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COLLABORATIVE PROPOSAL -- DYNAMIC RUPTURES FROM SIMULATIONS OF LONG-TERM SLIP HISTORIES: A FEASIBILITY STUDY

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Summary

Seismic-hazard driven research on ground-motion prediction and earthquake source dynamics requires the generation of large suites of earthquake rupture models consistent with observed source complexity. While it is trivial to create kinematic source models with slip heterogeneity for ground-motion calculation, this class of models is often strongly simplified in terms of its temporal rupture evolution and may also violate basic principles of earthquake source physics. Pseudo-dynamic models, in contrast, represent an improvement over simple kinematic ruptures, but the question remains on how to generate the initial stress/slip distribution whose properties reflect the geometrical complexity and spatial variability of fault friction of natural faults. Dynamic rupture models share a similar difficulty in defining initial and boundary conditions for heterogeneity in stress and friction that lead to sustained dynamic events which leave behind a heterogeneous stress field which produces aftershock seismicity or subsequent larger events.

In this project we perform 3D-simulations of long-term slip histories using quasi-dynamic multi-cycle simulations (*Hillers et al.*, 2006; *Hillers et al.*, 2007) governed by rate- and state-dependent (RS) friction (*Dieterich*, 1979; *Ruina*, 1983). Each simulation is controlled by a 2D distribution of the critical slip distance, L, and depth dependent frictional rate parameters (a and b). The simulation results are then be used to construct the appropriate input for spontaneous dynamic rupture calculations: stress drop, strength excess, critical distance are extracted from the multi-cycle simulations and then used in full-dynamic single-event rupture modeling (*Pitarka*, 1999; *Dalguer and Day*, 2007) under the slip-weakening friction law (*Ida*, 1972; *Andrews*, 1976). In this process the microscopic RS critical slip distance, L, is scaled to the macroscopic slip weakening distance, d_c, using two different relations. Subsequent spontaneous rupture modeling produces full sustained rupture models for a group of events while some events cannot exceed an initial nucleation zone, or stop in the middle of the prescribed faulting plane. Our approach provides a physics-based way of generating suites of dynamic rupture models on a strike slip fault plane with imposed structural heterogeneity, incorporating laboratory derived friction and spatially heterogeneous control variables.

Below we briefly summarize the key steps taken in our approach and describe the initial results we obtain, along with the difficulties encountered in the course of the work. This research has been presented at the 2008 Annual SCEC meeting as a poster, and the discussions and interactions with SCEC scientists indicated great interest in this work, leading also to a number of helpful comments and constructive criticism.

Multi-cycle simulation with rate- and state-dependent friction

The geometry of our earthquake source model consists of a 2D vertical strike-slip fault plane embedded in a homogeneous half space. The fault is constantly loaded by aseismic plate motion below 24 km depth. The upper 24 km are governed by the "aging" formulation of the rate- and state-dependent friction law. We apply *depth-dependent a and b*, where horizontal regions of different stability are defined by depth-dependent changes of the *a-b* parameter (*Ruina*, 1983). The unstable region between 3-12 km depth is parameterized by $b>a$, leading to an effective velocity-weakening behavior, where earthquakes can nucleate. Velocity strengthening above and below that zone is governed by $b<a$; note that earthquakes can propagate into these strengthening regions. Moreover, we develop *heterogeneous 2D L distributions*, using "spatial random-fields" of *L*, characterized by correlation lengths along strike and depth (*Mai and Beroza*, 2002), and the range of *L* values distributed on the fault. The inhomogeneous distributions of the time-invariant critical slip distance *L* are used to parameterize different degrees of geometrical or structural complexity on the 2D numerical fault plane (*Hillers et al.* 2007; *Hillers and Wesnousky*, 2008): relatively short correlation lengths and a lognormal distribution of *L* values generates frequency-size statistics that resembles that of more mature fault zones. Using this parameterization in most of our current simulations results in a sufficient number of synthetic large events to be used for subsequent ground motion simulations.

