

# DFN.lab: Software platform for Discrete Fracture Network models

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## 1 INTRODUCTION

Fractures in rocks are complex structures, with many elements that range from millimeters to kilometers and exhibit complex patterns in terms of geometry, spatial organization and physical properties. In various applications, such as hydrogeological studies or geomechanical simulations, an effective tool is required to handle such complexity.

DFN.lab is a modular computational suite to deal with fractured rocks based on three-dimensional discrete fracture networks (DFN) models. It is developed by the Fractory, a joint laboratory between the French institute for scientific research (CNRS), the university of Rennes and Itasca Consultants S.A.S, to study the behavior of multiscale fractured media for various research topics including safety assessment for long-term nuclear waste storage, geothermal applications, mining, etc. DFN.lab can generate and compute flow and solute or heat transport on large DFNs containing millions of fractures. Core modules are developed in C++ for high performances and a Python API is provided for easy use.

The main originality of DFN.lab is in its capacity to deal with multiscale heterogeneities at both the fracture and network scales. Thanks to its computing capacities, DFN.lab can deal with fracture sizes ranging over more than 3 orders of magnitude.

## 2 SOFTWARE CAPABILITIES

A 3D DFN is defined as a collection of planar fractures, defined either as disks or convex polygons, embedded within a polyhedral domain. The domain can contain boreholes, tunnels and topographies and these structures are taken into account for flow and transport analyses and calculations. The rock matrix is considered impervious.

### 2.1 DFN geometry and properties generation

A key component of DFN software is the DFN generation. Since fractures play a major role in rock properties, the ability to generate advanced DFN models, with fractures having a spatial organization and characteristics as close as those of natural fractures, is the most important. DFN.lab can generate stochastic DFN in two ways:

- The properties of fractures, i.e. positions, sizes and orientations, are derived independently from statistical distributions (normal, log-normal, Fisher, bootstrapped, etc.). This is the classic approach, which gives so-called Poisson DFN.
- Fractures are generated using the genetic modelling framework developed in (Davy et al. 2010, Davy et al. 2013). This approach is a dynamic generation of fractures mimicking the mechanical

processes of fracture creation, i.e. nucleation, growth and arrest. It results in so-called UFM-DFN with a spatial organization closer to that observed on the fields, with small fractures abutting large fractures and T terminations.

For the same distribution of fracture sizes, orientations and transmissivities, genetic models behave significantly differently from Poisson's models (Maillot et al. 2016).

In addition to fracture geometries, DFN.lab is able to manage the associated hydraulic properties while considering their spatial heterogeneity. For each fracture, the hydraulic properties (transmissivity and aperture) can vary locally either deterministically, or statistically according to correlated random fields. A “sealing” algorithm was developed to model fracture patches that are clogged by mineralization, based on correlated random fields (CRF) with different correlation structures (Gaussian, exponential, self-affine).

Thus, DFN.lab can generate advanced 3D DFN combined with heterogeneous properties (Fig. 1).

