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Modeling of microseismicity associated with rock deformation and fracturing

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Summary

Microseismicity monitoring is a popular tool to assess the effectiveness of hydraulic fracture treatments. Often substantial differences are estimated between the total input energy inferred from fluid injection rates and pressures, the fracture energy to pry apart the walls of a single very large fracture, and the radiated energy observed from recorded seismicity. We use a bonded-particle model to investigate the link between brittle failure and microseismicity. Modeling of well documented laboratory rock fracturing experiments is used for calibration. The first results show a large discrepancy between the total injected energy and the energy retrieved from the microseismic events, just like for large scale hydraulic fracturing of geothermal or oil/gas reservoirs. The failure mechanisms inferred from the breakages of bonds between particles in the model vary between opening and closing with some shearing, like the mechanisms found for large-scale microseismicity, even if no fluid is injected into our model. We find the kinetic energy to be about 5% of the input energy, and the radiated energy to be 50-100 times smaller than the kinetic energy. This suggests that the radiated energy calculated using the Gutenberg-Richter relationship between moment magnitude and energy may underestimate the energy incurred from brittle failure.

Introduction

Microseismicity monitoring is increasingly being used to asses in real time the effectiveness of hydraulic fracture treatments. As this tool continues to become more prevalent, questions regarding the observed microseismicity are being asked. In particular, why is failure occurring in specific locations and not others? What are the failure mechanisms? Where does the input energy go? Often substantial differences are estimated between the total input energy inferred from fluid injection rates and pressures, the fracture energy to pry apart the walls of a single very large fracture, and the radiated energy observed from recorded seismicity. The injected energy is 10^4 –10^7 times larger than the estimated radiated seismic energy, and the fracture energy is inferred to equal 15 – 40 % of the input energy (Maxwell et al., 2008; Boroumand and Eaton, 2012). In general, these questions are difficult to answer from the recorded seismicity alone as the geomechanical behaviour of the reservoir depends on the in situ stress field, the local rock properties, and any pre-existing areas of weaknesses such as faults, fractures or joints. Geomechanical modeling by numerical simulation has become a viable candidate for providing a better understanding of both brittle and ductile deformation in the reservoir due to hydraulic fracturing.

We present here results obtained from simulations with a bonded-particle model. The behaviour of a sandstone sample under triaxial compression is reproduced. The first results show that both the energy budget and the microseismicity share strong similarities with large scale hydraulic fracturing experiments without any addition of fluid.

Modeling

To investigate the fracturing of rock we use a bonded-particle model (BPM). The BPM is an aggregation of bonded spherical particles that can reproduce the macroscopic properties of a desired rock when the right microproperties of bond strengths are set up. Limit conditions are applied by walls (Figure 1 left). Then displacement of particles and stress changes are computed one after the other for each time step (Figure 1 middle). If the local stress exceeds the bond strength, the bond breaks (Figure 1 right). Bond breakages, and the associated release of strain energy, form seismic events (Hazzard et al., 2000). The energy released during bond breakages triggers further cracking by increasing local stresses. The coalescence of neighbouring microcracks constitutes a macrorupture. The moment tensor corresponding to an event can be computed by analyzing the force changes at contacts around the source particles (Hazzard and Young, 2004). The moment tensor is then calculated at each time step over the duration of the event by assuming that a shear fracture propagates at half the shear-wave velocity of the medium. If a new crack forms within the source surface of an active crack, the two cracks are considered part of the same seismic event. The failure mechanisms are inferred from the way the bond breaks: in tension, compression or shearing. Hence a catalogue of microseismic events with different magnitudes is listed.

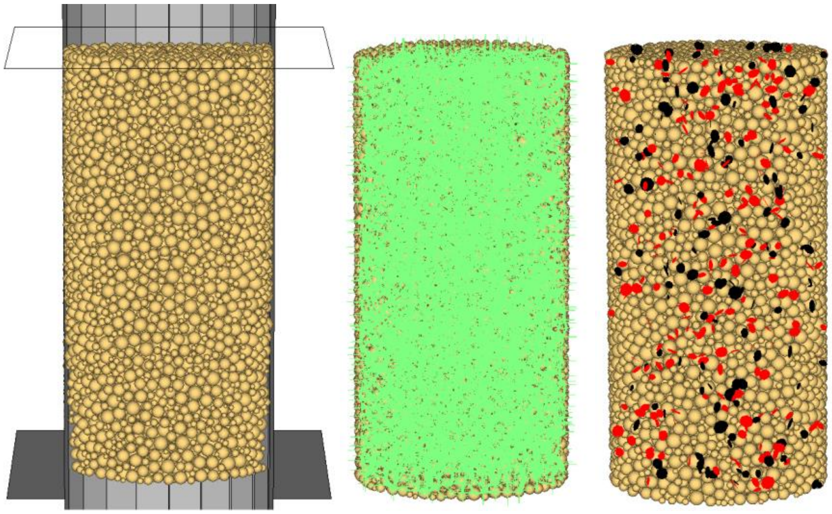

Figure 1: Model sample with particles in yellow and the surrounding walls in grey (left), the bond forces in green (middle) and some bonds which broke in tension in red and in compression in black (right) (from Chorney et al., 2012).

