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The Influence of Fault Roughness and Damage Zones in 3D Earthquake Cycle Simulations

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Recent reports related to theme of this project:


Summary:

We are developing a numerical method for simulating full earthquake cycles with multiple events on geometrically complex faults, with heterogeneous material properties, off-fault plasticity and rate-and-state friction. The volume discretization present in our model allows us to incorporate these features, where we use finite differences and weak enforcement of boundary and interface conditions. The method is currently developed to study problems in the 2D plane-strain setting where quasi-dynamic earthquakes nucleate at a fault interface which separates material with differing elastic properties. Our adaptive time-stepping method allows us to integrate quickly through the interseismic period as well as fully resolve quasi-dynamic rupture. We have used this method to investigate the role of bimaterial properties in the earthquake cycle, and have found that material mismatch affects stress conditions on the fault that in turn influences rupture directivity. We found that material
mismatch influences the stress conditions along the fault prior to rupture, which often leads to rupture in the preferred direction (direction of particle motion of the side of the fault with slower shear wave velocity). Stress conditions from past events however can be favorable to allow rupture to propagate in the non-preferred direction however. In addition, we have developed the method to incorporate rough fault geometry and as an initial study have investigated earthquake cycles on a dipping fault.

Progress:

Our group is developing a physics-based earthquake cycle model in order to gain an improved understanding of seismic hazards. This project has focused on the development of the computational framework for simulating long periods of slow deformation from tectonic loading and how this affects the nucleation process and ensuing rupture. The long term goal of our project is the 3D development of the method for simulating both the interseismic period and fully dynamic rupture on geometrically complex faults, with heterogeneous material properties and off-fault inelastic response. We are interested in understanding the evolution of fault-resistance and the stress state prior to a large event, the effects of material and frictional heterogeneities, the role of fault roughness, the extent of damage zones, and how these features influence the earthquake cycle over many thousands of years.

The necessity for modeling the full earthquake cycle, from the interseismic period through dynamic rupture, stems from the fact that the stress state prior to an event remains largely unknown. Thus it is often the case in dynamic rupture modeling that events are nucle-
ated under an assumption of a spatially uniform initial stress state. The method we have
developed however, is capable of evolving the system through the quasi-static period, there-
fore generating self-consistent initial conditions prior to earthquake rupture. We have spent
the past year developing an efficient time-stepping method for earthquake cycles in the
2D plane-strain setting where rupture is generated in a quasi-dynamic setting for computa-
tional efficiency. This is a new development from our initial framework to study cycles
in the anti-plane context which we applied to the study of sedimentary basins (Erickson
and Dunham, 2014). The method solves the equations of static-equilibrium and applies the
radiation-damping approximation to the inertia term.

We are interested in the role that material mismatch plays in the earthquake cycle. Both
laboratory studies and dynamic rupture simulations on a bimaterial fault interface show
that the material contrast can cause the rupture to take a “preferred” direction, where the
rupture propagates predominantly in the direction of particle motion of the side with slower
shear wave velocity. Because increased ground motion damage and triggered seismicity are
often observed in the forward direction of rupture, an understanding of rupture direction
would be helpful in improving seismic hazard estimates.

To study the influence of bimaterial properties we assume a flat fault where tectonic
loading is accounted for at the remote boundaries at a rate $V_p \approx 32$ mm/year. Quasi-
dynamic events nucleate at the fault which separates two sub-domains, denoted (a) and (b),
see Figure 1. The two sub-domains are coupled through interface conditions that enforce
continuity of the traction vector as well as slip across the interface. The left and right
boundaries of the computational domain are periodic. The off-fault material is discretized
with finite differences and boundary/interface conditions are imposed weakly, see Erickson
and Dunham (2014); Erickson and Day (2015) for details.

The fault interface is governed by rate-and-state friction with strike-variable frictional
properties, so that the sides of the fault are velocity strengthening (undergo stable creep
at rate $V_p$) and the center of the fault is velocity weakening (the seismogenic region). In
the rate-and-state framework, the shear stress on the fault, denoted by $\tau$ is equal to fault
strength:

$$\tau = F(V, \psi)$$

where fault strength $F$ is normal stress $\sigma_n$ times the friction coefficient $f$. The fault strength
is a function of slip velocity $V(x,t)$ and a state variable $\psi$ which undergoes its own time
evolution. While there are other forms for state variable evolution, we have chosen to use
the “aging law,” where state can evolve in the absence of slip and may therefore be more
appropriate for models accounting for the period of interseismic loading. Details of the
friction law and the time stepping method to evolve the system through the interseismic
period and quasi-dynamic rupture is described in Erickson and Dunham (2014); Erickson

