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Interaction between crack tip advancement and fluid flow in fracturing saturated porous media

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ABSTRACT

We address stepwise crack tip advancement and pressure fluctuations, which have been observed in the field and experimentally in fracturing saturated porous media. Both fracturing due to mechanical loading and pressure driven fracture are considered. After presenting the experimental evidence and the different explanations for the phenomena put forward and mentioning briefly what has been obtained so far by published numerical and analytical methods we propose our explanation based on Biot's theory. A short presentation of three methods able to simulate the observed phenomena namely the Central Force Model, the Standard Galerkin Finite Element Method SGFEM and extended finite element method XFEM follows. With the Central Force Model it is evidenced that already dry geomaterials break in an intermittent fashion and that the presence of a fluid affects the behavior more or less depending on the loading and boundary conditions. Examples dealing both with hydraulic fracturing and mechanical loading are shown. The conditions needed to reproduce the observed phenomena with FE models at macroscopic level are evidenced. They appear to be the adoption of a crack tip advancement/time step algorithm which interferes the least possible with the three interacting velocities, namely the crack tip advancement velocity on one side, the seepage velocity of the fluid in the domain and from the crack (leak-off), and the fluid velocity within the crack on the other side. Further the crack tip advancement algorithm must allow for reproducing jumps observed in the experiments.

1. Introduction

In structural mechanics, according to Griffith's criterion [22], a crack propagates if the rate of elastic energy decrease per unit surface area of the increment step is equal to the (quasi-static) critical energy release rate G_C. The crack does not move if the elastic energy release rate is less than G_C. Following a phenomenological approach, crack propagation is usually addressed as function of the increasing load and the time has only an ordering role. As a consequence, there is no information on the crack evolution, which is usually assumed smooth. Time dimension only appears in special cases [11,17,23,29,56,64,65,78,81,82]. However crack advancement in geomaterials is intermittent as will be shown on several experimental results in fluid saturated situations. This is also true for dry material. The analysis of crack propagation in fluid saturated porous media, including fluid pressure induced fracture (hydraulic fracture), deserves particular care if realistic simulations are sought for [70]. At the macroscopic level it has to be take into account that the fracture lips are not stress free since the fluid pressure acts on them; besides this pressure (load) is varying both in time and along the fracture lips. A further difference from dry material is that there are three velocities involved: the crack tip advancement velocity on one side, the seepage velocity of the fluid in the domain and from the crack (leak-off), and the fluid velocity within the crack on the other side, each one with its time and length scales [15,19]. Hence the velocity of applied external loads (mechanical and/or pumping) must be defined in the real time domain, not only as an ordering quantity and this velocity represents a fourth time dependent quantity. There exist, however, other time/length scales besides those that have been

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mentioned above, which could be defined. The most important are (probably) the length of the fluid lag between the fluid front within the crack and crack tip, the length of the cohesive or process zone near the tip and the surface tension at the fluid front. All these time/length scales interact and strongly influence the outcome of the process and have to be accounted for if a physical solution is desired both locally and globally. Evidence of the interaction of the length scales can be found in the fact that the dynamic viscosity of fluids influences not only the length of the fracture and the pressure distribution but also its direction [70] and the advancement pattern [42]. Similar patterns can be obtained only with numerical solutions, in which the simplifying assumptions are usually fewer than in the asymptotic approaches. Intermittent crack advancement and interaction with the fluid phase is well known in Geosciences since the early 1970′s: when investigating the conditions for fracturing and fracture propagation in [54] is observed that “the growth of macroscopic tension fractures consists of short periods of extension of the crack by fracture, separated by longer periods during which the pore fluid flows into the crack. Consequently, the rate of crack propagation under constant differential stress depends on the porosity and permeability of the rock”. With reference to failure surfaces relevant for natural hydraulic fracturing it is found that, if the difference between the maximum and minimum principal stresses (differential stress) is less than four times the tensile strength of the rock, mode I fractures form, perpendicular to the minimum principal stress, while when the differential stress is larger than the above value the rock fails in shear in accordance with Coulomb criterion [54,74]. The following scenario is proposed in [54] for normal fault formation:

- i slow buildup of the differential stress until the critical stress conditions are reached under the prevailing pore water pressure;
- ii abrupt fracturing resulting in:
  - (a) the release of elastic strain energy in the form of compressional and distortional waves;
  - (b) a temporary reduction in fluid pressure on the leading edge of the fracture, due to an increase in volume, and
  - (c) a small reduction in the differential stress in the region of the fracture;
- iii permeation of the pore water into the fracture to restore the pore water pressure.

