Dynamic and Kinematic Modeling of Backthrust Faulting on the Ventura Fault System

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Investigators:
Dr. Percy Galvez, Mr. Jeff Bayless, and Dr. Paul Somerville
(AECOM)

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A. Introduction

Ground motion prediction equations are based on a single fault plane representation of the earthquake source, and therefore do not provide reliable estimates of ground motions from complex fault systems such as conjugate backthrust faults. Kinematic ground motion simulation can be used to estimate the ground motions from such complex faults, but there are many uncertainties in the details of how the main and backthrust fault segments interact which can only be addressed using dynamic rupture modeling. We need to understand how rupture initiates on the backthrust fault, so that we can kinematically model its location and timing. In the modeling of individual fault segments, we need to know which source parameters such as rise time, slip duration and final slip should be determined from the seismic moment of the backthrust segment rather than those of the overall event.

B. Objectives

The objective of this proposal is to use dynamic rupture modeling to investigate the conditions under which conjugate backthrust faulting can occur, and to use kinematic ground motion simulations, guided by the dynamic modeling, in broadband simulations of conjugate backthrust faulting. Special focus is placed on the Ventura fault system (Figure 1), which is the subject of a special fault study area.

Hubbard et al. (2015) proposed two alternative interpretations of how the Ventura Anticline is growing (Figure 1). In the first, the region below the Ventura Avenue anticline is highly fractured and close to failure. In this scenario the up-dip rupture in the Ventura fault could enhance the failure below the Ventura anticline and increase the uplift at the surface. Ma et al. (2012) ran dynamic simulations in which the fractured region in the toe of the wedge fails due to an up-dip rupture leading to doubling of the uplift. Plastic strain represents a significant portion of the total moment release in undrained cases.

In the second scenario, a pre-existing backthrust embedded in the faulted region below the Ventura anticline branches off the Ventura fault, as shown on the right side of Figure 1. An up-dip rupture on the Ventura fault reaches the branch and ruptures the back thrust, creating more uplift at the surface. Xu et al. (2015) performed dynamic rupture simulations and provide mechanisms of how backthrust faulting can be activated. However, up-dip rupture on the Ventura fault may not extend to shallow depths if the rupture branches onto the backthrust fault. This is one of the features we explore using dynamic rupture modeling.

C. Approach

Dynamic Rupture Modeling

We use SPECFEM3D (Galvez et al., 2014, 2016) to perform dynamic rupture modeling for branching faults. The fault geometry and the mesh for the Ventura-Lion fault is shown in Figure 2. The rupture process is simulated by rate-and-state friction with aging law (Dieterich, 1979). To compute the initial parameters, i.e (stresses, friction and state) prior to one event, we perform earthquake cycle modeling. We use a quasi-dynamic solver with adaptive time step to resolve the interseismic period and naturally nucleate the earthquake. Once the event nucleates, we import the stresses, friction and state to the dynamic solver to perform dynamic rupture modeling. In this way, we do not need to prescribe or guess the initial conditions needed for the dynamic modeling. Figure 3 shows the setup for the earthquake cycle modeling. The Dc (characteristic slip distance for rate and state friction) follows a lognormal distribution based upon Luo.
et al. (2017). The (a-b) and normal stress depth profiles are shown in Figures 3b and 3d respectively. Using this set up, we run the quasi-dynamic solver and nucleate events on Ventura fault. We nucleated several earthquakes along the Ventura fault and chose the event in Figure 3c. After the nucleation, we import stresses, state, slip velocity to the dynamic solver to perform splay ruptures.

Figure 4 shows the sequence of the splay rupture. Once the rupture nucleates on the deep section of the Ventura fault, the rupture propagates up-dip and reaches the junction with the Lion backthrust fault in about 5 seconds. At the junction, the rupture splays and breaks the Lion backthrust and dies out after a few seconds, breaking only the deep section of the Lion fault. The second rupture on the Ventura fault continues and breaks the free surface. Finally we take the rupture time, the slip functions, and final slip to perform kinematic rupture modeling, as described in the next section.

