Progress on Discrete Fracture Network (DFN) flow modeling

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Short abstract: We present progress on Discrete Fracture Network (DFN) flow modeling, including realistic advanced DFN spatial structures and local fracture transmissivity properties, through an application to the Forsmark and Laxemar site in Sweden. In particular, we present new DFN models, where fractures result from a growth process defined by simplified kinematic rules for nucleation, growth and fracture arrest. The differences with DFN models where fracture are randomly distributed in space are very important in terms connectivity, permeability and flow structure (channeling).

Introduction

In crystalline rocks and sedimentary layers with low matrix porosity, most, if not all, flow takes place within fractures, and the fracture network constitutes the basic structure that defines both permeability and flow path organization. Thus predicting both, which is required for groundwater management or environmental risk assessment, is intimately related to our ability to provide pertinent models of fracture networks. A modeling strategy consists in generating equivalent geological media made of 3D fracture networks. This discrete fracture network (DFN) approach is primarily a framework to combine fractures datasets from different sources and scales, and to interpolate them in combining statistical distributions, upscaling functions and stereological relations. Compared to continuum heterogeneous approaches, it allows for a better integration of geological data into flow models [1].

In this paper, we present progress on Discrete Fracture Network (DFN) flow modeling, including realistic advanced DFN spatial structures and local fracture transmissivity properties, through an application to the Forsmark site in Sweden.

A critical component of the DFN is the fracture size distribution, which is the upscaling function required to extrapolate fracture densities between data gaps, from borehole cores up to site scale. Another important feature of DFN models lays in the spatial correlations between fractures, with still unevaluated consequences on flow predictions. Indeed, although common Poisson's (i.e. spatially random) models are widely used, they do not reflect these geological evidences for more complex structures. We present recent DFN models that address both issues by mimicking the geological processes of fracturing. The eventual fracture network is obtained by using simplified kinematic rules of nucleation, growth and arrest [2, 3]. This model (so called "kinematic DFN") successfully describes two striking properties of natural fracture systems clearly important for connectivity and flow:

i) the power-law distribution of fracture lengths, which naturally emerges from the growth and arrest rules (as it should do in natural fracture systems),
ii) the large occurrence of T-intersections (a fracture ends up on another), which is a significant difference with Poisson's models. Both characteristics – upscaling function and T-intersections – are fully consistent with field observations.

Flow have been calculated for both kinematic DFNs and Poisson's model with the conformal mixed-hybrid finite element methods implemented in the development platform H2OLAB [4]. The consequences of using a "kinematic" DFN rather than a Poisson's model are very important in many aspects of the flow: connectivity, permeability and flow structure (channeling) [5]. The kinematic DFN structure is characterized by a critical scale l_c, which emerges from the kinematic rules and controls the network connectivity. More specifically l_c defines the size distribution of fractures that belong to the connected cluster. In general, the kinematic DFNs are less connected, less permeable, and more channeled than the Poisson's equivalent DFN (i.e. with the same density, and same distribution of fracture sizes and orientations). The differences between models can reach an order of magnitude for the different parameters.

In addition to the DFN structure, the hydraulic structure has a strong control on the permeability and flow structure. In the field examples that we refer to for this study (Swedish sites in Forsmark and Laxemar), 60-80% of the total fracture surface is sealed by secondary mineral deposition, and thus clogged for flow. Resulting flow is highly dependent on how sealed surfaces are distributed in terms of fracture sizes. We illustrate the differences with two end-members transmissivity models: in the former, the percentage of watertight fractures is independent of fracture size; in the latter, below a given scale l_c-*open*, the smaller the fractures the higher the proportion of impervious fractures (*Figure 1*). The resulting permeability and flow structure are then compared with data.

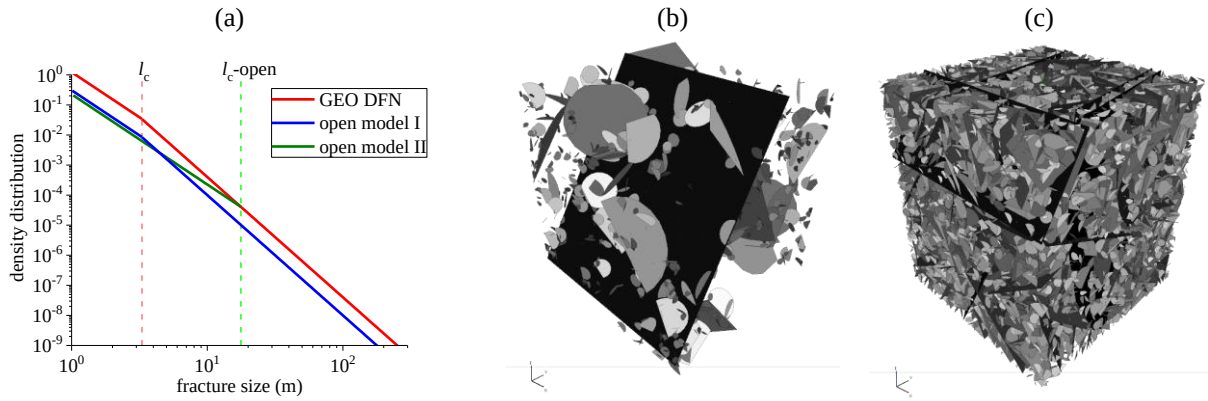

Figure 1: Illustration of the open fracture models with (a) the size distributions of the Geo-DFN, containing all fractures, and the two end models, (b) the DFN backbone (i.e. the fracture clusters connected to boundaries with dead-ends removed) of the first end model and (c) the DFN backbone of the second end model.

We also point out the importance of well defining the dependency of fracture transmissivity with size, and orientation (including the role of the applied stress on fracture transmissivity). Indeed, such a dependency changes the scaling of hydraulic properties, their spatial variability and increases the channeling.

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