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Two-dimensional fully dynamic spectral-element simulations of long-term in-plane shear fault slip

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Earthquake cycle simulations have been performed to successfully reproduce historical earthquake occurrences (eg. Tse and Rice 1986; Stuart, 1988). Most of them are based on a quasi-dynamic scheme, where inertial effects are approximated by the radiation damping term proposed by Rice (1993). This is because a “fully-dynamic” scheme that accounts for all the inertial effects requires quite large CPU and memory cost. Lapusta et al. (2000, 2009) developed a methodology capable of simulating seismic and aseismic slip and gradual process of earthquake nucleation over the entire earthquake cycle. Their fully-dynamic simulations have produced earthquake cycles considerably different from quasi-dynamic ones (Thomas et al., 2014). Those simulations have, however, never been performed for interplate earthquakes at subduction zones, because their models based on a spectral boundary integral method are currently limited to relatively simple fault geometry.

Many studies showed that, for rupture on a dipping fault such as interplate earthquakes at subduction zones, normal stress is altered during faulting due to the interaction with the Earth’s free surface. This change in normal stress not only affects the earthquake rupture process, but also causes the residual stress variation that might affect the long-term histories of earthquake cycles (Duan and Oglesby, 2005). Therefore it is important to account for both the dipping fault geometry and the dynamic effects.

Recently, Kaneko et al. (2011) have performed the fully dynamic spectral-element method (SEM) simulations of the long-term anti-plane fault slip. They combined quasi-static and fully-dynamic SEM schemes for simulating entire earthquake cycles. Aiming at simulating interplate earthquake cycles at subduction zones, we extend their study to simulations for in-plane shear faults and implement our numerical scheme in a dynamic rupture SEM code (Ampuero, 2002). Unlike the anti-plane cases, an in-plane shear fault requires modifications of the fault-perpendicular displacements, which were neglected in Kaneko et al. (2011). While this is implicitly calculated in BIEM (Boundary Integral Equation Method) simulations, we have to explicitly update such values in the domain method like SEM.

We perform fully-dynamic earthquake cycle simulations of long-term slip on a simple planar fault embedded in an elastic medium as described in Kaneko et al. (2011; Fig.2) except that we consider an in-plane fault and use quasi-dynamic updating scheme during the interseismic periods. The central portion of the fault is governed by the rate-and-state friction and both sides of the fault are steady-sliding velocity boundaries. Our numerical code is verified by the convergence of the results with several different discretization sizes, and by approximately the same recurrence times for the cases of anti-plane and in-plane faults, where the same nucleation sizes are obtained by adjusting frictional parameters. The code also works well for a vertical fault in an elastic half space. We discuss the differences between the dynamic and quasi-dynamic simulations.

We also discuss applications of our updated SEM scheme to the dipping fault. For dipping fault rupture such as the 2011 Tohoku earthquake in a homogeneous elastic half-space, we successfully simulate scenarios of single dynamic rupture propagation. However, we have some problems in simulating quasi-static interseismic simulations at present for this case.

Keywords: computational seismology, earthquake cycle, rate and state friction law, spectral element method, fully dynamic, interplate earthquake