Three-Dimensional Elastodynamic Simulations of Seismic and Aseismic Slip History of a Planar Strike-Slip Fault

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Abstract

Simulations of spontaneous slip accumulation in three-dimensional (3D) models enjoy a lot of interest because of their ability to clarify earthquake physics. We have been developing a 3D methodology for simulating the entire seismic and aseismic slip history of a fault subjected to slow tectonic loading. The algorithm, extended from the 3D study by Lapusta et al. (2000), allows us to resolve all stages of spontaneous slip accumulation in a single computational procedure, including quasi-static nucleation processes, dynamic rupture propagation, post-seismic deformation, and aseismic processes throughout the loading period. Simulating long-term deformation histories while accounting for dynamic effects of occasional earthquakes is quite challenging due to a variety of temporal and spatial scales.

We consider a vertical strike-slip fault embedded in an elastic half-space and governed by rate and state friction. On the fault, there is a seismogenic region, 30 km long and 15 km deep, with steady-state rate-strengthening properties. It is surrounded by steady-state rate-strengthening regions that slowly strengthen with applied loading.

We observe the following interesting phenomena:

1. The simulations produce realistic earthquakes and complicated patterns of interseismic slip.
2. The quasi-dynamic model, which ignores wave-mediated stress changes and hence significantly simplifies the computation of dynamic response, qualitatively captures most features of the fully dynamic simulation, but produces more sluggish earthquake behavior and seems unable to reproduce some dynamic features such as the superhedral burst.
3. An asperity (a small circular region 20% stronger than the surrounding fault) causes a supershear burst for the first earthquake in the simulation but not for subsequent events. This indicates that we have variable time stepping.

Snapshots of slip rate distribution during 1st and 2nd events

We add a circular patch of 1 km radius, centered at x = -12 km near the fault. The effective normal stress in the patch is 20%, larger than on the rest of the fault. The other parameters are the same as in Case 1. We find that the heterogeneity causes a superhedral burst for the first event. No Superhedral Burst in the Following Events

Snapshots of velocity distribution in the 1st event:

Case I: Fault with homogeneous seismogenic region

Model Geometry

We simulate earthquake sequences on a fault embedded in an infinite elastic half-space, subjected to slow tectonic loading (T = 35 yrs). The fault properties are extended from 2D studies (i.e., Lapusta et al. 2000), where a steady-state velocity-strengthening region of α = 0.37 and b = 0.01 is surrounded by steady-state velocity-strengthening regions of α = 0.09 and b = 0.11. Nucleation starts in the strip 15 m < x < 10 km at the initial shear stress that is set to be 10% higher than $\mu_{pl}V_o$. For z = 8 km, and the estimated critical nucleation sizes for in-plane problems are $R_{crit} = 10^{-3}$ mm.

The calculation is implemented using spectral boundary integral method. Since the analytical integral kernels are available only for the whole infinite half-space, we make a mirror image of the simulated fault to approximately represent the effect of the free surface.

We use variable time stepping. Throughout the computation, time steps change by more than 10 orders of magnitude, allowing us to do relatively few steps through the quasi-static loading periods, and to consider carefully earthquake nucleation and dynamic rupture propagation periods.

Snapshots of velocity distribution in the 2nd event:

Case II: Fault with a compact heterogeneity

The color scheme depicts the slip rate in m/s on a logarithmic scale. Each snapshot has two time marks. The first one is the assumed time of nucleation. The second one is the current time step multiplied by 30.

We add a circular patch of 1 km radius, centered at x = -12 km near the fault. The effective normal stress in the patch is 20%, larger than on the rest of the fault. The other parameters are the same as in Case 1. We find that the heterogeneity causes a superhedral burst for the first event.