3D HM-DEM model for Hydro-Fracturing

E. Papachristos, F.V. Donzé & B. Chareyre
Laboratoire Sols, Solides, Structures, Grenoble, France
efthymios.papachristos@3sr-grenoble.fr,, frederic.donze@3sr-grenoble.fr, *bruno.chareyre@3sr-grenoble.fr*
and
L.Scholtès
*Lab*oratoire *GeoRessources,Vandoeuvre-lès-Nancy, France*
luc.scholtes@univ-lorraine.fr

ABSTRACT

Numerical methods used to study hydraulic fracturing in low permeability rock masses need to take into account the interaction between the progressive failure mechanism of the intact rock matrix and the pre-existing natural fractures. A fully coupled hydro-mechanical 3D discrete elements model dealing with such interaction is presented here. The ultimate objective is to grasp the role of the rock-matrix failure on the propagation of the main fluid driven fracture under different stress fields and pre-existing fracture orientations. The proposed method provides the spatiotemporal distribution of the induced crack events which can be tracked during the simulations, making possible the identification of the local mechanisms leading to macro-failure in the rock matrix or reactivation of the discontinuity planes. A hydro-fracking experimental test was simulated and, is presented in this paper as part of the validation process of the model.

INTRODUCTION

With the expansion of shale gas and geothermal reservoirs exploitation, the technique of Hydraulic Fracturing (HF) has been widely used over the past years (McClure, 2012; Britt, 2012). Despite recent advances in micro-seismicity analysis or numerical modeling (Nagel et al., 2013), the way progressive failure of rocks affects the fluid flow depending on the in situ stress conditions or the rock heterogeneities is not fully controlled yet (Zoback, 2010).

In this work we focused on setting up a three-dimensional discrete elements model to study fluid driven fractures propagation. The intact rock is modeled by a discrete element method (DEM) able to reproduce fracture initiation and propagation (Scholtès and Donzé, 2013, Garcia et al., 2013). The pre-existing fractures are explicitly modeled and can be individually defined or be part of a discrete fracture network (DFN) (Harthong et al., 2012). Their mechanical response is fully coupled with the fluid within a HM-DEM framework. The fluid flow and it's interaction with the intact matrix and the pre-existing discontinuities is modeled through a Pore-scale Finite Volume (PFV) scheme (Chareyre et al., 2012, Catalano et al., 2014), specially enhanced for fractured rock modeling.

In order to validate the hydraulic fracture initiation and propagation, a comparison is made with a hydrofracking test performed in sandstone specimens (Stanchits et al., 2013). The overall response of the specimen to the mechanical and hydraulic loading is compared.

NUMERICAL MODEL

DEM model

A 3D coupled discrete element model was used for this study. This model is implemented in YADE OPEN DEM (Kozicky & Donzé 2008, 2009), an extendable open-source framework. A detailed description of the model can be found in several references (Šmilauer et al., 2010, https://yade-dem.org/doc/) and only a short description will be given here. The DEM model considers a set of discrete spherical elements interacting through cohesive-frictional brittle bonds with the possibility for near neighbor interaction. Scholtès and Donzé (2013) showed the advantage of such feature to obtain realistic brittleness ratios and nonlinear failure envelopes for various rock types. The cohesive-frictional bonds behave according to an elastic-brittle constitutive law. For the elastic domain, constant shear and normal stiffnesses are computed depending on the size of the discrete elements and the desired macroscopic parameters. Linear elasticity holds until shear or tensile local bond failure occurs. The failure criteria are expressed using a modified Mohr-Coulomb criterion based on three parameters, a friction angle φ and two stress-like values defining the maximum admissible forces F_s^{max} and F_n^{max} are derived. After brittle rupture, frictional interaction occurs between strictly contacting discrete elements. Such interaction presents no tensile strength, and a purely frictional shear resistance that depends on the friction angle φ. Overall, the DEM model for the rock matrix includes six parameters (Scholtès & Donzé, 2013).

