2020 SCEC progress report for Shaw

“Developing earthquake simulators for use in seismic hazard estimates: Improving fault geometry and source physics and contributing to WGCEP”

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We report here on two papers which were completed in the last year. The first one, (*Shaw*, 2019), was published in the Bulletin of the Seismological Society of America. The second one, (*Milner, Shaw, et al., 2020*) was submitted for publication. In addition to these publications, research related to the ground motions arising from the simulations was being pursued. We briefly discuss these three areas, the published results, the submitted paper, and the new research areas below.

Published paper on improved loading conditions

”Beyond Backslip: Improvement of Earthquake Simulators from New Hybrid Loa ding Conditions” (*Shaw*, 2019). A standard approach to loading earthquake simulators involving complex fault system geometries is the backslip method, where fault slip-rates are specified and stressing rates giving the specified slip-rates are calculated and imposed on the system. This often results in singularities in stressing rate at fault boundaries, and unrealistic hypocenters of events associated with these singularities. In this paper we present a new generalized hybrid loading method which combines the ability to drive faults at desired slip-rates, while loading with more regularized stressing rates, allowing faults to slip in a more natural way. The resulting behavior shows improvement in the depth dependence of seismicity, the distribution of sizes of events, and the depth dependence of slip. We discuss as well the physical implications of the new type of loading.

One figure illustrating some behavior improvements from the new hybrid loading model concerns the depth distribution of seismicity. With traditional backslip, one finds an excess of hypocenters near the edges of faults. This is due to the singular stressing rates arising from typically imposed slip profiles. Figure 1 shows the hypocenters with the new hybrid loading conditions, contrasted with those under a more traditional backslip loading. We see a vastly improved depth distribution with hypocenters now concentrated mainly at seismogenic depths (Nazareth and Hauksson, 2004). Interestingly, we also see a feature often discussed in the literature of having larger events preferentially initiating deeper arising in the hybrid loaded model (Manighetti et al., 2005; Mai et al., 2005).

Submitted paper on hazard from fully deterministic physical models

”A Prototype Probabilistic Seismic Hazard Model for California Constructed with Fully-Deterministic Physical Models” (*Milner, Shaw, et al., 2020*)

We investigate the efficacy of a multi-cycle deterministic earthquake simulator as an extended earthquake rupture forecast (ERF) for use in generating simulated ground motions for probabilistic seismic hazard analyses (PSHA). Although use of deterministic ground motion simulations in PSHA calculations is not new (e.g., CyberShake), prior studies relied on kinematic rupture generators to extend empirical ERFs. Fully-dynamic models, which

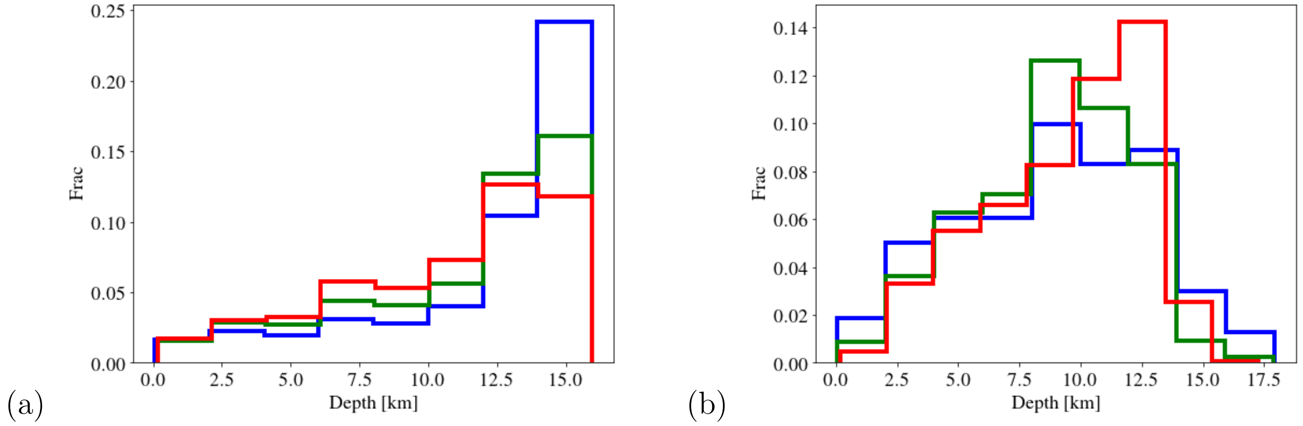

Figure 1: Depth distribution of seismicity (a) Backslip loaded. (b) Hybrid loaded. Colors represent different magnitude ranges, with M5 (5 ≥M< 6) in blue, M6 in green, and M7+ (7 <M) in red. Note the traditional backslip loaded model has an intense band of hypocenters on the bottom of the fault. For the hybrid loading, in contrast, most of the hypocenters occur in the seismogenic layer. Note also the feature of a higher proportion of the largest events initiating deeper relative to the moderate sized events in the hybrid loading model, something that emerges in the model.

