A coupled approach for the simulation of HF treatments in low permeability reservoirs

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Abstract

In geo-engineering, hydraulic fracturing (HF) is used to improve the oil/gas production and optimize well stimulation in low permeability reservoirs. To design HF treatments, it is necessary to predict the pattern of fracture geometry as a function of treatment parameters. In this contribution, a coupled hydro-mechanical approach is presented to simulate HF treatments and their consequences on fracture distribution and permeability enhancement in the stimulated rock. The approach, developed in the framework of continuum mechanics, is based on the constitutive description of the rock via a recently developed model of brittle damage. The model was presented in (De Bellis 2016) in the linearized version and in (De Bellis 2017) in finite kinematics and it is based on the explicit micromechanical construction of connected patterns of parallel equi-spaced cracks. Fracture patterns are not arbitrary, but their inception, orientation and spacing follow from energetic consideration. The model stems from the proposal of (Pandolfi 2006) and extended to porous media by the introduction of the effective stress concept and of friction as a further dissipation mechanism. The capability of the model to predict the mechanical response of brittle rocks subject to triaxial tests at the material point level has been evidenced in (De Bellis 2016) and (De Bellis 2017): remarkably, the model is also able to predict porosity and permeability evolution due to both rock matrix deformation and fault development.

The mechanical model has then been implemented into a coupled hydro-mechanical finite element code, where the linear momentum and the fluid mass balance equations are numerically solved via a staggered approach (see Caramiello 2018 for further details). Beyond the classical poro-mechanics coupling terms, further hydro-mechanical coupling is provided by the explicit dependence of rock permeability on fault spacing, orientation and opening evaluated in each integration point. The coupled code has been used to simulate laboratory and field scale fracturing processes induced by an increase in pore pressure, under the assumption of fluid saturated porous medium.

Laboratory scale application

The coupled hydrodynamic code has been validated by simulating an experiment performed in the laboratory by (Athavale and Miskimins 2008), consisting in a small scale fracking process. In the experiment, a cement block of size 28 cm x 28 cm x 38 cm containing a cylindrical cavity at the center was initially subject to a compressive anisotropic state of stress; a fluid has then been injected in the cavity, up to failure (see Figure 1a). The fluid pressure evolution inside the cavity measured by the Authors is shown in Figure 1b. The hydraulic fracture test has been simulated by discretizing the specimen into 8,945 10-noded tetrahedral elements, (corresponding to 38,313 nodes) and by applying the measured fluid pressure history to the nodes belonging to the volume of the cavity. The results of the simulation are visualized in Figure 1c, in terms of spatial distribution of the damaged zone, and in Figure 1d in terms of time evolution of the fracture volume. In particular, damage has been expressed in terms of the norm of the opening fault displacement vector in any point, while the fracture volume is a global variable expressing the total volume of the opened faults, thus proportional to the normal component of the fault opening vector. As expected, due to the absence of proppant inside the fracking fluid, the time evolution of the fracture volume is strongly influenced by fluid pressure history and becomes null when excess pore pressure has been dissipated.

Field scale application

The code has also been used to simulate hydraulic fracturing processes at the reservoir scale. Several simulations have been performed in order to evaluate the influence of different operational parameters on the outcomes of the process, e.g. the number of wellbore perforations, the distance between the different perforation slots, the wellbore deviation from the minimum principal stress direction axis, the imposed fluid pressure history, fluid rheological properties and proppant size. Figure 2a and 2b show two possible outputs of the model, i.e. the spatial distribution of the damaged zone and of rock permeability after the fracking job. The simulation has been performed by considering a parallelepiped domain of size 3.5 km x 2.15 km x 2.15 km, subjected to a far-field compressive state of stress characterized by a vertical stress of 40 MPa, a maximum horizontal stress of 50 MPa and a minimum horizontal stress of 40 MPa. The initial pore pressure is assumed to be uniform and equal to p = 24 MPa and the domain is crossed by a horizontal borehole parallel to the direction of the maximum principal stress. Details of the simulations performed can be found in (Caramiello 2018).

