3D Simulations of Earthquakes on Parallel Offset Faults with Homogeneous Stress Conditions

Kayla A. Kroll, Keith B. Richards-Dinger, James H. Dieterich, and David D. Oglesby
kroll5@llnl.gov; keithrd@ucr.edu; dieterichj@ucr.edu; and david.d.oglesby@ucr.edu

LLNL-POST-891088; Prepared by LLNL under Contract DE-AC52-07NA27344.

Abstract

Several recent large earthquakes, (e.g. 2002 M_w7.9 Denali, AK, 2010 M_w7.2 El Mayor-Cucapah, Mx, and the 2016 M_w7.8 Kaikoura, NZ events) have ruptured up to a dozen fault segments. Understanding how ruptures are able to jump across geometrical complexities is of critical importance for estimates of seismic hazard and earthquake forecasting, as earthquake magnitudes are strongly affected by total rupture length. Large event clusters such as the Landers-Big Bear-Hector Mine sequence in CA and the 2011 cluster in Christchurch, NZ are of additional concern in forecasting and hazard analysis. Here, we employ two earthquake rupture codes (FaultMod & RSQSim) to investigate the characteristics of rupture propagation (e.g. stress drop, slip, renucleation location, and jump distance) across parallel strike-slip faults with uniform initial stresses at increasingly larger offsets. We also explore the possibility that time-dependent nucleation effects inherent to rate-state friction cause individual fault segments to slip as part of a large event cluster, rather than in a single jumping rupture at larger offsets. We perform this analysis for fault systems classified by high (relative fault strength S=0.49) and low (S=1.25) initial stress states.

We show that results from RSQSim compare favorably with those from FaultMod. We find that the average slip is inversely related to offset in both simulations. However, slip is largely asymmetric in FaultMod, with more slip on the nucleating fault compared to the receiver fault. Average source and receiver fault stress drops in both methods vary considerably with larger offsets. Receiver fault renucleation locations lie within lobes of increased static stress for extensional and compressional offsets. For models with S=1.25, the maximum jump distance is ~0.5 km for both simulation methods. For models with S=0.49, FaultMod simulations jump larger offsets (~3 km) than those produced with RSQSim (~2 km). However, when large event clusters are considered in RSQSim, the jump distances increase and are nearly equal to those in FaultMod. These results indicate that 1) RSQSim is capable of producing ruptures similar to those of the fully dynamic simulations, 2) rupture characteristics vary as a function of offset, and 3) time-dependent nucleation allows for larger jump distances. This work suggests that large event clustering due time-dependent rupture effects should also be considered in earthquake forecasts and seismic hazard analysis.

Model Set up

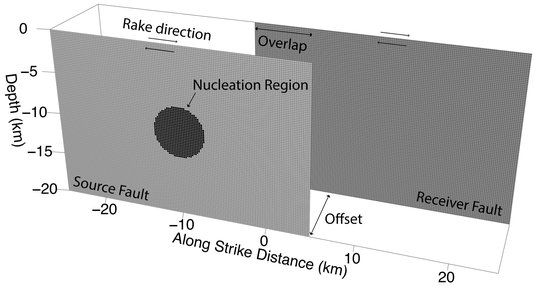

Figure 1: Example of the fault system used in the 3D simulations of rupture across a stepover. This system consists of two 30 km by 20 km right-lateral strike-slip planar fault structures that overlap by 10 km. We systematically increase the offset from 200 m in extension or compression at 100 m and 200 m intervals for RSQSim and FaultMod, respectively. Ruptures are always nucleated on the source fault and jump onto the receiver fault. Extensional steps are defined by positive offsets and are generated by moving the receiver fault to create a left step. Models are controlled by slip-weakening friction in FaultMod and rate- and state-dependent friction in RSQSim. All ruptures are artificially nucleated at the center of the source fault (black circle; 3 km radius). We nucleate ruptures in FaultMod by reducing the yield stress and in RSQSim by reducing the state-variable.