DEM modeling of pre-existing rock discontinuities

Due to the spherical shape of the discrete elements, planar discontinuity surfaces cannot be described without being dependent of the discretization. For this reason, the present model uses the smooth-joint model (SJM) proposed by Mas Ivars et al. (2011). The SJM is applied to all interactions located across pre-existing discontinuity surfaces. The SJM modifies the orientation of the interaction according to the orientation of the pre-existing discontinuity. A frictional elastic-plastic behavior is prescribed along the discontinuity surface, with very small influence of the roughness generated by the spherical elements. The SJM's behavior is characterized by four parameters: normal and tangential joint stiffnesses, a local joint friction angle ϕ and a dilation angle ψ. It is important to note that ϕ corresponds to the resulting macroscopic friction angle of the simulated discontinuity surface, unlike the matrix, where the internal friction angle of the medium does not correspond to the friction angle φ defined at the bond scale (Scholtès & Donzé, 2012).

Fluid Modelling based on a PFV scheme

The numerical approach for simulating the rock mass behavior under fluid injection uses a pore-scale finite volume (PFV) scheme which enables the model to simulate the fluid flow through the rock-matrix as well as through the fractures (see Chareyre et al., 2012, Catalano et al., 2014). This scheme offers the possibility to set up a complete hydromechanical coupling by means of fluid forces applied on the discrete elements and pore fluid deformation as a function of the displacement of the latters. The pore network model is built through a weighted Delaunay triangulation over the discrete element packing. The discrete elements form the vertexes of the tetrahedrons which represent an elementary pore unit. The Voronoi diagram defines a pipe network that connects the pores one with each other. The permeability of these pipes is defined either through a parallel plate model for pre-existing fractures and induced cracks or through a pipe model for the rock matrix.

The fluid flow formulation characterizing the flow through cracks or pre-existing joints, is based on the cubic law. Considering a normalized width per length unit, the fluid discharge can be expressed such as,

$$q_{ij} = \frac{(a_0+a)^3}{12\mu}\Delta P \tag{1}$$

Where q_{ij} is the discharge from pore i to pore j, μ the dynamic viscosity, ΔP the pressure variation, a_0 is the residual fracture aperture and a, the aperture that corresponds to the relative displacement between interacting discrete elements acting at the edge of the neighboring pore cells.

If the flow from pore i to pore j, takes place through facets without cracks, i.e. inside the rock matrix, the discharge is given by,

$$q_{ij} = \alpha \frac{R_h^2 A_{ij}}{\mu}\frac{\Delta P}{L_{ij}} \tag{2}$$

with α being a scaling factor, A_{ij} the area of the facet, R_h^2 the hydraulic radius and L_{ij} the inter-pore length.

The model enables one to use either incompressible fluid (Chareyre *et al.*, 2012) or compressible fluid (Scholtès *et al.*, 2014).

NUMERICAL SETUP

The mechanical properties of the rock matrix were chosen to ensure the simulated behavior to be representative of Colton sandstone. The properties of the medium are summarized in Table 1. The mechanical properties of the interaction making the joint planes were selected to simulate non-cohesive fracture surfaces (cohesive and tensile strength set up to zero), with a friction angle equal to 30° and a dilation angle ψ of 5°.

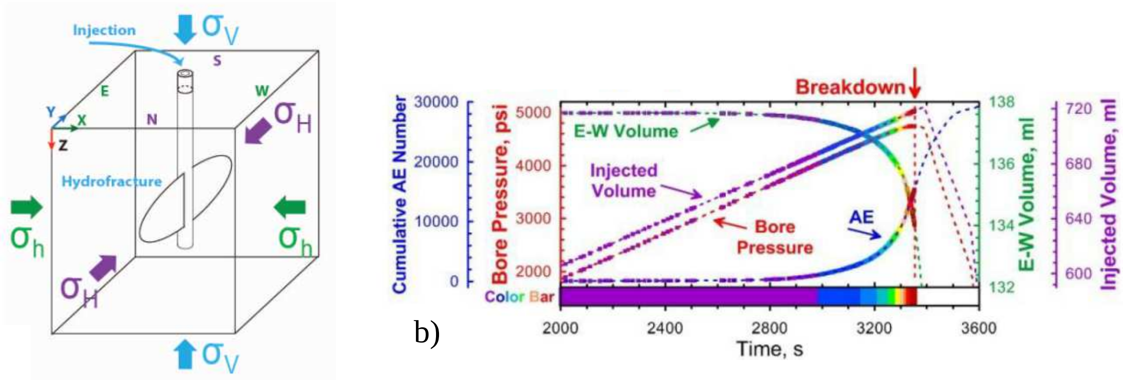
Table 1 – Rock properties

Parameters	Values
Density [kg/m^3]	2500
E [Pa]	20.4×10^9
ν [-]	0.2
UTS[MPa]	3
UCS[MPa]	30
Rock matrix permeability [m^2]	4×10^{-16}
Fracture aperture (zero confinement) [m]	0.001