Spontaneous dynamic rupture modeling with slip-weakening friction

We performed ~100 spontaneous rupture calculations under the slip weakening friction law using the input models from the multi-cycle simulation. The only free parameter we need to determine in the spontaneous rupture is the slip weakening distance (d_c), which can be effectively inferred from the critical distance, *L*, and rate- and state-variables saved during the multi-cycle simulation. While there is no simple analytical transformation from rate-and-state variables to the slip-weakening parameterization, we can utilize similarities between the stress drop, strength excess, and the weakening distances to carry out a conceptual comparison of the two friction parameterizations (*Bizzarri et al.*, 2001). Monitoring temporal stress evolution, recording the maximum stress at each cell during an event and then subtracting the stress value from the beginning of the event (at the trigger instance), t_0, we can measures the strength excess; similarly, stress drop is the difference between t_0 and the stress at event termination. This approach improves earlier (*Cocco and Bizzarri*, 2002). *Bizzarri and Cocco* (2003) derive an estimate to obtain d_c as a function of the state variable at the rupture onset, θ_{init}, the velocity v_0 at the instance when the state variable reaches its minimum θ_0 during the breakdown process, and the local *L* value. We adopt this result, thus extracting these parameters associated with an individual event during our simulations, by tracking the velocity and state evolution during an instability, and record θ_{init} and v_0. These values will then be used to compute the spatially variable scaling factor between *L* and d_c .

Main results

Coseismic slip re-scaling: As shown by *Lapusta and Liu* (2008), quasi-dynamic simulation generate ~20% less coseismic slip than the full-dynamic simulation. To resolve this discrepancy, we may need to re-scale the resulting slip distribution from the quasi-dynamic simulation and re-compute static stress drop from the re-scaled slip distribution before they are used in the full-dynamic simulation.

Rough slip models: Simulated earthquake rupture sequences should exhibit some of the complexities observed in natural seismicity (i.e. heterogeneity in the rupture propagation and final slip maps). Although the overall properties of our simulated slip distributions agree well with those of past earthquakes, most synthetic slip maps in the current simulation database show only little complexity, i.e., they consist mostly of one large-slip area and are thus rather smooth. This smoothness is a direct consequence of the limiting factors of our current implementation: (1) the range of the 2D L-distributions that favor the propagation of large events is limited to the lognormal L-distributions with short correlation lengths, while spatial smoothness in L translates into smooth slip distributions; (2) a higher spatial resolution (smaller cell size h) allows for a wider L-range, hence favoring the formation of small-scale features during rupture (*Hillers and Wesnousky*, 2008); (3) while fully elasto-dynamic calculations show a wide range of rupture behavior (rupture jumping or pulse-like rupture bursts *Ripperger et al.*, 2008), the quasi-dynamic rate-and-state implementation produces fairly homogeneous crack-like rupture propagation patterns. To improve upon these limitations requires significant modifications of the current numerical technique. However, as a test we utilize canonical 2D chessboard L-distributions (*Hillers et al.*, 2006). Although the resulting distributions of the stress drop, strength excess and L-d_c scaling look less realistic compared to results from simulations using random-field L distributions, some of the final slip maps do show several large slip areas, and may thus help to assess the importance of complexity in the relevant parameter distributions.
Nucleation phase: Initial nucleation phases are also monitored and saved in the multi-cycle simulation, but it is difficult to directly use this information in the full-dynamic modeling at the current stage because of the limited resolution in the quasi-dynamic modeling.
Differences between fully- and quasi-dynamic solutions: *Lapusta et al.* (2000; 2008) compare the differences between the quasi-dynamic solution, which is numerically advantageous yet approximates dynamic effects of the rupture propagation, and the computationally expensive, physically more accurate elasto-dynamic solution, which incorporates stress changes during rupture due to elastic wave propagation. The quasi-dynamic approach results in smaller slip velocities, slower rupture speeds, less co-seismic slip, and correspondingly smaller stress drops. *Lapusta et al.* (2008) explored the possibility of tuning quasi-dynamic simulations by using a reduced shear wave speed to increase the similarity between quasi- and elasto-dynamic solutions, and found that some of the inadequacies can be reduced – a potential departure for future work.