Slip Distribution

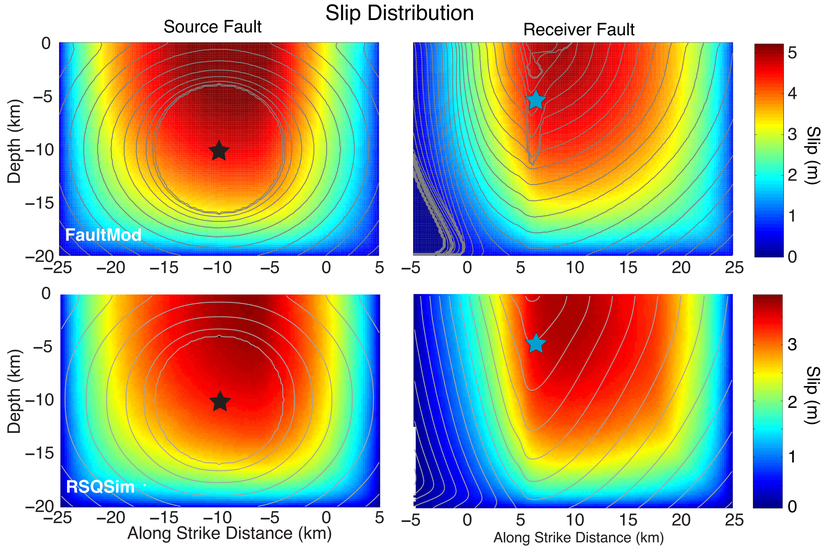

Figure 2: Representative slip distribution for the source (left) and receiver (right) fault for FaultMod (top) and RSQSim (bottom), simulations of rupture across a 600 m compressional stepover for low pre-stress conditions (i.e. S = 1.25). Nucleation is forced in a patch of the source fault with 3 km radius, centered on the black star. The renucleation location on the receiver fault it shown by the blue star. Color shows the maximum slip on each element in the fault system, given by the color bar to the right. The qualitative pattern of slip is very similar in both models with the maximum slip occurring up-dip of the nucleation patch in the source fault and near the surface above the re-nucleation location on the receiver fault. Maximum slips are larger in the FaultMod simulation most likely due to dynamic stress changes that are not included in the RSQSim computation. Consequently, the seismic moment, magnitude and stress drop are larger in FaultMod. Rupture time is contoured at 0.5 sec. Ruptures in FaultMod consistently propagate slower than in RSQSim. This is like because rupture propagation in RSQSim is controlled by stress transfer rather than a speed limit.

Renucleation Locations

The renucleation location is defined as the first position along strike of the receiver fault that nucleates and leads to a through-going rupture. In RSQSim, the renucleation location is easily defined and can be determined automatically in 3D. In some FaultMod simulations, particularly at larger offsets, a small region near the surface of the receiver fault begins to slip, however, upon inspection of rupture animations, it is clear that this feature is not the location where the renucleation actually occurs. It is likely a result of the traction-free surface boundary condition in the simulation. Therefore, the renucleation location for all FaultMod simulations had to be visually inspected after the application of additional rules for automatic determination. Here, we define the renucleation location in FaultMod to be the 3D location where rupture begins and continues propagate bi-laterally. This rule is applied to all extensional offsets and compressional offsets at stepover widths larger than 1000 m. At closer compressional offsets, the node at that ruptures first on the receiver fault accurately describes the renucleation location.

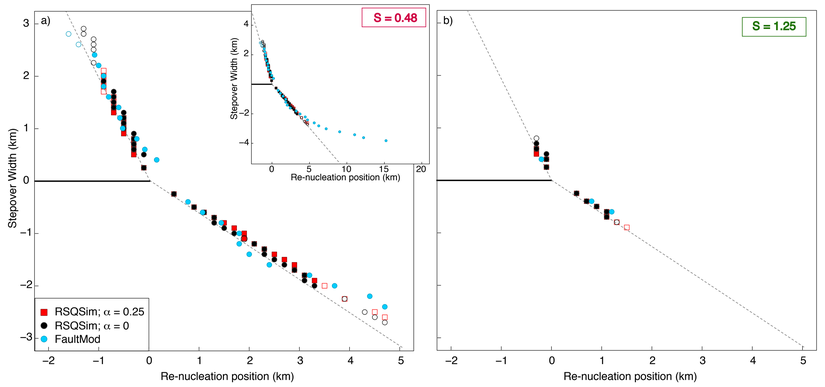

Figure 3: Renucleation locations for FaultMod (blue circles) and RSQSim (red and black symbols) simulations. Left) High pre-stress models with S = 0.48. Right) Low pre-stress models with S = 1.25. With rate-state friction (RSF), the affect of normal stress on the state-variable is controlled by the parameter, α, which ranges between zero and the nominal coefficient of friction (here, $\mu_0 = 0.6$). Large values of α indicate a strong normal stress dependence. In this study we use α values of 0.25 (red symbols) and 0 (black symbols). Open symbols for RSQSim indicate the renucleation position on the receiver fault for an event that ruptures as part of a large event cluster due to delayed nucleation affects inherent to RSF. Open symbols for FaultMod simulations indicate a receiver fault rupture that is delayed by 30 sec or more after the source fault rupture. Note that these are not "delayed nucleation events" as in RSQSim, since the FaultMod simulations employ slip-weakening friction. Dashed lines show the move out of renucleation locations described by Harris and Day, (1993) for 2D simulations with high pre-stress conditions when S = 0.49 (their Figure 6). We see good agreement between our RSQSim and FaultMod renucleation locations and with those of Harris and Day (1993) who suggest the moveout is controlled by the pattern of static stress imparted by the source fault rupture. The maximum jump distances for high pre-stress models are ~2800 m in extension for both models when time-dependent jumps are considered. FaultMod compressional ruptures jump offsets up to 3800 m, whereas RSQSim ruptures jump offsets up to 2600 m. For low pre-stress models, the maximum jump distances are significantly reduced in both models to less than 800 m extensional and compressional offsets.