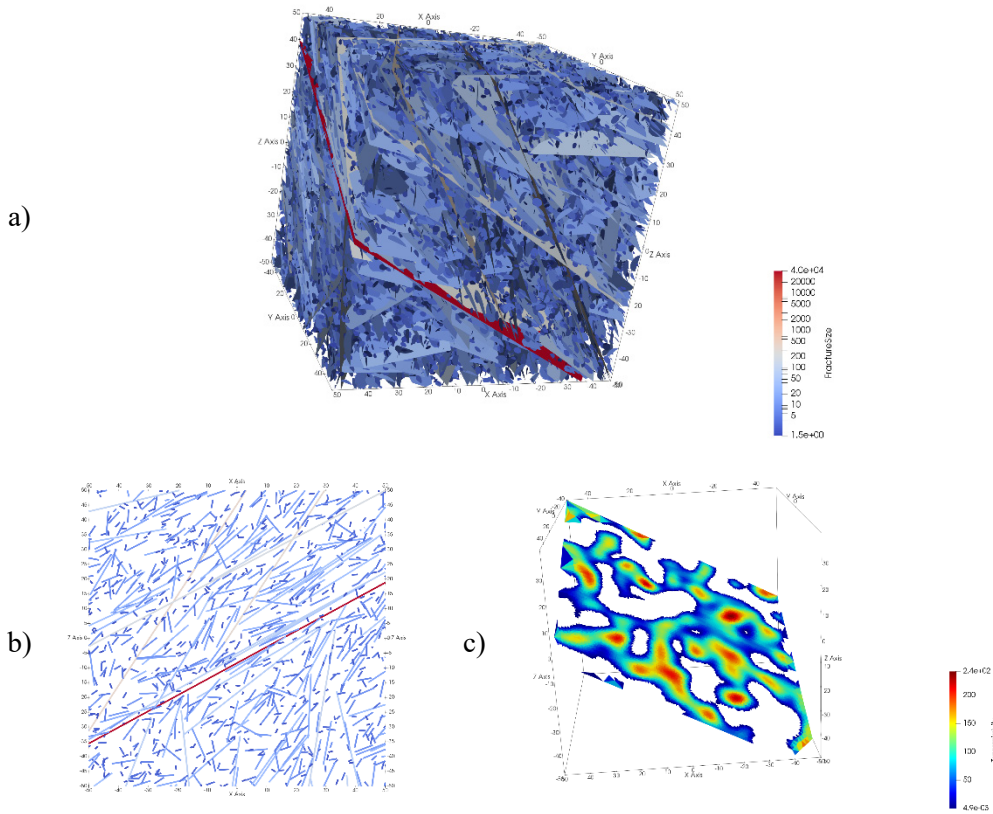


Figure 1. Illustration of a UFM DFN with transmissivities modeled as a random field with Gaussian correlation. a) 3D view, b) a 2D cut view colored by fracture size, and c) the transmissivity within the largest fracture. Holes are the sealed areas of the fracture.

## 2.2 Connectivity

DFN.lab can compute intersections between fractures and between fractures and geometries. A graph algorithm was developed to derive the connectivity of fractures and open patches at the network scale, so that DFN.lab can derive:

- The clusters of connected fractures, in relation with boundary conditions,
- The DFN backbone, defined as all flow paths connecting two active boundaries (excluding null Neumann conditions) without dead ends.

### 2.3 Mesh

Meshing capabilities are crucial for deriving the properties of a DFN. The generated mesh must indeed respect the DFN geometry and its complexity, from the smallest intersection up to the system size. In DFN.lab, pre- and post-processing procedures are built around the 2D mesh generator BAMG (Hecht 1998) to generate conforming triangular meshes of any 3D DFN while keeping all fractures and all intersections with almost no simplifications.

The mesh generator considers geometries, by refining the mesh around boreholes and tunnels. It is also possible to remove the sealed mesh elements so that, in DFN with a high proportion of sealed areas, the number of mesh elements is significantly reduced.

### 2.4 Flow and solute transport

DFN.lab computes the steady-state and transient flow from the generated mesh, the hydraulic properties of fractures and boundary conditions. It supports both Neumann and Dirichlet conditions, applied to system boundaries, geometries or intersections. The numerical model is based on the Mixed Finite Element method to ensures both local and global mass conservation and to obtain a precise velocity field for subsequent transport simulations. It solves the Darcy equation along with conservation of flow:

$$\nabla(T \cdot \nabla h) = 0 \quad (1)$$

with  $T$  the possibly heterogeneous fracture transmissivities and  $\nabla h$  the head gradient. The equation system is solved with Eigen 3 (Guennebaud 2010).

DFN.lab contains post-processing modules to get the flow per mesh element, per intersection, per fracture or throughout the system, to get advanced statistics on the flow properties (equivalent permeability, channeling indicators, etc.).

A time-step particle-tracking algorithm is used to compute advective transport of inert particles within the DFN, with particles being injected onto any element. The results can be used to derive transit time, F factors, etc.

