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Regularization of rupture dynamics along bi-material interfaces: a parametric study and simulations of the Tohoku earthquake

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Faults are often interfaces between materials with different elastic properties. This is generally the case of plate boundaries in subduction zones, where the ruptures extend for many kilometers crossing materials with strong impedance contrasts (oceanic crust, continental crust, mantle wedge, accretionary prism). From a physical point of view, several peculiar features emerged both from analogic experiments and numerical simulations for a rupture propagating along a bimaterial interface. The elastodynamic flux at the rupture tip breaks its symmetry, inducing normal stress changes and an asymmetric propagation. This latter was widely shown for rupture velocity and slip rate (e.g. Xia et al, 2005) and was supposed to generate an asymmetric distribution of the aftershocks (Rubin and Ampuero, 2007).

The bimaterial problem coupled with a Coulomb friction law is ill-posed for a wide range of impedance contrasts, due to a missing length scale in the instantaneous response to the normal traction changes. The ill-posedness also results into simulations no longer independent of the grid size. A regularization can be introduced by delaying the tangential traction from the normal traction as suggested by Cochard and Rice (2000) and Ranjith and Rice (2000)

$$\frac{\partial \sigma_{eff}}{\partial t} = \frac{\alpha\,|v| + v^*}{\delta_\sigma}\,(\sigma_n - \sigma_{eff})$$

where σ_{eff} represents the effective normal stress to be used in the Coulomb friction. This regularization introduces two delays depending on the slip rate and on a fixed time scale.

In this study we performed a large number of 2D numerical simulations of in plane rupture with the spectral element method dynamic and we systematically investigated the effect of parameter selection on the rupture propagation, dissipation and radiation, by also performing a direct comparison with solutions provided by numerical and experimental results.

We found that a purely time-dependent regularization requires a fine tuning rapidly jumping from a too fast, ineffective delay to a slow, invasive, regularization as a function of the actual slip rate. Conversely, the choice of a fixed relaxation length, smaller than the critical slip weakening distance, provides a reliable class of solutions for a wide range of elastic and frictional parameters. Nevertheless critical rupture stages, such as the nucleation or the very fast steady-state propagation may show resolution problems and may take advantage of adaptive schemes, with a space/time variation of the parameters.

We used recipes for bimaterial regularization to perform along-dip dynamic simulations of the Tohoku earthquake in the framework of a slip weakening model, with a realistic description of the geometry of the interface and the geological structure. We finely investigated the role of the impedance contrasts on the evolution of the rupture and short wavelength radiation. We also show that pathological effects may arise from a bad selection of regularization parameters.