Slip Profiles

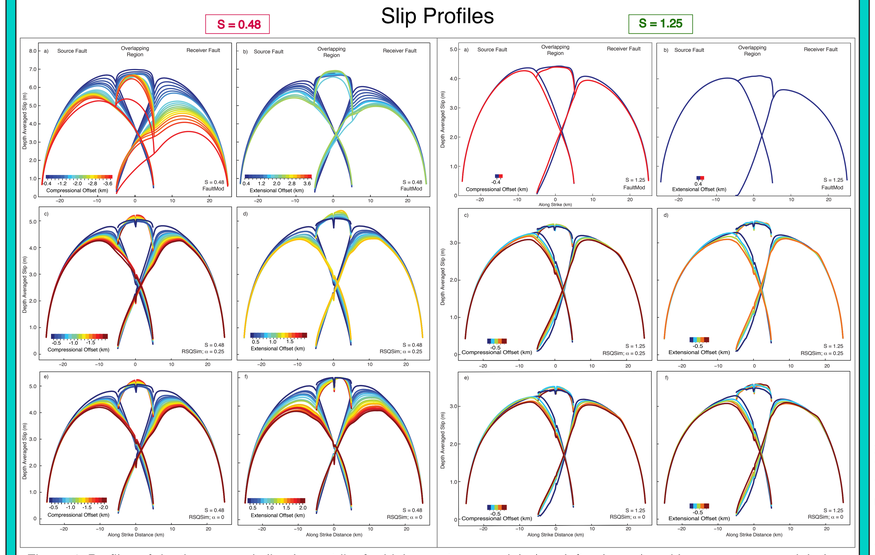

Figure 4: Profiles of depth averaged slip along strike for high pre-stress models (two left columns) and low pre-stress models (two right columns) for FaultMod simulations (top row), RSQSim with $\alpha = 0.25$ (middle row) and RSQSim with $\alpha = 0$ (bottom row). Color represents the width of the offset given by the color bar in each panel. Compressional offsets are shown in columns 1 and 3 and extensional offsets are shown in columns 2 and 4. Average slip in all models decreases with increasing offset distance. The slip in the FaultMod solutions becomes increasingly more asymmetric for increasing offsets, with receiver fault slip decreasing by ~50%. Combine slip across both faults because less elliptical (as might be expected for a single fault of the same length) as offset increases. Slip profiles are more varied for compressional steps than extensional steps. The average slip in RSQSim models also decreases as offset increases, however slip profiles are much more symmetric than those from the FaultMod solutions. Low and high pre-stress models show similar results.

