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Simulation of dynamic triggering of microseismic events using a bonded-particle model

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Summary

Microseismic events are commonly recorded during hydraulic fracturing experiments. In microseismic interpretations, each event is often regarded as causally independent and uncorrelated to neighboring ones. In reality, both the rock deformation (static stresses) and transient wave motion (dynamic stresses) associated with microseismic events influence the stress field together with the external loading (fluid injection). It is is thus very likely that many microseismic events are caused by both static and dynamic stress changes. In other words, some events may be caused by propagation of transient waves instead of the stress changes purely related to fluid injection. We study dynamic triggering of microseismicity using numerical simulations of a biaxial deformation test by means of a bonded-particle method. We apply an external vibration at the bottom platen of the model to study the influence of transient wave motion on failure in a controlled fashion. Our results show that the external vibration can both advance or delay the formation of additional cracks depending on the amplitude. Small amplitudes seem to enhance compaction, thus stabilizing the sample and delaying failure. Conversely, large amplitudes have the opposite effect by facilitating failure since the final yield stress is reached sooner.

Introduction

Dynamic triggering is defined as the seismic events triggered by dynamic stress changes from seismic waves (Shearer, 2002). It has been extensively studied in global seismology for natural earthquakes. Belardinelli et al. (1999) found dynamic triggering by linking the spatiotemporal evolution of dynamic stress of the first subevent in the 1980 (M_s 6.9) Irpinia earthquake and the next two subevents. Using numerical simulation, Ferdowsi et al. (2014) reported dynamic triggering of slip in a sheared granular layer. They found that adding external vibrations can lead to accelerated failure, confirming laboratory observations (Johnson and Jia, 2005). We investigate if dynamic triggering also plays a role in acoustic emissions in biaxial deformation tests. Our long-term objective is to investige if more effective hydraulic fracturing treatments can be devised by exploiting dynamic triggering.

Theory and/or Method

Bonded-particle methods(BPM) model a real material as an assembly of particles bonded together according to user-defined microproperties, to mimic macroproperties, e.g. the modulus, of the real material. The particles are linked by contact forces. The method applies the law of motion to each particle and the force-displacement law to each contact iteratively until forces are balanced in the system, within a tolerance range. Under an applied loading, bonds can break in Mode I (tensile) or Mode II (shear) spontaneously when a user-specified strength criterion is exceeded. Bond failure produces acoustic emissions and subsequently propagating seismic waves. Local failure may be due to static and/or transient stress perturbations. BPM has been extensively used to study the mechanical behavior of rocks (Hazzard et al, 2000), interaction between hydraulic fracturing and natural fractures (Zhao and Young, 2011), the energy budget of triaxial tests (Chorney et al., 2012), wave propagation in granular material (O'Donovan, 2012). More details on bonded-particle methods can be found in Potyondy and Cundall (2004).

We simulate a compressional test and monitor the failure development. The rock model is confined at 10MPa (σ_c) and loaded in the axial direction. This is called the reference run. We have another experiment identical to the reference run except we add a sinusoidal vibration at the bottom platen (Fig.1) during a specific time interval to mimic the propagation of waves induced by previous events. The perturbed and reference simulations are compared to examine their history of global axial stress and coordination number. The coordination number is defined as the average number of active contacts per particle. An active contact has either a nonzero normal force or a parallel bond which establishes elastic interaction between particles.

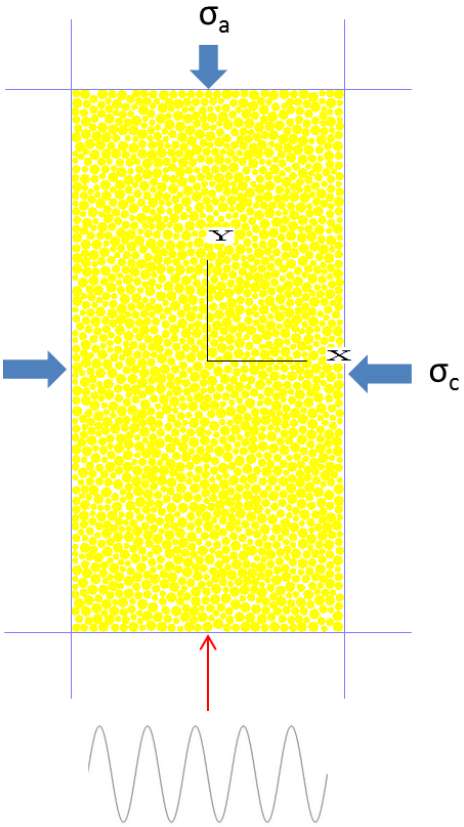

Figure 1. Model setup: the model is confined at stress σ_c and loaded in the axial direction with increasing stress σ_a. An external vibration is applied at the bottom platen during a specified time interval.

