PS13

Keynote Speaker - Lessons from the Lab: Evolution of Fracturing during Deformation in Porous Granular Materials

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SUMMARY

Introduction

The injection or withdrawal of fluids from the subsurface can lead to changes in stress and strain that are sufficient to induce earthquakes on a range of scales. Sometimes this is deliberate, as in controlled hydraulic fracturing for geothermal energy, and sometimes as an unintended consequence of production or re-injection of waste water. However, the processes that lead up to dynamic failure in porous media on a range of scales are complex and non-linear, placing a premium on understanding these sufficiently well to anticipate and mitigate the environmental hazards associated with such subsurface engineering.

In this contribution we describe the results of a fully dynamic, discrete element model for the failure of a porous granular medium under controlled laboratory conditions at the core scale. Despite some simplifications the model reproduces quantitatively many observations of the behaviour observed independently in the laboratory.

Method

The discrete element model is comprised of spherical particles with a log-normal distribution of diameter, conditioned on a typical laboratory rock sample (Mair et al., 2000). The particles are dropped one by one under gravity into a cylindrical container, and allowed to settle, reproducing a realistic structural disorder in the sample, captured for example in the co-ordination number of touching particles. Adjacent particles are then cemented by bonds that can break in tension or shear depending on their relative strength and the local stress. The container is removed, leaving an intact digital rock. This is then subjected to vertical loading at a constant strain rate at the top of the cylindrical sampling.

On loading the strain increases linearly at a constant rate. Local fracturing events associated with the breaking of one or more bonds in a single dynamic cascade can cause acoustic emissions (phonons) that travel through the rock. One of the main advantages of the discrete model is that source rupture properties can be determined within the numerical resolution – no inference from the wave field is needed.

Results

At first the deformation is elastic – stress and strain increase linearly with time, and no acoustic emissions are generated. Acoustic emissions appear quite early in the cycle, well before any sign of a yield point in the stress-strain graph. The rate is initially stable increasing slowly and then more markedly after yield, and asymptotically towards a singularity after peak stress. The form of this evolution in event rate can be fitted with an inverse power law relation, with final dynamic failure occurring at a singularity in the event rate after a period of strain softening.

At the same time the slope b of the frequency-magnitude distribution changes to accommodate a greater proportion of larger events, achieving a minimum at the time of dynamic failure. The clustering properties of the acoustic emissions are quantified by the correlation dimension D in their hypocentres. Both evolve in a manner similar to those in real rocks.

The structure of the sample at the moment of dynamic failure is captured by the image of re-assembled fragments in Fig. 1. The damage zone itself is diffuse and has a complex architecture. The size distribution of intermediate-scale aggregated particles is a power-law, qualitatively similar to that seen in deformation bands in the laboratory.

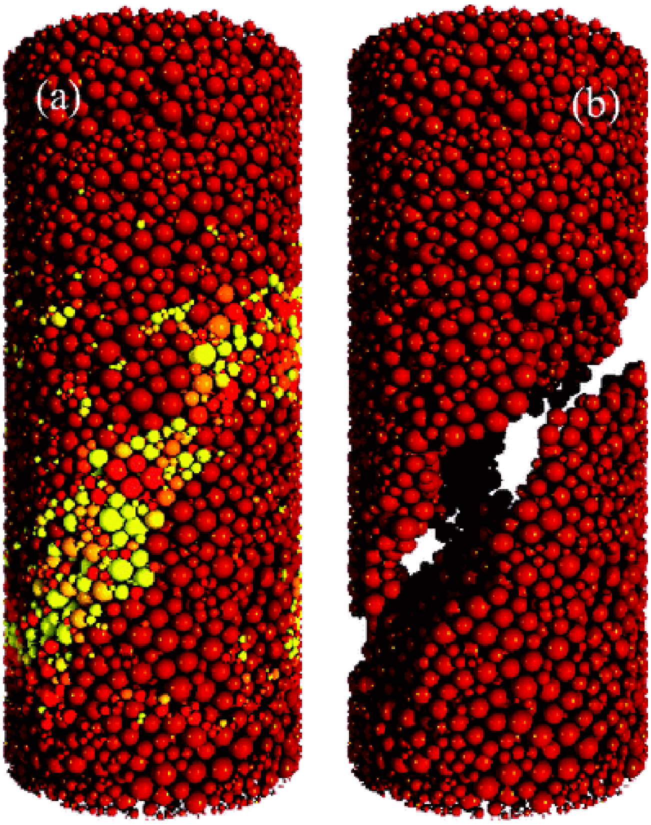

Figure 1 *(a) Re-assembled sample in the final state of the simulation, with particles coloured according to the size of the fragment they originally belonged to. The two big intact blocks are dark red, single particles are yellow, and other colours indicate fragment sizes between these two limits. (b) Image of the two intact blocks, with all disaggregated particles and smaller fragments removed.*

Conclusions

A digital rock has been developed that reproduces for the first time all of the scaling relations observed in the laboratory, and their evolution. With the exception of the power law exponent of the deformation band particle size distribution (most likely because grain crushing is not explicitly included), all of the metrics studies match quantitatively the scaling and temporal evolution of behaviour observed in the laboratory. More work is needed to quantify the effect of a pore fluid, a three-dimensional bounding stress field and time-dependent weakening, but the work here shows the scaling and temporal evolution that emerges spontaneously from the disorder alone provides a surprisingly accurate model for the evolution of fracturing observed in the laboratory.

Acknowledgements

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References

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