Average Stress Drop and Slip as a Function of Offset

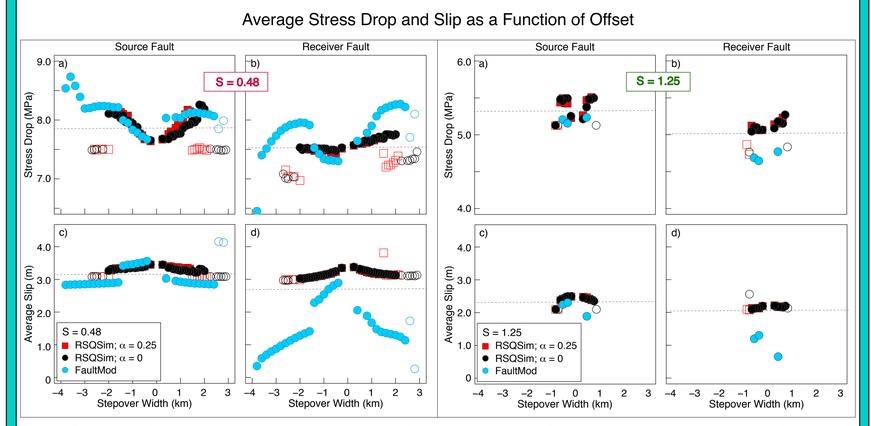

Figure 5: Average stress drop (top row) and average slip (bottom row) for high pre-stress (left two columns) and low pre-stress (right two columns) on the source fault (columns 1 and 3) and receiver fault (columns 2 and 4). As in Figure 4, FaultMod results are shown by the blue circles, RSQSim with $\alpha = 0.25$ are in red, and $\alpha = 0$ in black. The mean for each population is given by the gray dashed line. In general, average slip and stress drops for both simulation methods are within 5 - 15% of the population mean. Stress drops generally increase as a function of increasing offset, while the average slip deceases for both values of pre-stress for both simulation methods. While this appears to contradict elastic behavior, we note that the variability in the linear relationship between slip and stress drop is small. Decreases in slip on both the source and receiver faults is due to the reduction in stress transfer between faults as the stepover distance increases, which has a more pronounced affect on receiver fault slip. Dynamic stress transfer and the asymmetric slip distribution lead to larger variability in the FaultMod simulation results compared to RSQSim.

Time-dependent Rupture Jumps

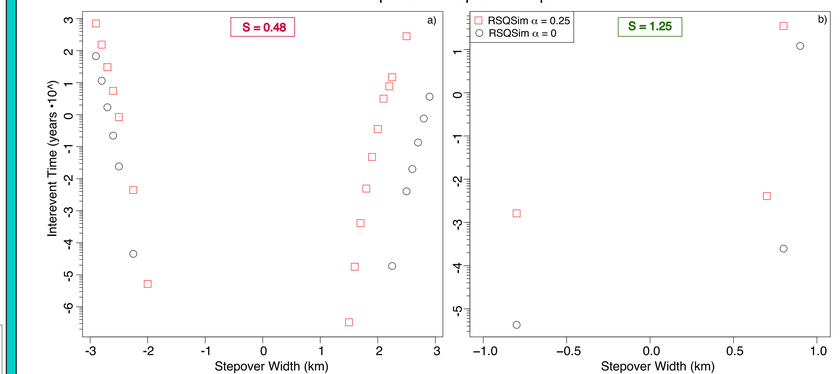

Figure 6: It is possible that slip on the source fault is such that it does not cause the receiver fault to rupture immediately. In such instances, it is likely that the receiver fault is brought closer to failure. This phenomenon is similar to aftershock triggering, is referred to as delayed nucleation, and can be explained by RSF. The time between successive source and receiver fault ruptures, known as the interevent time, allows us to determine which receiver fault events are linked to source fault ruptures, thus forming a large-event cluster. The Interevent time is plotted for all offsets larger than those at which an immediate jump occurs. The time of rupture on the receiver fault is advanced by the source fault rupture. In these models, slip on the source fault advanced the time of receiver fault rupture by more than 3.2 million years. When considering these time-dependent nucleation events (i.e. large event clusters), the maximum jump distance increases for both step directions and for both levels of pre-stress. Consideration of time-dependent nucleation effects increases the probability of rupture jumps across fault stepovers (Figure 7).

Probability of Time-Dependent Rupture Jumps in Multi-cycle Simulations

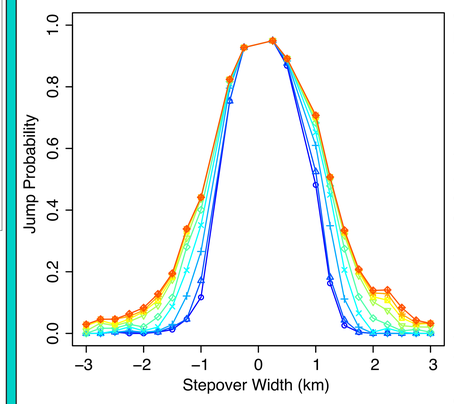

Figure 7: RSQSim is capable of simulating events over multiple earthquake cycles. This provides the opportunity of explore the probability of rupture jumping across an fault stepovers over thousands of years. In these simulations, the stresses evolve naturally due to fault interaction. This figure is an example of the jump probability as a function of offset for every event that jumps the stepover in a 100,000 year long simulation. The color represents the interevent time (ranging from 0 to 4 years) between successive source and receiver fault ruptures. The probability of a rupture jumping a stepover of a given width increases as the interevent time increases. As discussed in Figure 6, delayed nucleation is an inherent property of RSF, which is believed to be operating on natural faults. This result may explain the discrepancy between the maximum jump distances observed in nature (~5 km) and those produced in numeric simulations (~5 km with high pre-stresses, but only 1 km with low). It may be that these pre-stress conditions are much higher than those exhibited by natural fault systems. If so, the initial conditions clearly bias the jump results. As the results presented here are from a simulation where stresses evolve more realistically, they may be a better representation of a natural system.