Examples

The black curve in Fig.2 shows the stress-time history for the reference simulation. Stresses increase until local failure, seen as a sudden stress drop. Fig.2 also shows the change of coordination number. The initial increase in coordination number is due to the loading which compresses the medium, bringing more particles in touch. Then the contact number decreases due to bond breakages, e.g., at *2.55* and *2.9 ms*, corresponding to two major stress drops. The decrease of coordination number implies the weakening of the model.

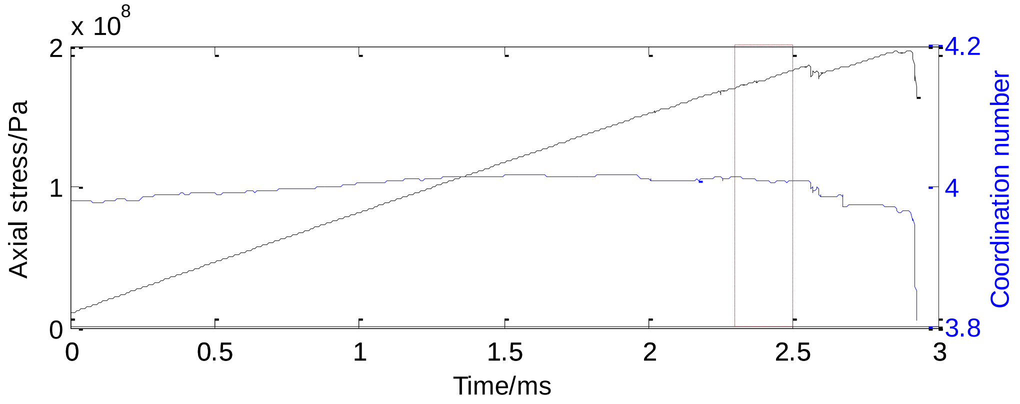

Figure 2. Reference run showing evolution of the axial stress (black curve) and coordination (blue curve). The time duration when perturbation will be added are highlighted in red rectangular.

We add an vibration to the bottom platen to mimic the influence of transient seismic waves. We conduct a series of runs with different amplitudes of vibration. The result is shown in Figure.3 with comparison to the reference run (black curve). The perturbation changes the failure process systematically. The application of vibration during the period *2.3~2.5 ms* leads to immediate mobilization of particles, as expressed by oscillations in the stress-time curves. When the vibration is small (cyan color), the deviation in coordination number recovers to the reference run after the termination of vibration. However for large amplitudes (magenta curves), coordination number changes are more profound, more cracks are forming, thus weakening the model. This leads to an advance of the first stress drop compared with the reference run (around *2.55 ms*). The influence of the vibrations continues after their termination. In the majority of the cases, vibrations with large amplitudes expedite the faliure process, leading to clock advance of the failure. While for most runs with small amplitudes, the failure process is prolonged, especially for the final failure (at *2.9 ms* in the reference run).

Conclusions

Addition of an external vibration during biaxial deformation tests reveals a complex pattern in failure characteristics. Final failure can either be delayed for small vibration amplitudes, likely due to facilitated material compaction, creating a stronger sample, or final failure can be advanced in case of larger amplitudes, likely since the combination of static and transient stresses leads to faster convergence to the yield stress. In both cases, more cracks are observed to form and hence more released energy.

Acknowledgements

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References

Chorney, D., Jain, P., Grob, M., and van der Baan, M., 2012, Geomechanical modeling of rock fracturing and associated microseismicity: The Leading Edge, 31, no. 11, 1348–1354.

Ferdowsi, B., Griffa, M., Guyer, R. A., Johnson, P. A., Marone, C., & Carmeliet, J. (2014). Three-dimensional discrete element modeling of triggered slip in sheared granular media. Physical Review E, 89(4), 042204. Hazzard, J. F., Young, R. P., & Maxwell, S. C. (2000). Micromechanical modeling of cracking and failure in brittle rocks. Journal of Geophysical Research: Solid Earth (1978–2012), 105(B7), 16683-16697.

Hazzard, J. F., & Young, R. P. (2002). Moment tensors and micromechanical models. Tectonophysics, 356(1), 181-197.

Johnson, P. A., X., Jia, 2005, Nonlinear dynamics, granular media and dynamic earthquake triggering: Nature,437, no. 7060, 871-874.

O'Donovan, J., O'Sullivan, C., & Marketos, G. (2012). Two-dimensional discrete element modelling of bender element tests on an idealised granular material. Granular Matter, 14(6), 733-747.