![Ventura - Lion Fault.](image)

Figure 2. (a) Ventura fault system. Source: Hubbard et al. (2015). (b) 3-D mesh built with CUBIT and used for dynamic rupture modeling. The global grid size of one element is 500 meters. We use 5 interpolation points in each element, therefore the minimum grid size will be around 125 meters around the fault plane.
Figure 3. (a) Characteristic slip distance taken for the earthquake cycle modeling. Based on Luo et al. (2017), we imposed log normal distribution of $D_c$ (b) along the Ventura-Lion faults. (d) The normal stresses and (a/b) profiles chosen for this study. For the cycle modeling, a quasi-dynamic solver (QDYN, Luo et al., 2017) was used. Using this solver we nucleate the event as shown in (c).

Figure 4. The snapshot sequence of the splay rupture for Ventura-Lion faults. This earthquake nucleates on the ramp of the Ventura fault.
Kinematic Rupture Modeling

We use the Graves and Pitarka (2015; GP hereafter) broadband simulation method, and perform the broadband kinematic simulations on the SCEC Broadband Platform. Our first trial, “Trial A” uses three pieces of information from the dynamic simulations: the fault dimensions, the final slip distributions, and the rupture initiation timing on both faults. With these in hand, we created a GP source description standard rupture format (SRF) file for the Ventura and Lion faults separately. These SRFs use the GP recipe for the scaling and shape of the slip rate functions on each subfault (which is a modified version of the Liu et al. (2006) slip rate function.) The resulting Ventura and Lion ruptures have M7.0 and M6.0, respectively. The final slip distributions on each fault, along with rupture front contours, are shown in Figure 5. We then performed a broadband (0-10 Hz) simulation to obtain the simulated ground motions at the sites of interest (Figure 6). We selected 11 sites; one is the approximate location of the city of Ventura, and the other 10 are comprised of two fault-normal arrays on the hanging wall of the Ventura and Lion faults, located at 10 and 40 km west of the eastern end of the faults (Figure 6). The results for the Ventura city site are presented in this report.

On our second trial, “Trial B”, we used the full slip velocity time histories on each subfault from our dynamic simulations in the kinematic simulation. This trial also used the fault dimensions and rupture initiation timing on both faults from the dynamic simulations. To use the SCEC Broadband Platform, it was necessary to convert the slip velocities on each subfault into SRF format, and then proceed with the broadband simulations.

Figure 7 shows a comparison of the two types of slip velocity time histories at four locations on the Ventura fault. The blue slip velocities are created using final slip from the dynamic simulations, but with the GP recipe for slip rate. The red slip velocities are taken directly from the dynamic simulations.

Figure 5. Final slip used in the kinematic modeling on the Ventura (left) and Lion (right) faults.
Figure 6. The Ventura (blue) and Lion (black) rupture model grids, along with the simulation sites (red).

Figure 7. A comparison of slip velocity functions at various locations on the Ventura fault. Red lines are those from the dynamic simulations in this study and blue lines are from the Graves and Pitarka (2015) recipe using the final slip from the dynamic simulations as input. X and Z coordinates are along strike and down dip coordinates, with the origin at the eastern end of the surface trace of the Ventura fault.
D. Results

Trial A used the fault dimensions, the final slip distributions, and the rupture initiation timing on both faults from the dynamic simulations in the kinematic simulation. Trial B used the full slip velocity time histories on each subfault from our dynamic simulations in the kinematic simulation. The resulting ground motions and response spectra of the Ventura, Lion, and combined contributions are shown in Figures 7, 8 and 9. The contribution of the Lion backthrust fault to the combined ground motion is quite small. Use of the full dynamic slip velocities instead of the kinematic slip velocities results in much lower ground motions at intermediate and long periods, and increases the contribution of the Lion backthrust.

Figure 7. Trial A waveforms at the Ventura city site, resulting from the kinematic broadband simulations.

Figure 8. Trial B waveforms at the site of interest, resulting from the kinematic broadband simulations.
E. Conclusions

We used dynamic rupture modeling to investigate the conditions under which conjugate backthrust faulting can occur, and to use kinematic ground motion simulations, guided by the dynamic modeling, in broadband simulations of conjugate backthrust faulting. Special focus is placed on the Ventura fault system, which is the subject of a special fault study area. Once the rupture nucleates on the deep section of the Ventura fault, the rupture propagates up-dip and reaches the junction with the Lion backthrust fault in about 5 seconds. At the junction, the rupture splays and breaks the Lion backthrust. The rupture front breaks the Lion backthrust fault and dies out after a few seconds, breaking only the deep section of the Lion fault. The second rupture on the Ventura fault continues and breaks the free surface. We used the rupture time, slip functions, and final slip to perform kinematic rupture modeling of the ground motions.

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F. References