Using this modeling approach the complex behaviour of rock rupturing due to a set of boundary conditions can be investigated in a controlled fashion. We calibrate a sample to that of sandstone on which a number of triaxial tests are conducted. These simulations are performed over a range of confinement pressures.

Results

The stress-strain curves at different confinement pressures are shown in Figure 2. Their shape is similar to the ones of real lab experiments, so our model can reproduce the global behaviour of sandstone under triaxial compression conditions. Bond breakages are sparse throughout the sample with shear fracture planes nucleating post peak stress. The failure mechanisms show variations between rupture in compression and tension with some shearing (cf Figure 3). The Hudson plots in Figure 3 looks surprisingly similar to the ones obtained for real data by Baig and Urbancic (2010).

We also monitor the total input energy of the system while measuring both the total kinetic energy emitted from bond breakages, and the energy deduced from the moment magnitudes of the microseismic events. We find the kinetic energy to be about 5% of the input energy, and the radiated energy to be 50-100 times smaller than the kinetic energy. We propose the possibility that the radiated energy calculated by using the Gutenberg-Richter relationship between moment magnitude and energy may underestimate the energy incurred from brittle failure (Chorney et al., 2012). When examining the radiated or kinetic energy from brittle failure, in either case, the energy is substantially lower than the input energy. This confirms observations by Maxwell et al. (2008) and Boroumand and Eaton (2012). It seems reasonable to conclude that ductile or slow, aseismic deformation must be a significant term in the energy budget for both the proceeding simulations and for hydraulic fracturing experiments in general.

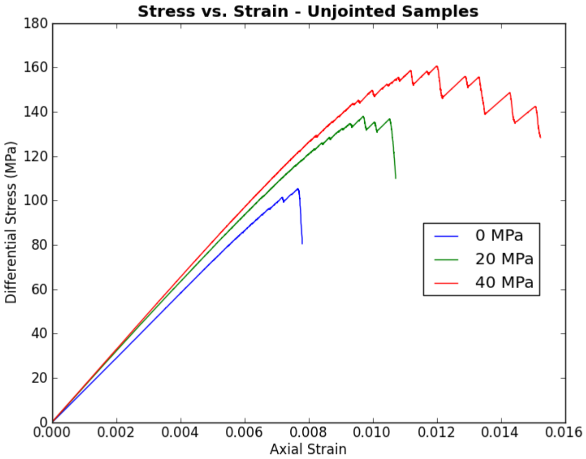

Figure 2: Stress-strain curves for different confining pressures (from Chorney et al., 2012).

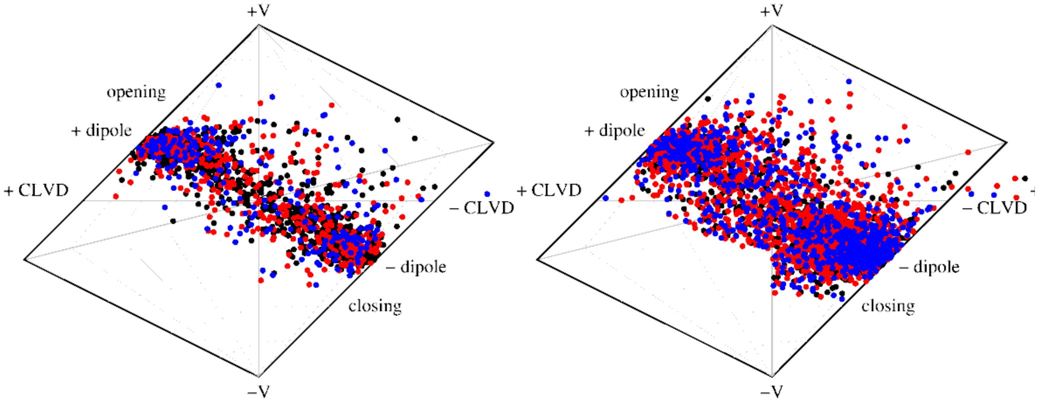

Figure 3: Diagrams of the failure mechanisms for events in the simulations at 0 MPa (left) and 40 MPa (right). The colors represent the time: pre-peak stress events are in black; events happening around peak stress are in red and post-peak events are displayed in blue (modified from Chorney et al., 2012).

Conclusions

An important question in the monitoring of a reservoir is what the exact link is between the recorded microseismicity and the actual geomechanics. Independent observations of event locations, source mechanisms and stresses are used to infer their relationship but often observations are not made at the same location (around wells for stresses, further away and deeper for microseismic events) or at the same scale. The interaction between rupture mechanisms and recorded events can be investigated by the use of modeling.

We have used the bonded particle method to explore the rupture mechanisms of a sandstone model under differing confinement pressures. We find the radiation energy to be about 50-100 times smaller than the kinetic energy from brittle failure. This suggests the possibility that radiated energy calculated by the Gutenberg-Richter relationship may underestimate the energy incurred from brittle failure. Whatever the case, energy from brittle failure is substantially lower than the input energy suggesting ductile deformation is a significant term in the energy budget. These numerical experiments produce both interesting and quantifiable results suggesting the bonded particle method is a viable approach for modeling more complicated scenarios.

Acknowledgements

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