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Fracture morphology and viscous transport

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Abstract

The morphology of a fracture in a granite block is sampled using a high resolution profiler providing a 3999 × 4000 pixel image of the roughness. We checked that a self-affine model is an accurate geometrical model of the fracture morphology on the basis of a spectral analysis. We also estimated the topothesy of the experimental surface to be $l_r \approx 2 \times 10^{-7}$ mm and the roughness exponent to be $\zeta \approx 0.78$. A finite difference scheme of the Stokes equation with a lubrication approximation was used to model the viscous flow through a fracture aperture defined as the gap between the experimental fracture surface and a flat plane. We finally compare our numerical results to experimental measurements of the flux through the fracture of a glycerol/water mixture (to be at sufficiently low Reynolds number where Stokes equations holds) changing the average aperture of the fracture. The comparison is successful despite a limited resolution of the experimental measurements. Interestingly we show that only long wavelengths of the fracture morphology control the fracture hydraulic conductivity.

Keywords: Fracture roughness; Fluid flow; Hydraulic conductivity

1. Introduction

The modelling of the fluid transport in low permeable crustal rocks is of central importance for many applications [1]. Among them is the monitoring of the geothermal circulations in the project of Soultz-sous-Forêt, France [2]. The transit time of the brines into the natural and induced fractures between injection and production wells has to be carefully estimated in order to provide precise estimates of the production running time. Water flux controls both the heat transfer to the fluid and the cooling of the massif [3–5].

As shown from previous studies [5–7] only a few important fractures, closely associated in clusters [8] are controlling the fluid exchange between wells. Accordingly the study of the flow within a single fracture appears of central interest. It is also important for large scale numerical simulations of the convective circulation in the massif [9,10]. Up to now, only very simple models for fractures, i.e. parallel plates models, have been considered, ignoring the impact of the fracture morphology on the fracture transmissivity [5].

For a parallel plate model, the steady state solution of the Navier–Stokes equations for incompressible laminar flow yields the cubic law, where the volumetric flow rate Q depends linearly on the macroscopic pressure gradient in the flow direction, and is proportional to the cube of the plate separation a:

$$Q = -L_y \frac{a^3}{12\eta} \nabla P, \tag{1}$$

where L_y is the width of the fracture perpendicular to flow and η is the fluid viscosity [11,12].

In this study, we are interested in the influence of a realistic geometry of the fracture on its hydraulic permeability [13–21]. The morphology of fresh fractures is sampled and compared to a geometrical model that can be used in numerical codes for the fluid flow. We will also use the measured aperture profile as boundary conditions for numerical simulations. A contrario, the existence of a simple geometrical model of fracture morphology will allow to generate many realizations of synthetic fracture aperture, and thus study systematic effects when good

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statistics are needed. Our goal is to show that realistic fracture morphology can be introduced as a perturbation of the parallel plate model. However we show that strong influences on the transport properties might emerge owing to the long spatial correlations of the asperities morphology even in the limit of laminar flows. We have to mention that we assume that altered fractures partly coated with secondary minerals are still correctly described by a similar geometrical model [22–24]. In any case, as long as the coating process redistribute masses within a finite range, the geometrical model considered will properly describe the large scale morphology of the fracture aperture—i.e., at first, only small scale modifications of the aperture profile will happen. This large scale morphology will be shown to strongly control the fracture transmissivity, and the morphological model for fresh fracture is thus hopefully also relevant for the transmissivity of altered fractures.

We limit ourself to viscous flow characterized by low Reynolds number ($Re \ll 1$) although turbulence might develop at high flow rate [25,26]. The Reynolds number Re that can be defined from the Navier–Stokes equation is the ratio of the inertial terms to the terms describing the viscous forces. It is typically defined as: $Re \approx (\rho/\eta)\ u_{\parallel} l_h$ where ρ is the fluid density, $u_{\parallel}$ is a characteristic velocity along the mean fracture plane direction and l_h the characteristic aperture of the fracture [27]. A more precise estimate of the Reynolds number that compares only terms of the Navier–Stokes equation along the mean fracture plane direction is: $Re^* = Re\ l_h/l_{\parallel}$ where $l_{\parallel}$ is a characteristic length scale for flow variations along the mean fracture plane [23]. Since the aspect ratio of fracture is typically very small (see Section 2.3), we obtain: $Re^* \ll Re$.