Conclusions

Combining a multi-cycle quasi-dynamic simulation using the rate- and state-dependent friction law with a single-event full-dynamic simulation using the slip weakening friction law, we are able to provide a physics-based approach of generating a series dynamic source models on a single fault system through a cycle of the fault evolution. The intrinsic features of dynamic ruptures are investigated through full dynamic spontaneous rupture modeling under the slip weakening friction law, using physically self-consistent dynamic input parameters inferred from the multi-cycle simulation. The full-dynamic rupture simulation shows that dynamic input models generated in the multi-cycle simulations can be successfully used in subsequent spontaneous rupture modeling, although some re-scaling of the input models may be necessary to resolve the numerical discrepancy between the quasi- and fully-dynamic simulations.

Figures

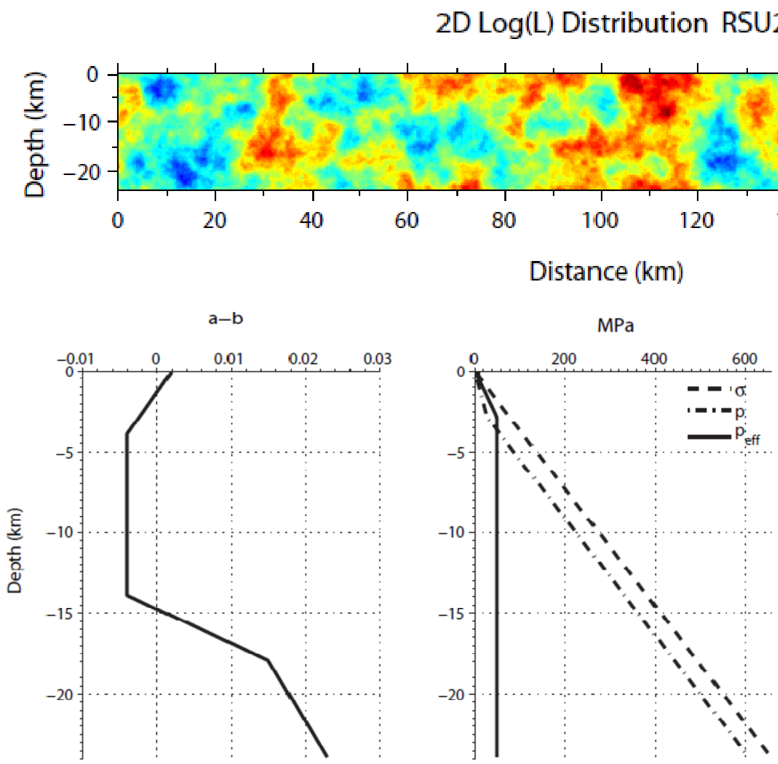

Figure 1. (Top) 2D *L* distribution obtained by spatial random field modeling (Mai and Beroza, 2002). (Left) Depth-dependent input profiles (*a* and *b*, normal stress (σ_n) and pore pressure (p)).