simulate rupture nucleation and propagation of static and dynamic stresses, are still computationally intractable for the large simulation domains and many seismic cycles required to perform PSHA. Instead, we employ the Rate-State Earthquake Simulator (RSQSim) to efficiently simulate hundreds of thousands of years of M ¿ 6.5 earthquake sequences on the California fault system. RSQSim produces full slip-time histories for each rupture, which, unlike kinematic models, emerge from frictional properties, fault geometry, and stress transfer; all intrinsic variability is deterministic. We use these slip-time histories directly as input to wave propagation codes with the Southern California Earthquake Center (SCEC) BroadBand Platform for one-dimensional models of the Earth and SCEC CyberShake for three-dimensional models to obtain simulated deterministic ground motions.

Resultant ground motions match empirical ground motion model (GMM) estimates of median and variability of shaking well. When computed over a range of sources and sites, the variability is similar to that of ergodic GMMs. Variability is reduced for individual pairs of sources and sites, which repeatedly sample a single path, which is expected for a non-ergodic model. This results in increased exceedance probabilities for certain characteristic ground motions for a source-site pair, while decreasing probabilities at the extreme tails of the ergodic GMM predictions. We present these comparisons and preliminary fully deterministic physics-based RSQSim-CyberShake hazard curves, as well as a new technique for estimating within- and between-event variability through simulation.

Some figures illustrating some of the results are included below. Figure 2 illustrates a seris of improvements made in the source physics of the simulator to improve the propagation velocity to obtain more realistic directivity effects. These improvements, include: (1) improving the accuracy of the stiffness matrix by considering not just the finite area of the source patch, but the finite area of the receiver patch as well. (2) eliminating fixed sliding speed approximation during fast earthquake slip, and replacing it with slip velocity which is determined by the shear impedance relationship. (3) rather than instantaneous stressing rate updating, introducing a time delay to stress rate updating on other elements which is motivated by a retarded green's function effect from finite wave speeds. An approximation of this effect uses a fixed delay for all elements related to the source patch dimension, to maintain a minimum of updating steps and preserve the fast algorithm. Together these source physics improvements lead to improved propagation velocity.

Figure 3 shows spectra plots of an individual event, and an ensemble of events, compared with empirical Ground Motion Models (GMMs). This gives an example of how the model ground motions are calibrated and validated against empirical observations.

Figure 4 shows an example of a full hazard curve calculated at a single site from the full simulator catalog using a full 3D velocity model in Cybershake. This illustrates a fully deterministic calculation of PSHA using the deterministic sequence of events and source motions from the siumlator, with no stochastic aspects.

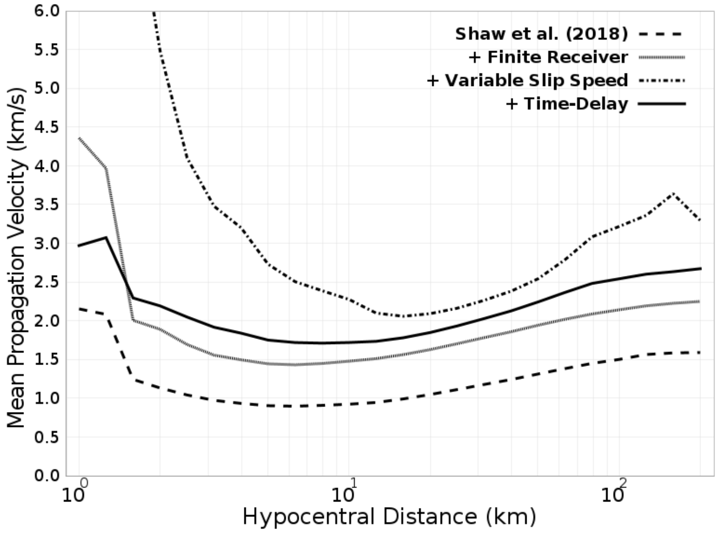

Figure 2: Propagation velocity as a function of patch hypocentral distance for four different RSQSim parameterizations, each of which incorporates a new feature over the previous model. The base model is the catalog used in *Shaw et al.* (2018), plotted with a dashed line. The first modification, plotted with a dotted line, adds a new finite receiver patch capability to the stiffness matrix calculations. The second modification, plotted with a dotted and dashed line, adds variable slip speed capabilities to RSQSim with stepwise updating of sliding velocity on a patch during earthquake slip. The final model, plotted with a solid line and used for PSHA calculations in this study, also includes a time-delay to the static-elastic interaction. From [Milner, Shaw, et al., 2020].

