Flow simulations in geology-based Discrete Fracture Networks

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HAL Id: hal-01900605
https://hal.inria.fr/hal-01900605

Submitted on 22 Oct 2018

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1. Motivation

The underground is a reservoir of natural resources (water, oil and gas, heat,...) and a potential warehouse storage solution. Using these resources and storage facilities in a sustainable way requires a good understanding of the physical, chemical and biological processes happening there. Also, the geometry of the subsurface couples these processes together. Here, numerical models are very useful: they reduce the costs and risks of *in situ* experiments and allow long-term predictions.

2. Geometric model

At first, we need to build a geometric model of the subsurface. Observations and experiments (investigations of drill cores and drill cuttings, lineament characterization, measurements of reflection seismics, transient electromagnetic soundings, ... [1]) give data for soil characterization and fracture locations. Fractures cannot be neglected as they critically impact the response of subsurface systems through their complex organisation over a broad range of scales. However, the information collected via the measurements are local. To derive an image of the full geometry, numerical models come into play. It is quite challenging to process tremendous amounts of noisy data, scattered and at different scales. Nevertheless, hydrogeologists are able to derive models for the subsurface, and especially for fracture systems [2]. The one we rely on is based on a spatial organization of fractures satisfying two main regimes: a dilute regime for the smallest fractures, where they can grow independently of each other, and a dense regime for which the density distribution is controlled by the mechanical interactions between fractures [3, 4]. In these models, called UFM (likely Universal Fracture Model), the fracture size distribution matches the observations and large fractures inhibit the smaller ones, creating T-termination configurations. Models mix spatial dimensions as fracture networks consist in a large number of 2D fractures interconnected in the 3D space [5]. These models are implemented in a dedicated software, called `UFMLab`. UFM networks may contain millions of fractures.

3. Flow problem

Let us focus on a simple process, which is the flow of water within the fractures. The surrounding rock matrix is assumed impervious. The associated problem is governed by the Poiseuille's law and the mass conservation equation in each fracture combined with continuity conditions at the intersections between fractures. The transmissivity within the fractures is assumed heterogeneous and modeled by random fields whose parameters are given by the experiments.

4. Mesh generation

The next step is to build a mesh of the domain. To easily enforce the continuity conditions at the intersections, we request a mesh which takes the intersections into account, either with matching or non-matching grids at the intersections. However, even in the non-matching cases, the intricate configurations of the fracture systems make it difficult for standard planar meshers to generate a mesh of the geometry. The idea is then to discretize first the border and intersections to build a geometric model, valid for the planar mesher. It implies automatic corrections to build valid curve discretizations. These corrections are implemented in the software `BLSURF_FRAC` [1]. Then a planar mesher is called, for example, `BL2D` [6] or `BAMG` [7]. Up to now, the largest network successfully meshed with this technique contains 508,339 fractures which generate 1,031,231 intersections. It is meshed in 15 minutes using the combination of `BLSURF_FRAC` and `BL2D`, with 4 threads on a PC Intel Core i7 4 cores CPU @ 2.90 GHz, 32GB RAM memory. The final mesh contains 8,112,299 of triangles and 1,630,682 of intersection edges. Notice that the computational time can be improved on a computer with more RAM memory as memory swapping was detected during this numerical experiment. Also, we identified some sequential parts of `BLSURF_FRAC` that can be parallelized.

5. Numerical methods and implementation

The next step is to solve the flow problem efficiently. We propose to solve this problem using a Mixed Hybrid Finite Elements Method (MHFEM) [8, 9, 10]. Possible non-matching grids at the intersections between fractures are handled by using suitable Mortar conditions [11, 12, 13, 14, 15]. In both, the matching and non-matching grids cases, we end up with a linear system whose matrix is symmetric positive definite. It is a sparse matrix with a L-shape structure. The linear system can be solved either with a direct solver (Cholesky factorization) or with an iterative solver (preconditioned conjugate gradient or multigrid). A way to improve the computational time of iterative solvers is to use domain decomposition techniques [16, 17]. We developed a Matlab code, called `NEF-Flow`, which implements the MHFEM either for matching or non-matching meshes, with sink/source terms and contrasts in transmissivities. Efficiency is obtained using Matlab vectorization. For example, we solved the flow problem in the largest network described above in 21 minutes on a PC Intel Core i7 4 cores CPU @ 2.90 GHz, 32GB RAM memory with a direct solver. Here again memory swapping was detected. Further numerical experiments are now performed with iterative solvers to reduce memory requirements. Also to keep an accurate solution with less triangles, we are investigating the use of a higher order hybridizable discontinuous Galerkin technique, the HHO method [18], combined with *a posteriori* error estimates [19] in order to refine only the fractures that carry most of the flow.

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