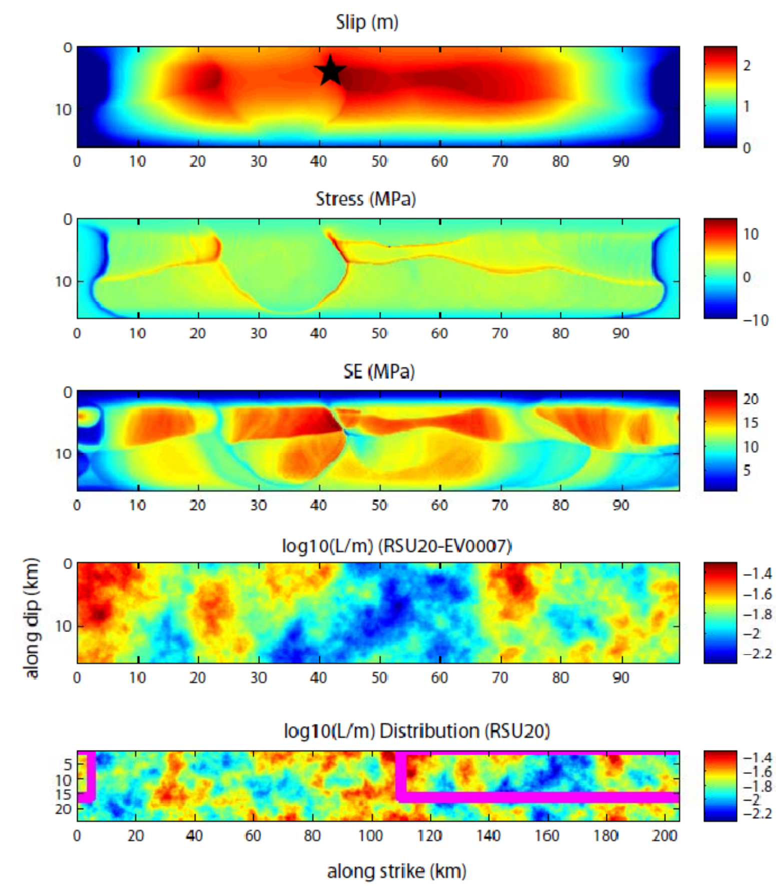

Figure 2. Input models generated by the multi-cycle simulation (stress drop, strength excess, *L*). The bottom plot indicates the location of a selected event.

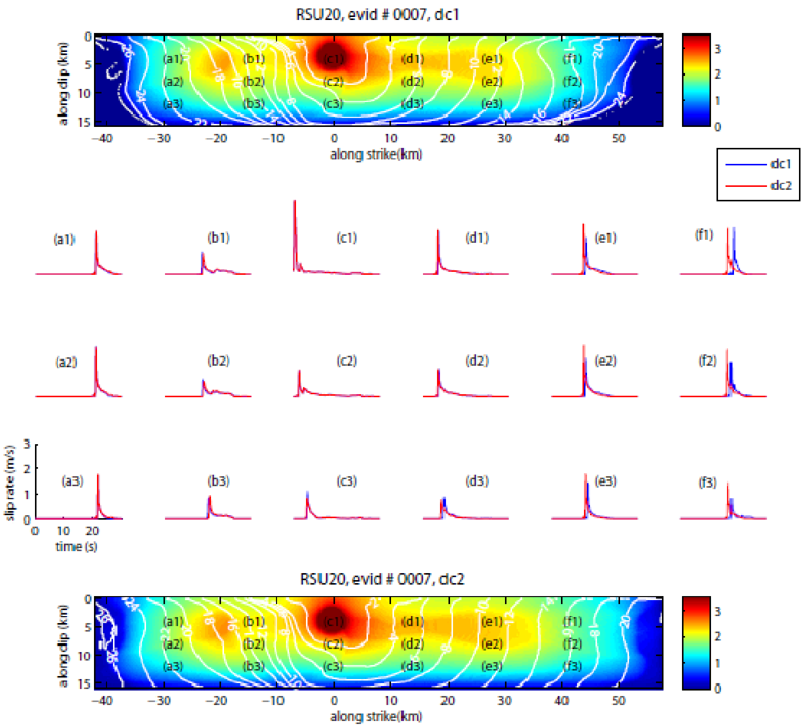

Figure 3. Spontaneous rupture models with d_{c1} and d_{c2}. This event occurred in a region of relatively small L. In this event the two L to d_c conversion schemes produce about the same d_c distribution, generating similar rupture propagation patterns and slip evolution on the fault.

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