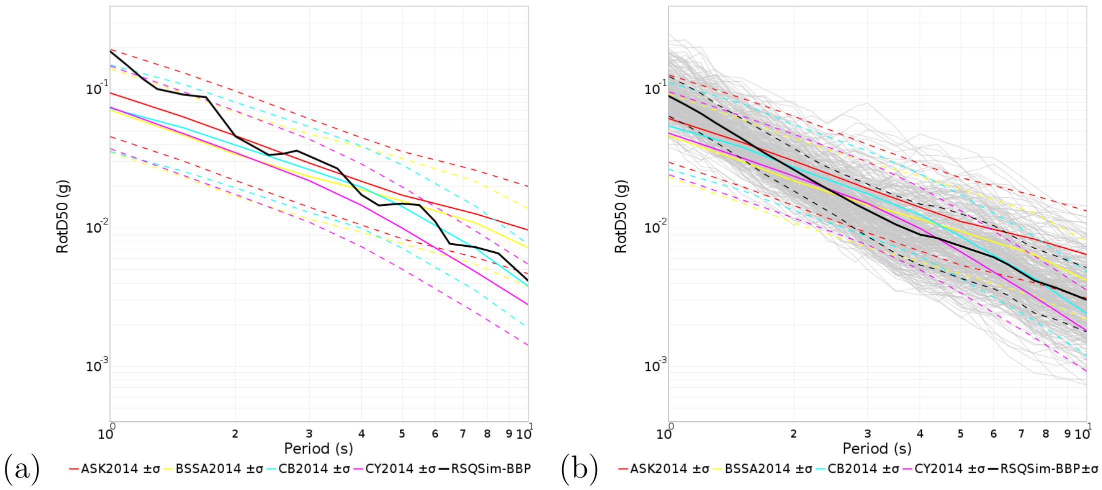

Figure 3: Example ground motions from simulator events compared with Ground Motion Models (GMM). RotD50 spectra for site USC from ruptures on the Mojave section of the San Andreas Fault, computed with a one-dimensional (1D) velocity structure with VS30=500 m/s in the Southern California Earthquake Center (SCEC) BroadBand Platform (BBP). (a) Spectrum for the M 7.48 rupture on the Mojave section of the San Andreas Fault in Figures 2 and 3 plotted as a thick black line. (b) Spectra for 185 different $7.0 \leq M \leq 7.5$ RSQSim ruptures on the Mojave section of the San Andreas Fault simulated at USC plotted with thin gray lines, the mean of all 185 ruptures as a thick black line, and the mean plus and minus one standard deviation with dashed black lines. GMM comparisons (with plus and minus one standard deviation bounds marked with dashed lines) are plotted with colored lines. GMM predictions are slightly different for (b) because distributions are averaged across those predicted for each of the 185 RSQSim ruptures (rather than for a single M 7.48 rupture in (a)). From [Milner, Shaw, et al., 2020].

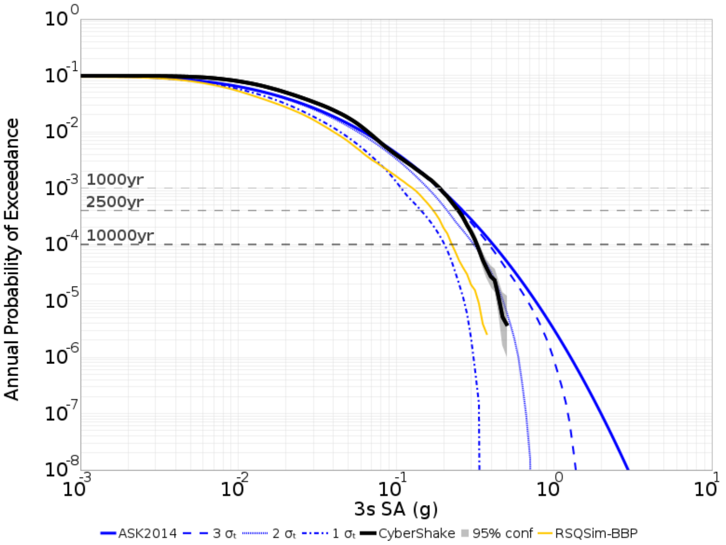

Figure 4: Example of full deterministic PSHA calculation using 3D cybershake and simulator ruptures, done at a single site. RSQSim simulation hazard curves at USC. CyberShake (3D) is plotted with thick, black lines. (a) ASK2014 GMM comparisons curves in blue, with the complete hazard curve plotted as a thick solid line. GMM curves computed from truncated log-normal distributions at three-, two-, and one-sigma are plotted with dashed, dotted, and dotted and dashed lines respectively. The 1D BBP hazard curve is included in yellow, and 95% confidence bounds assuming a binomial distribution (representing sampling uncertainty from a finite catalog duration) on the 3D simulated curve as a gray shaded region. From [Milner, Shaw, et al., 2020].

References

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