Potyondy, D., and Cundall, P., 2004, A bonded-particle model for rock: International journal of rock mechanics and mining sciences, 41, no. 8, 1329–1364.

Shearer, P. M. (2009). Introduction to seismology. Cambridge University Press.

Zhao, X., & Paul Young, R. (2011). Numerical modeling of seismicity induced by fluid injection in naturally fractured reservoirs. Geophysics, 76(6), WC167-WC180.

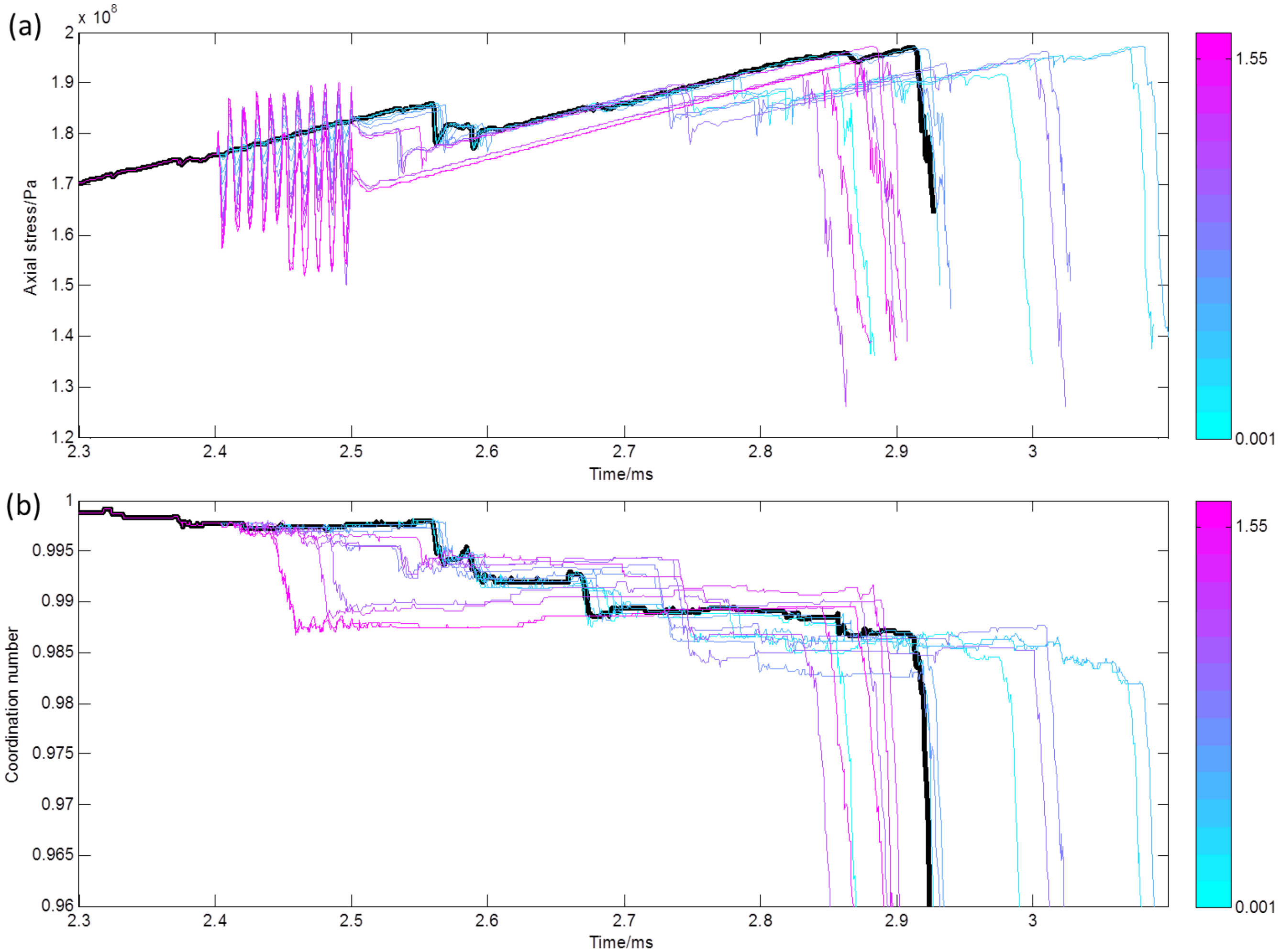

Figure 3. Evolution of (a) axial stress and (b) normalized coordination number of perturbed runs. The reference run is represented with the black curve and all the other curves are coded according to the amplitude of the vibration.