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Porous media fracturing dynamics: stepwise crack advancement and fluid pressure oscillations

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ABSTRACT

We present new results explaining why fracturing in saturated porous media is not smooth and continuous but is a distinct stepwise process concomitant with fluid pressure oscillations. All exact solutions and almost all numerical models yield smooth fracture advancement and fluid pressure evolution, while recent experimental results, mainly from the oil industry, observation from geophysics and a very few numerical results for the quasi-static case indeed reveal the stepwise phenomenon. We summarize first these new experiments and these few numerical solutions for the quasi-static case. Both mechanical loading and pressure driven fractures are considered because their behaviours differ in the direction of the pressure jumps. Then we explore stepwise crack tip advancement and pressure fluctuations in dynamic fracturing with a hydro-mechanical model of porous media based on the Hybrid Mixture Theory. Full dynamic analyses of examples dealing with both hydraulic fracturing and mechanical loading are presented. The stepwise fracture advancement is confirmed in the dynamic setting as well as in the pressure fluctuations, but there are substantial differences in the frequency contents of the pressure waves in the two loading cases. Comparison between the quasi-static and fully dynamic solutions reveals that the dynamic response gives much more information such as the type of pressure oscillations and related frequencies and should be applied whenever there is a doubt about inertia forces playing a role - the case in most fracturing events. In the absence of direct relevant dynamic tests on saturated media some experimental results on dynamic fracture in dry materials, a fast hydraulic fracturing test and observations from geophysics confirm qualitatively the obtained results such as the type of pressure oscillations and the substantial difference in the behaviour under the two loading cases.

1. Introduction

Fracture propagation in saturated porous media is intriguing and challenging to interpret. A controversy started in 2013–2014 with an experimental paper by Pizzocolo et al. (2013) and a numerical one by Secchi and Schrefler (2014) showing that fracture in such media, induced respectively by mechanical action and by fluid pressure is a stepwise process with

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fluid oscillation. On the contrary, until that period, all exact solutions e.g. by Perkins and Kern (1961), Rice and Cleary (1976), Huang and Russel (1985a, 1985b), Detournay and Cheng (1991), Advani et al. (1997), Garagash and Detournay (2000), Adachi et al. (2007), Lecampion and Detournay (2007) and Garagash et al. (2011), either neglected propagation or gave smooth results. Smooth results were also obtained with numerical solutions, except for a few mentioned below, independently of the method used: Extended and Partition-of-Unity Finite Elements (Réthoré et al., 2007, 2008; Kraaijeveld et al., 2013; Mohammadnejad and Khoei, 2013a, 2013b; Remij et al., 2015), interface elements (Boone and Ingraffea, 1990; Carier and Granet, 2012), strong discontinuity (Nguyen et al., 2017), Phase Field (Wheeler et al., 2014, 2015; Miehe et al., 2015; Mikelic et al., 2015; Lee et al., 2017; Heider and Markert, 2017; Mauthe and Miehe, 2017) and lattice models (Grassl et al., 2015). In the meantime, several experiments from the petroleum industry became available evidencing the stepwise behaviour: Black *et al.* (1988) (tests related to lost circulation, reported in Feng et al. (2015, 2017)), L'homme et al. (2002), L'homme (2005) (tests with low viscosity fluid and high injection rate), Zhang and Chen (2010) and by Razavi et al. (2016). Stepwise advancement is further known from field data from hydraulic fracturing operations (Morita et al., 1990; Fuh et al., 1992; Okland et al., 2002; Fisher and Warpinski, 2012; Soliman et al., 2014; de Pater, 2015). By analyzing field data from the Marcellus shale and the Eagleford shale, Soliman et al. (2014) pointed out the difference between the major pressure changes which are observed when a fracture intersects naturally existing faults and the minor fluctuations which are linked to intermittent advancement. The ability to distinguish between the two has an important implication for the exploitation since it would help to diagnose problems and identify potential sand-out very early in the treatment.