We are interested in the effect of material mismatch across the fault interface over the
earthquake cycle. The presence of bimaterial properties generates perturbations in normal
stress $\sigma_n$, a consequence of the coupling between slip and normal stress changes introduced
by the material mismatch, not present in the mono-material case, and often referred to as
Figure 2: Cumulative slip profiles for (a) the mono-material problem with $D_c = 8$ mm, (b) $\mu^{(b)} = 25$ with $D_c = 8$ mm, (c) $\mu^{(b)} = 25$ with $D_c = 4$ mm. Slip profiles plotted in solid blue contours every 5-a during the interseismic period (when $\max(V) \leq 1$ mm/s) and in dashed red contours every second during quasi-dynamic rupture.

the “bimaterial effect”, see (Erickson and Day, 2015) and references therein. Perturbations in $\sigma_n$ therefore increase or decrease fault strength and we are exploring how this phenomenon influences stress conditions on the fault, earthquake nucleation and rupture features.

We keep the material density $\rho$ and Poisson’s ratio $\nu$ constant across the fault. We fix $\mu^{(a)} = 30$ GPa, and vary the shear modulus $\mu^{(b)}$. We also consider various values of frictional parameter $D_c$ (critical slip distance in rate-and-state friction). For the mono-material case, with $D_c = 8$ mm, the problem is symmetric about the center point of the fault $x = L_x/2$, see Fig. 2a. The slip profiles are plotted in solid blue contours every 5 years during the interseismic period (when the maximum value of the slip velocity $V$ along the fault is less than 1 mm/s) and in dashed red every second during quasi-dynamic rupture. Two events nucleate simultaneously at either end of the fault, propagate inward and meet at the center of the fault. In Fig. 2b we take a 20% shear modulus contrast ($\mu^{(b)} = 25$ GPa). Given the loading conditions (see Fig. 1), the preferred rupture direction is to the right (particle motion of the side of the fault with lower shear wave velocity). The ruptures all nucleate on the left hand side and propagate to the right (in the preferred direction), relieving stress across the entire length of the fault. This occurs because the normal stress perturbation present due to material mismatch is tensile in the preferred direction and compressive in the non-preferred direction, making rupture to the right more favorable. These results change by reducing $D_c$ to 4 mm, as we do in Fig. 2c. Both small and large events emerge, although all large events propagate in the preferred direction only. The small events do not occur simultaneously, but are separated by several years. The first small event to nucleate propagates in the preferred
direction, which relieves stress on only the left hand side of the fault. The right hand side of the fault however is quite close to failure, allowing the small event to propagate in the non-preferred direction. The ability for some small events to propagate in the non-preferred direction, is made possible by stress concentrations leftover from previous events, detailed in Erickson and Day (2015). We are currently working towards a deeper understanding of what factors allow ruptures to propagate in the non-preferred direction on large, strike slip faults (like the San Andreas Fault in California) which occasionally host events rupturing in the non-preferred direction.

In order to understand the role of fault geometry on the earthquake cycle, we have developed the method to handle non-planar faults, where the finite difference grid conforms to the the fault interface, and the domains are transformed to logical space using the transfinite interpolation method, see Fig. 3 (Erickson and Day, 2014a,b). As an initial study we considered a dipping fault at angle $\theta$ with mono-material properties. In this scenario we load the system from the left and right boundaries, rupture nucleates down dip near the transition from velocity strengthening to velocity weakening. For $\theta = \pi/4$, and $\mu^{(a)} = \mu^{(b)} = 30$ GPa, small events emerge periodically, which fail to rupture all the way to Earth’s free surface. These are followed by much larger events which do propagate the length of the fault. It will be interesting to see how more complex fault geometries (like large-scale bends and branches, as well as small scale roughness) influence the earthquake cycle, which we plan to do in future work.

Figure 3: (a) The fault dips at angle $\theta$ with a velocity weakening zone reaching to the surface, and transitioning to velocity strengthening down-dip. The physical domains of sides (a) and (b) are both transformed to logical space using the transfinite interpolation method. (b) Cumulative slip for $\theta = \pi/4$, $D_c = 8$ mm, mono-material $\mu^{(a)} = \mu^{(b)} = 30$ GPa, where slip is plotted in solid blue contours every 5-a during the interseismic period, and every second during quasi-dynamic rupture.