}{S} \tag{3}$$

$$S = i(x, y)^{B/2} \tag{4}$$

where $h$ is the asperity height, $P_0$ the multiplier amplitude, $h_0$ is the normalised random height distribution $i$ the location of a point and $B$ the amplitude scaling factor influencing the roughness. A small $B$ value produces rough fractures, whereas large $B$ values produce smooth fracture topographies. The power $B/2$ is used because the power spectral density is proportional to the amplitude squared. The fracture aperture distribution is a normalized Gaussian distribution as it is commonly observed for natural fracture surfaces. The script allows to produce fracture surfaces of 100x100 mm or any other quadratic size.

Assuming that tensile fracturing will naturally produce two fracture surfaces that are perfectly matching and equal in shape, two equal surfaces are generated and super-positioned based on their minimum contacting points. The aperture is calculated as the subtraction of the upper and the lower asperity height at each point. When both fracture surfaces have no displacement relative to each other, the overall aperture is zero, since both fracture are perfectly matching. To implement a shear displacement, the top surface is displaced relative to the bottom surface by shifting the spatial point cloud data by a 1 mm increment in the y-direction to a maximum displacement of 50 mm. Every point that has no spatial correlation on the bottom surface is again added to the opposite side of the fracture using the "circshift" function in Matlab (fig. 1a). This means that by displacing the upper fracture surface by 100 mm, both surfaces are again matching. The distance between the two surfaces, i.e. the aperture, is recalculated at every step based on the minimum contacting points. Therefore, each change in displacement leads to a change in mean aperture (fig. 1b). The advantage of this approach is that the length of the fracture stays constant. However, this approach excludes any mechanical deformation of the fracture asperities, i.e. fracture asperities have an infinite stiffness. The