Steady state growth of pressure induced fractures on the other hand has been observed by L'homme et al. (2002) and L'homme (2005) in their tests on Colton Sandstone when using high viscosity fluid and low injection rate (which does not correspond to the general field conditions in case of fracking). Steady state growth has also been obtained theoretically and numerically by Noselli et al. (2016) when studying the quasi-static propagation of a semi-infinite parent crack in an infinite polymer gel in Mode I conditions and immersed in a solvent. Further, Okland et al. (2002) observed that a "jagged saw tooth shape of the fracture propagation appeared at pressures 10–15 bars above the minimum horizontal stress" and "thus of the theoretical minimum pressure necessary for lost circulation by induced hydraulic fracturing", i.e. the loss of drilling fluid due to onset and propagation of pressure induced fracturing. "Saw tooth" shape means that "the fracture tip propagates as a distinct number of minimum breakdown events alternating with periods of no fracture propagation and balloon-like inflation of the fracture". The existence of two propagation regimes, - the steady state propagation and stepwise advancement - suggests that the steady state propagation may become unstable above a certain advancement speed, a point worth investigating.

Following the experimental evidence Okland et al. (2002), Schrefler et al. (2006), Secchi and Schrefler (2012), Zeini Jahromi et al. (2013), Kim et al. (2014), Ahn et al. (2014), Kim and Moridis (2015), Sachau et al. (2015), Milanese et al. (2016, 2017, 2018), Cao et al. (2017), Feng and Gray (2017) and Yushi et al. (2017) were able to reproduce the stepwise advancement numerically. These authors used either standard Finite Element, Finite Volume, Finite Difference or lattice models and none of the above mentioned "advanced" numerical methods. Only Milanese et al. (2016) used successfully XFEM discretization in space but at the expense of such fine meshes that the crack advance in one time step intersects more than one element; such meshes are however against the "raison d'être" of XFEM, i.e., coarse meshes and no remeshing.

Intermittent fracture advancement in saturated formations is also known from geophysical observations (Phillips, 1972; Sibson, 1994; Cesare, 1994; Cox, 1995; Obara et al., 2004; Schwartz and Rokosky, 2007; Burlini and Di Toro, 2008; Burlini et al., 2009; Beroza and Ide, 2009; Nolet, 2009; Obayashi et al., 2009; Beroza and Ide, 2011). Without such a behavior, the non-volcanic (subduction) tremor and volcanic tremor are difficult to explain. The two types of tremor have different signatures: distinct frequency peaks for volcanic tremor while subduction tremor lacks such distinct peaks (Schwartz and Rokosky, 2007); they are believed to be due to different loading conditions: pressure induced fracture in the first and mechanical one in the second case. There is clearly a need for numerical models able to reproduce these different signatures.

Inhomogeneity of the solid material alone can be excluded as the origin of the intermittency because in the experiments by L'Homme et al. (2002), L'Homme (2005) and by Pizzocolo et al. (2013) a material has been chosen to be as homogeneous as possible. Hydrogel is one of the most homogeneous materials, as is Colton sandstone too. Hence the behavior must be of different physical origin. For instance, the behaviors of the pressure in the fracture and in the sample differ substantially for fracture induced by fluid pressure as opposed to that by mechanical action as already expected in geophysics. This is the case in mode I fracturing and often in mode III fracturing. Sharp pressure peaks at fracture in mode I in case of mechanical loading and sharp pressure drops in case of hydraulically driven fracture have been observed in numerical simulations; see Fig. 1.

This difference was first evidenced by Milanese et al. (2016) for quasi-static situations when studying with methods of statistical physics the avalanche behavior at fracture of heterogeneously saturated porous media, and has been confirmed with the Standard Galerkin Finite Element Method (SGFEM) in Cao et al. (2017). Recall that an avalanche indicates a number of failing elements in the domain per loading step.

The following explanation for this behavior has been given based on Biot's theory (Milanese et al., 2016): if a load, pressure, or displacement boundary condition is applied suddenly (all these conditions acting on the equilibrium of the solid-liquid mixture), then the fluid bears initially almost all the induced load because its immediate response is undrained (rigid and non-flowing). Then through the coupling with the fluid, the overpressures decrease and the solid gets loaded. Hence we have a pressure rise upon rupture. Pressure and stresses evolve out of phase (first partial scenario). On the contrary, if the flow is specified its effect is transmitted to the solid through the pressure coupling term in the effective stress.