Induced seismicity associated with fluid injection into a fractured rock mass

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We investigate via numerical modeling the growth of an aseismic rupture and the possible nucleation of a dynamic rupture driven by fluid injection into a fractured rock mass. We restrict to the case of highly transmissive fractures compared to the rock matrix at the scale of the injection duration and thus assume an impermeable matrix. We present a new 2D hydro-mechanical solver allowing to treat a large number of pre-existing frictional discontinuities. The quasi-static (or quasi-dynamic) balance of momentum is discretized using boundary elements while fluid flow inside the fracture is discretized via finite volume. A fully implicit scheme is used for time integration. Combining a hierarchical matrix approximation of the original boundary element matrix with a specifically developed block pre-conditioner enable a robust and efficient solution of large problems (with up to $10^6$ unknowns). In order to treat accurately fractures intersections, we use piece-wise linear displacement discontinuities element for elasticity and a vertex centered finite volume method for flow.

We first consider the case of a randomly oriented discrete fracture network (DFN) having friction neutral properties. We discuss the very different behavior associated with marginally pressurized versus critically stressed conditions. As an extension of the case of a planar fault (Bhattacharya and Viesca, Science, 2019), the injection into a DFN problem is governed by the distribution (directly associated with fracture orientation) of a dimensionless parameter combining the local stress criticality (function of the in-situ principal effective stress, friction coefficient and local fracture orientation) and the normalized injection over-pressure. The percolation threshold of the DFN which characterizes the hydraulic connectivity of the network plays an additional role in fluid driven shear cracks growth. Our numerical simulations show that a critically stressed DFN exhibits fast aseismic slip growth (much faster than the fluid pore-pressure disturbance front propagation) regardless of the DFN percolation threshold. This is because the slipping patch growth is driven by the cascades of shear activation due to stress interactions as fractures get activated. On the other hand, the scenario is different for marginally pressurized / weakly critically stressed DFN. The aseismic slip propagation is then tracking pore pressure diffusion inside the DFN. As a result, the DFN percolation threshold plays an important role with low percolation leading to fluid localization and thus restricted aseismic rupture growth.

We then discuss the case of fluid injection into a fault damage zone. Using a linear frictional weakening model for the fault, we investigate the scenario of the nucleation of a dynamic rupture
occurring after the end of the injection (as observed in several instances in the field). We delimit the injection and in-situ conditions supporting such a possibility.