RESULTS

Hydraulically driven fracture propagation experiment

The model was used to simulate a laboratory experiment carried out by (Stanchits et al., 2013) on a Colton sandstone block. The objective was to investigate the hydraulic fracture initiation by means of acoustic emissions and volumetric measurements. Among the different tests, the fracture was hydraulically induced in an anisotropic stress field by injecting a highly viscous fluid (2.5 kPa.s) into a vertical borehole. The experiment was monitored such that the injection pressure, acoustic emissions (AE) and volumetric deformations were recorded during the test. The tested rock block was about 279.4 mm × 279.4 mm × 381 mm in size (Figure 5a). The hydraulic fracturing test was conducted by injecting the fluid into the borehole at a flow rate of $0.83\text{x}10^{-7}$ m^3/s. The borehole was drilled up to the center of the specimen and two longitudinal scribes were made along the slot to facilitate the initiation of the hydrofracturation along a preferential direction (perpendicular to the minor principal stress). The vertical normal stress (along the borehole or y-axis) represented the major principal stress with a magnitude of σ_v = 4000 psi. The intermediate principal stress of σ_H = 2000 psi was horizontal in the y-direction; the minor principal stress of σ_h = 1000 psi was in the x-direction. The stress state was maintained during the experiment (Figure 5b). The experimental results of the fluid injection test into the Colton sandstone block, i.e. borehole pressure, volume of the injected fluid, lateral deformation of the specimen and AE measurements, are shown in Figure 5b. The injection resulted in the fluid pressure increase until the breakdown pressure of about 4700 psi was reached. Then, fluid injection was interrupted few seconds after breakdown, resulting in high pressure decay. Post-mortem observations showed that, as expected, the vertical HF propagated in the x- direction perpendicular to the minor principal stress with a pancake like shape. A major finding of this study is that hydraulic fracturing initiated significantly earlier than the pressure breakdown as emphasized by AE measurements.



a) b)

Figure 1 – On the left (a), a schematic which represents the experimental test. On the right (b) the recorded data during the injection test. It shows the evolution of the volumetric deformation along the axis of the applied σ_{min} (E-W Volume), the cumulative injected volume (Injected Volume), the corresponding pressure in the borehole (Bore Pressure) and the recorded acoustic emissions (AE) (from Stanchits et al., 2013).

Hydraulically driven fracture propagation model results

This experiment was simulated numerically in order to verify the ability of the model to reproduce the fracture path, injection pressure and the progressive failure in relation to the AE data. The simulations were run by injecting a compressible fluid with a viscosity significantly lower than in the experiments (25 Pa.s). Besides this lower fluid viscosity, the difference to the experiment lies in the fact that the injection was done in a pre-existing penny shaped crack of 50 mm diameter, located at the center of the numerical model In addition, injection was not interrupted after the breakdown as in the experiments. The resulting micro-crack pattern within the simulated block is presented in Figure 6 (bottom) and its spatial distribution is compared to AE hypocenters recorded in the experiment (top). As observed for the AE in the experiment, micro-cracks coalesced to form a vertical hydro-fracture, which propagated from the borehole towards the model boundary perpendicularly to the minor principal stress direction (x axis). The localization and the time evolution of the simulated micro-cracks are in reasonably good agreement with the AE events. However, micro-cracking and AE measurements, even though correlated, cannot fit exactly (Figure 7). Indeed, several micro-cracks can be part of a unique acoustic event, leading to an earlier activity in terms of micro-cracking. Because of that, the evolution of the micro-cracking over time is slightly different from the AE measurements and their spatial distribution is more diffuse. Note that current works are currently carried out to relate micro-cracking to acoustic events (Raziperchikolaee et al., 2014). The evolution of the borehole pressure and as well as the micro-cracking evolution are presented in Figure 7. Despite the assumptions made in the simulation, the pressure breakdown value is comparable to the one obtained experimentally. The overall evolution of the pressure matches fairly well the laboratory data. The pressure linearly increased up to the peak then decay progressively. Nonetheless, the pressure increase exhibits an earlier and more pronounced departure from linearity compared to the experiment.