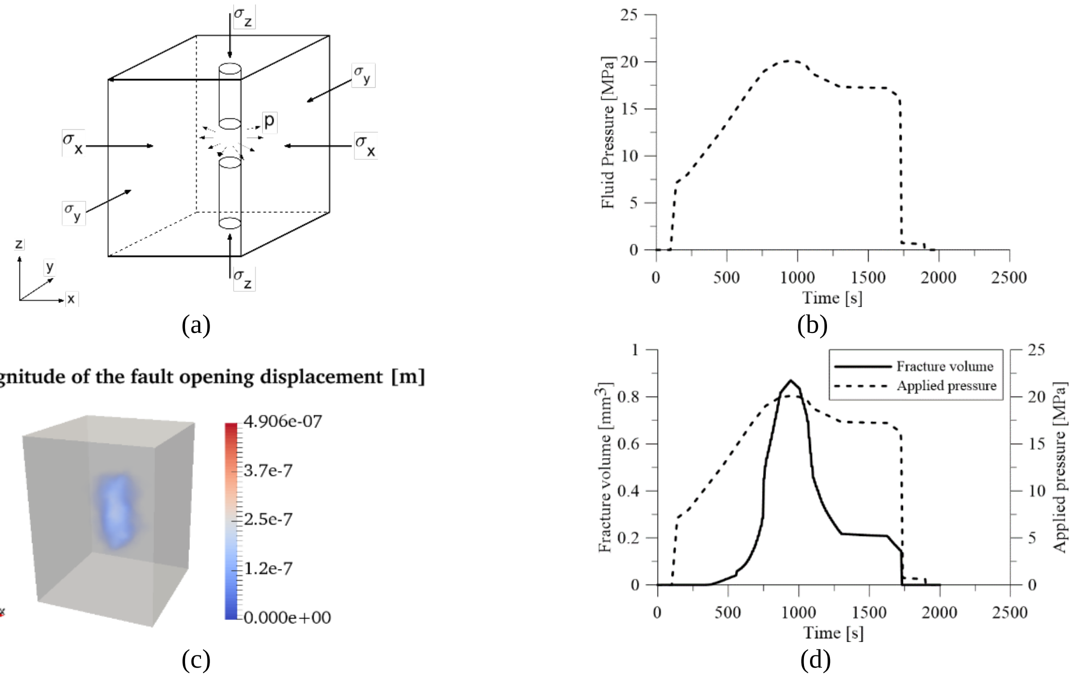

Fig. 1: a) Scheme of the laboratory test and of the boundary conditions, b) Time evolution of the fracturing fluid pressure , c) Visualization of the distribution of the damage in terms of magnitude of the opening displacements d) Time history of fracture volume.

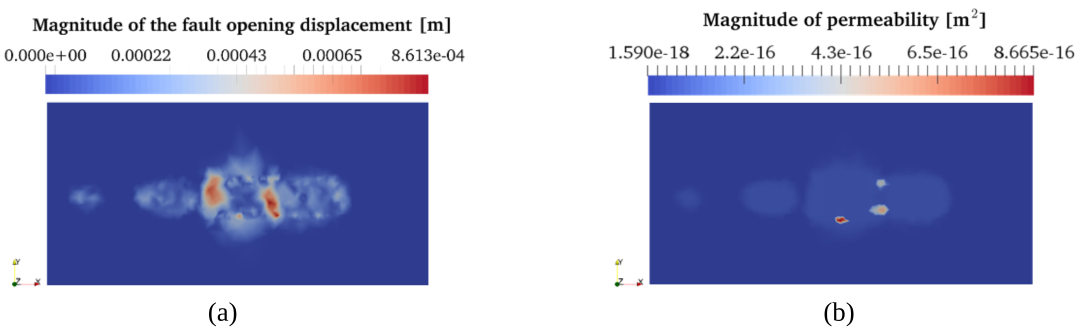

Fig. 2: a) Damage distribution after the fracking job, b) Permeability distribution after the fracking job

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