Localization of deformation in porous granular media

I.G. Main, F. Kun, G. Pál, and Z. Jánosi

The spontaneous emergence of localized cooperative deformation is an important phenomenon in the development of shear faults and brittle rheology in porous media. It can be studied by empirical observation, by laboratory experiment or by numerical simulation. Here we investigate the evolution of damage and fragmentation leading up to and including system-sized failure in a numerical model of a porous rock, using discrete element simulations of the strain- controlled uniaxial compression of cylindrical samples of different finite size, in comparison with those observed in natural experiments and in the Earth. The model includes structural disorder or fluctuations introduced in the sedimentary processes forming the rock from particles of different sizes, and interactions associated with local rules for contact forces and the breaking of bonds representing cement between particles. Bonds may fail individually, or collectively in dynamic avalanches of contiguous broken bond sites.

As the system approaches macroscopic failure the number of fractures and the energy release rate both increase as a time-reversed Omori law, with scaling constants for the frequency-size distribution and the inter-event time, including their temporal evolution, that closely resemble those of laboratory experiments. Initially-distributed damage progressively localizes in a narrow shear band, ultimately producing a fault ʼgougeʼ containing a large number of poorly-sorted, non-cohesive fragments on a broad bandwidth of scales, with properties similar to those of natural and experimental faults. The position and orientation of the central fault plane, the width of the deformation band and the spatial andmass distribution of fragments resemble those in real deformation experiments.

The width $w$of the deformation band relative to system size $l$decreases systematically as a power law of l, implying deformation becomes progressively sharper for larger samples. The probabilitydistribution of the angle of the damage plane converges to a central limit of around 30 degrees, representing an emergent internal coefficient of friction of 0.7 or so, as observed in the laboratory and in Earth's upper crust. The mass of fragments is power-law distributed, with an exponent that does not depend on system scale, and is near that inferred for experimental and natural fault gouges. The fragments are in general angular, with a clear self-affine geometry which is more pronounced for larger samples. The consistency of this model with experimental and field results confirms the critical roles of (i) pre-existing disorder or spatial fluctuations in material properties at the microscopic scale, elastic interactions, and (ii) finite system size to grain size ratio on the development of faults.

At this stage of modelling there is no explicit time-dependence, for example chemically-enhanced weakening or sub-critical crack growth. We conclude by examining the experimental evidence for such processes, the extent to which these might modify the first order behaviour controlled by the fluctuations and stress interactions alone, and the implications for forecasting or even controlling the likelihood of system-sized failure with suitable monitoring of the 'crackling noise' radiated by the local avalanches.