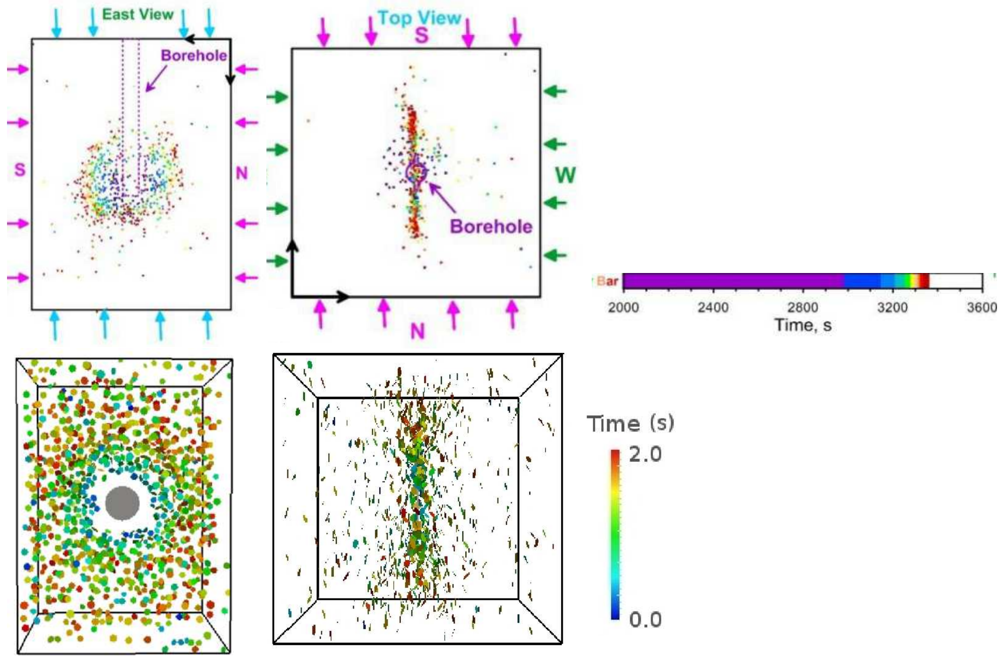


Figure 2 – On the top, two orthogonal projections of AE hypocenters from the experiment (Stanchits et al, 2013) are presented. On the bottom, two orthogonal projections of cracks inside the numerical model are shown.

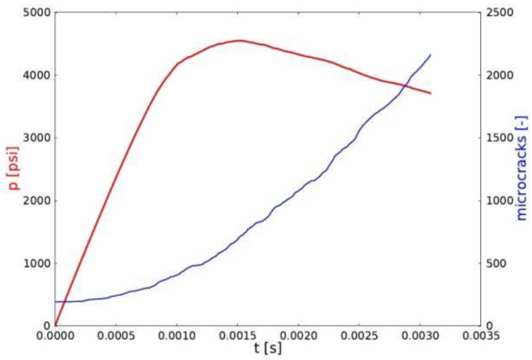


Figure 3 – Crack and pressure history (time in seconds).

CONCLUSION

A 3D coupled DEM model, able to deal with fluid driven fracture propagation in rock with pre-existing and newly created fractures is presented. The model is using explicit dynamic DEM to simulate the rock phase of the system and an enhanced pore-scale finite volumes scheme able to deal with porous matrix and fractures, to represent the fluid phase. The coupling between the fluid phase and the fractures (newly or pre-existing) is based on the initial aperture, residual aperture and the relative displacement of the elements involved in the cracks.

Hydraulic fracturing in homogeneous, non-homogeneous or jointed medium can be considered by the model. Different stress fields defined by magnitudes and orientations of the principal stresses can be also considered. The first code predictions shows a good agreement with laboratory data.

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