Repeat of the cycle.

The scenario is similar also for hydrothermal solutions that may rise from below and form a sheet of fluid on the fault planes. If the differential stress is near the critical value for fracturing, hydrothermal solution at a pressure only slightly in excess of the prevailing pore water pressure would cause an extension of the fault.

By analyzing the relative rates of flow and fracturing it is found that “fracturing occurs abruptly, and the fracture extends at a rate which is greater than the velocity of entry of fluid and may in some cases approach one fifth of the speed of sound. The formation of the fracture results in a sudden drop in the pressure at the leading edge of the sheet of fluid which consequently rushes into the newly forming fracture” [57].

The above concepts are used to explain the veining found in rocks [9,13] and are also relevant for magma flow [6]. Pressure fluctuations are evidenced in hydraulic fracturing for unconventional oil development [77], where a large amount of data from two fields, the Marcellus and the Eagle Ford shale are reported. According to [53] and [51] for a given formation, crack width is essentially controlled by fluid pressure drop in the fracture and the fracturing pressure is a power function of time according to $p(t) = \alpha t^e$. Bounds for the exponent e are given both for Newtonian and non-Newtonian fluids. Wellbore pressures are measured during constant injection rate either down-hole or with surface

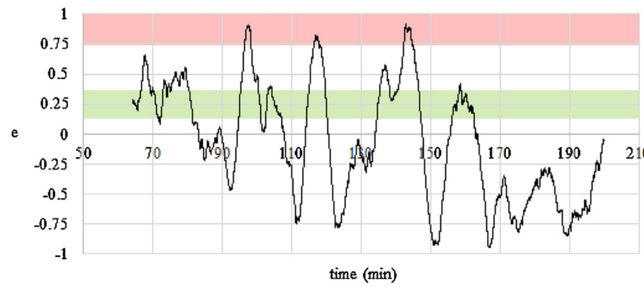

Fig. 1. Fracture growth exponent plot for stage 9 of Eagle Ford shale. Reprinted with permission from Hydraulic Fracturing Journal.

pressure gauges. Fluctuations of these pressures demonstrate fracture intermittent advancing and Soliman and coworkers [77], by elaborating the measured pressures with the above power law, put into diagrams the exponent e, which represents at the same time the exponent of the time pressure profile and the fracture growth. Three main possible regimes are identified, with the pertinent e values, to clarify the field data interpretations of Fig. 1:

- negative e: there is a large decrease of pressure corresponding to the well crossing permeable and fractured formations;
- e in the range of 0.13–0.30: crack propagation (green zone in Fig. 1);
- e in the range of 0.75–1.0: crack screening off, i.e. tip arrest, among other (pink zone in Fig. 1).

It is noteworthy that these interpretations hold in the presence of nearly constant forcing function (slurry rate) [77]. The major pressure changes are observed when a fracture intersects naturally existing faults; the minor fluctuations are linked to intermittent advancement, which according to these authors would be due to alternative “mini-periods of propagation intermingled with periods of dilation”. It is argued that “identifying these periods of dilation and growth in length would help to diagnose problems and identify potential sand-out very early in the treatment.” Hence the problem at hand has an eminent practical importance in fracking. Strong pressure fluctuations can also be found in some graphs of [52] referring to treatment in coal with very strong containment. The observed mean value of the net pressure from wellhead data is seen to be falling while pumping clean fluid at a constant rate. This is in accordance with what was found in [68] and in [79] for an impermeable formation (compare Fig. 3(top)). If the reasoning of [77] is applied, clearly stepwise tip advancement ensues.

An experimental study of hydraulic fracture propagation in Colton Sandstone has been carried out [42]. The material has been chosen for its homogeneity and low permeability. Viscous silicon oil behaving nearly Newtonian has been injected into the borehole of the samples. Tests carried out with high viscosity fluids and low flow rate were characterized by a linear pressure increase before breakdown and a stable slow propagation of the fracture after breakdown. On the contrary, three out of four tests carried out with low viscosity fluids and high flow rate where characterized by multiple fluid pressure rises during the injection stage. “After the sharp pressure decline following the first breakdown event, the borehole pressure rose several times with similar pressurization rates, to reach local maxima which were all in the range of ±10% of the first breakdown pressure. Each pressure maximum was associated with an almost instantaneous rise of the notch inlet opening, followed by a rapid drop. The difference between the borehole pressure minima in between the peaks was not more than 10% of their average value. However the minima of the notch inlet opening after each breakdown event increase progressively” [41]. Post mortem visualization of the fracture plane suggests that the fracture