Thus, DFN.lab can run flow and transport simulations on complex, heterogeneous 3D DFN (Fig. 2).

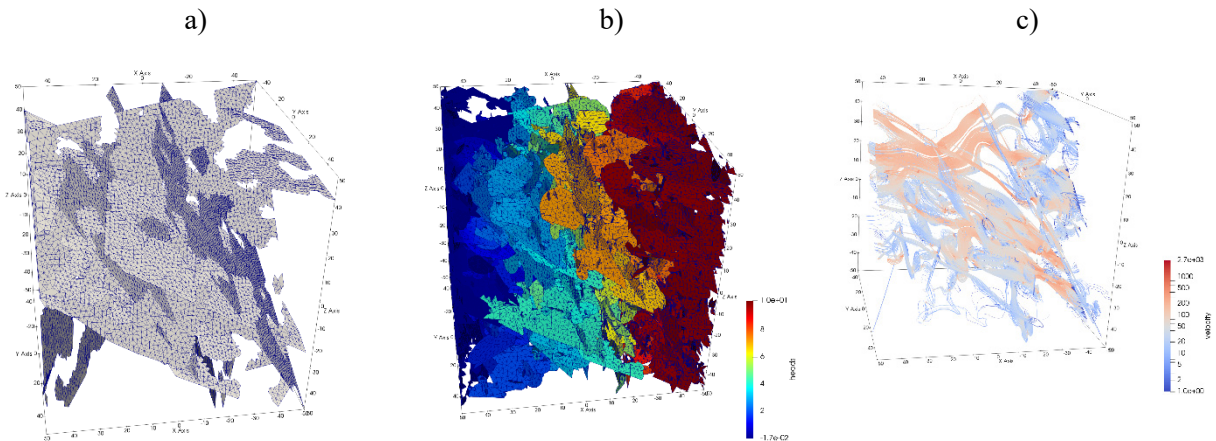


Figure 2. Illustration of flow computation on a UFM DFN with about 36,000 fractures with (a) mesh of the largest fractures, (b) heads and (c) particle paths.

### 2.5 Performances

We present some performances on a i7-8700K CPU with 32GB RAM. The complexity of mesh generation is in  $O(n_t^2)$  with  $n_t$  the number of triangles, for flow computation it is in  $O(n_t^{1.3})$  and in  $O(n_p)$  with  $n_p$  the number of particles for the particle tracking. Note that DFN.lab has not yet been improved in terms of performances (e.g. not multi-threaded).

Table 1 presents the CPU time for those operations. The base network is a UFM DFN generated in a 200 m cube with fractures sizes ranging between 1.5 and 200 m. It contains many small T intersections (0.6 m). Transmissivities are modelled with a CRF with values obeying a log-normal distribution of log-mean 1 and log-std 2. Flow is computed at steady state in permeameter conditions (imposed heads on two opposite boundaries, no flow condition elsewhere) while transport is computed with  $10^5$  particles injected simultaneously at the inflow boundary and until the last particle leaves the system. To vary the number of fractures, we consider fractures in smaller cubes of size  $L = 10, 50, 150$  and 200.

Table 1. Performances (CPU time) of DFN.lab for mesh, flow and transport computation.

fractures	intersections	Mesh elements	mesh (min)	Flow (s)	Transport (min)
22,800	37,900	$2.6 \cdot 10^5$	1	2.5	1
170,000	300,000	$2 \cdot 10^6$	14	39	1
570,000	1,000,000	$7 \cdot 10^6$	50	150	1
1,300,000	2,400,000	$16 \cdot 10^6$	300	440	1

### 3 CONCLUSIONS

DFN.lab is an efficient and robust simulation tool, which provides a full workflow for generating, analyzing and simulating flow and transport in 3D fracture networks. It can generate realistic DFN (e.g. UFM-DFN) with heterogeneous properties and handles the complexity at all levels: meshing, flow and transport. It can handle millions of fractures with sizes ranging over more than 3 orders of magnitude.

Future work includes a novel simulation method for heat transfer and the integration of mechanical computation in elastic conditions.

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