We also assume that the lubrication approximation holds, i.e. that the velocity components in the direction transverse to the average fracture plane can be neglected. By integrating the Stokes equation over transverse direction, a further simplification of the Stokes equation emerges leading to a local cubic law. According to detailed analysis of the range of validity of the Stokes equation and this lubrication approximation [27], for the experiments performed here at Reynolds numbers (Re) ranging from 0.001 to 0.25, this Stokes lubrication approximations should be valid. Accordingly flow properties are only a function of the local apertures and not of the aperture gradients. This property implies that open fractures with different pairs of surface fractures, one on the top $z^+(x,y)$ and one on the bottom $z^-(x,y)$, but with the same aperture field $a(x,y) = z^+(x,y) - z^-(x,y)$, will have the same hydraulic behavior. Among this set of equivalent fractures, a semi-fracture, made of a rough surface facing a flat plate can be defined as $z^+(x,y) = a(x,y)$ and $z^-(x,y) = 0$. This equivalent semi-fracture will show the same aperture field. We will base our experimental approach on this property and reduce our problem to such a semi-rough fracture. The flat plate is chosen to be transparent (PMMA) which allow to follow optically tracers if necessary (e.g. in ongoing experiments on reactive fluids).

At larger Reynolds numbers where the Stokes equation would not hold any more, an alternative numerical approach would be to use directly the Navier–Stokes equation in the three dimensional fracture geometry. This has been shown to produce results in agreement with experimental flow in natural fractures [20,21]. The scope of the present work is on smaller Reynolds numbers where the treatment of the full Navier–Stokes equation is not required. Relatively to these studies [20,21], the present work focuses on a finer statistical description of the fracture morphology, and on the influence of the various modes of wavelength of the fracture morphology on the transport properties. We will show indeed that the largest wavelengths of the fracture opening control its hydraulic conductivity.

2. Fracture morphology

2.1. Roughness measurement

We studied the viscous flow imposed inside a fresh fracture that extends over an area of 10 cm × 10 cm. Grains are typically millimetric (0.5 mm). The fracture was obtained from a mode I failure under a three point bending load of a 10 cm × 10 cm × 20 cm granite block from Lanhélin, France. The fracture was initiated from a linear initial notch that was machined in the middle of the block before triggering the breaking procedure, and crossed the sample dynamically. The granite is a two-mica granite containing both muscovite and biotite, and K-felspars [23].

To get a fast and precise topography measurement of the fracture surfaces, we used an optical profiler (see Fig. 1) [23,28]. The instrument provides a height measurement without any contact of the surface which allows a fast on-flight acquisition of the topography (up to 70 points per second). However this technique requires not to measure

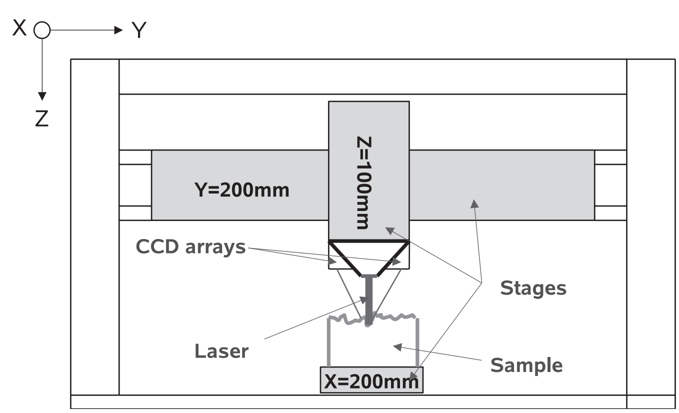

Fig. 1. Sketch of the optical profiler. The laser sensor sends a laser beam of 30 μm in diameter normally to the surface and records diffuse reflection from two ccd arrays. Height is deduced from a triangulation estimate. The sensor is attached to the Z-axis which is vertical and moved horizontally by the Y-axis, over the sample. The X-axis is the second horizontal translation stage that moves the sample. Maximum range of each translation stage is explicited. Their mechanical resolution is 1 μm.