Continued Development of OpenSHA/UCERF3 in Support of Operational Earthquake Forecasting, Hazard Assessment, and Loss Modeling

Report for SCEC Award #18142
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Investigators: Thomas H. Jordan (USC), Edward H. Field (USGS), & Kevin Milner (SCEC)

I. Project Overview

A. Abstract

In the box below, describe the project objectives, methodology, and results obtained and their significance. If this work is a continuation of a multi-year SCEC-funded project, please include major research findings for all previous years in the abstract. (Maximum 250 words.)

Substantial progress was made comparing the RSQSim full-cycle physics-based earthquake simulator to UCERF3 (published in Shaw et al. 2018), and computing deterministic ground motions with RSQSim rupture slip-time histories. We found strong agreement in hazard maps computed with the UCERF3 and RSQSim models. We also compared the RSQSim ruptures with the UCERF3 multi-fault rupture plausibility criteria, which found 80% agreement. Initial CyberShake PSHA calculations with RSQSim were completed in 2018. Previously, CyberShake has combined empirically-based ERFs (UCERF2, accessed through OpenSHA) with kinematic rupture generators to produce three-dimensional deterministic physics-based PSHA estimates. In 2018, we added capabilities in OpenSHA to use RSQSim catalogs as input to CyberShake, producing the first ever three-dimensional end-to-end physics-based PSHA assessment. These RSQSim-based CyberShake hazard curves were the first PSHA estimate computed without assuming any statistical distribution in the earthquake rate model, rupture generation, or ground-motion estimation.

We also rewrote much of the UCERF3-ETAS code in order to make it accessible to outside researchers. We held a training session at the 2018 SCEC Annual Meeting which was attended by 6 researchers, who learned to run the model locally and on HPC resources. The code, scripts, and examples are published on GitHub (https://github.com/opensha/ucerf3-etas-launcher). Additional progress was made on the USGS Fast-ETAS operational aftershock forecasting model, powered by OpenSHA. This included a new ability to efficiently compute hazard maps from ETAS forecasts directly on the users machine in minutes.

B. SCEC Annual Science Highlights

Each year, the Science Planning Committee reviews and summarizes SCEC research accomplishments, and presents the results to the SCEC community and funding agencies. Rank (in order of preference) the sections in which you would like your project results to appear. Choose up to 3 working groups from below and re-order them according to your preference ranking.

Earthquake Forecasting and Predictability (EFP)
Ground Motions
Community Modeling Environment (CME)

C. Exemplary Figure

Select one figure from your project report that best exemplifies the significance of the results. The figure may be used in the SCEC Annual Science Highlights and chosen for the cover of the Annual Meeting Proceedings Volume. In the box below, enter the figure number from the project report, figure caption and figure credits.

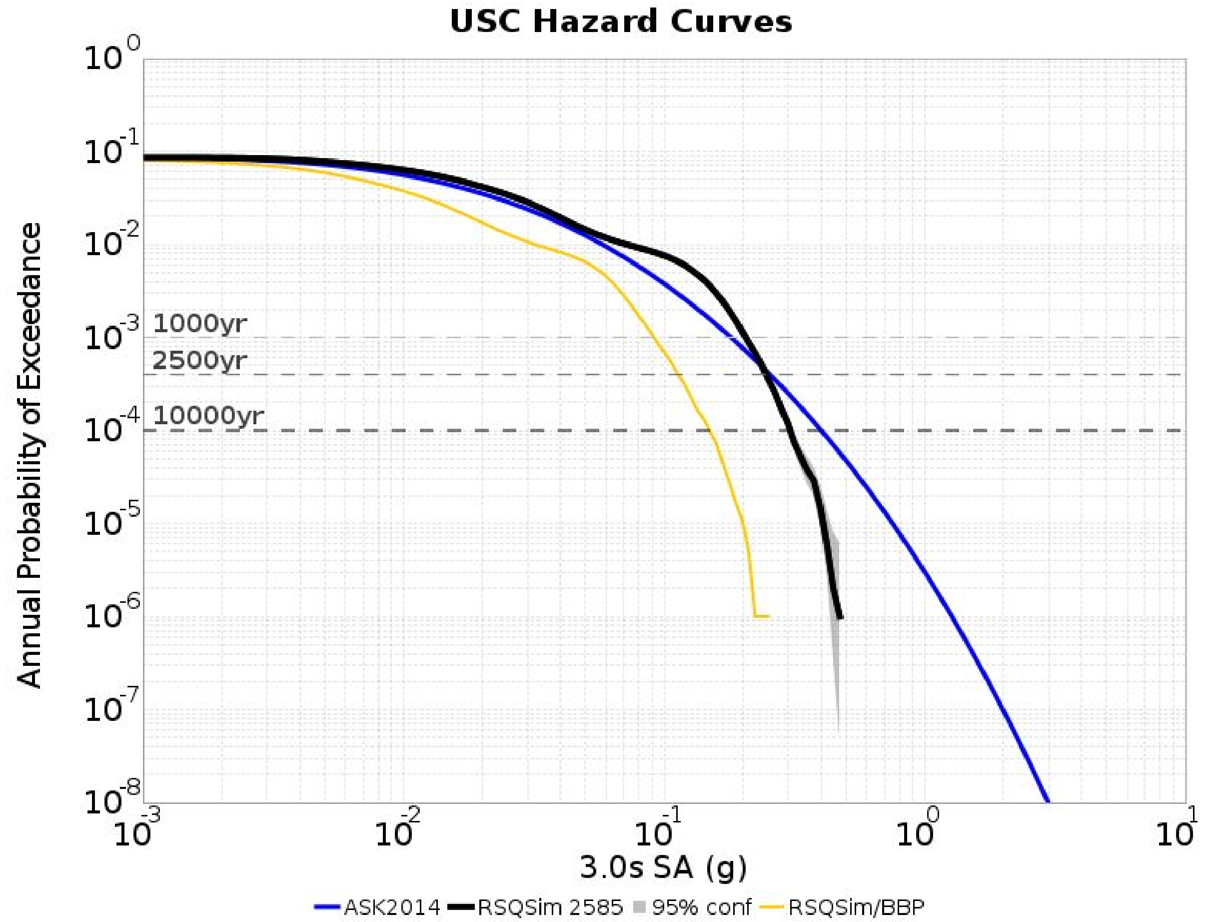


Figure 1
First probabilistic seismic hazard curves computed only with deterministic, physical models (RSQSim). This study uses rupture descriptions (including slip time histories) from RSQSim directly as input to the CyberShake 3-D PSHA simulation platform. Prior Cybershake studies have used kinematic rupture generators to extend empirical earthquake rupture forecasts. Initial hazard curves for the RSQSim catalog used in Shaw et al. (2018) is shown above, computed at the USC CyberShake site. The 3-D CyberShake-RSQSim curve is in black, 1-D BroadBand Platform-RSQSim in gold, and an empirical ground motion model (Abrahamson et al. 2014) in blue.
Credits: Kevin Milner (USC)

D. SCEC Science Priorities

In the box below, please list (in rank order) the SCEC priorities this project has achieved. See *https://www.scec.org/research/priorities* for list of SCEC research priorities. *For example: 6a, 6b, 6c*

P4.c, P4.d, P5.a, P5.c, P5.d

E. Intellectual Merit

How does the project contribute to the overall intellectual merit of SCEC? *For example: How does the research contribute to advancing knowledge and understanding in the field and, more specifically, SCEC research objectives? To what extent has the activity developed creative and original concepts?*

One of the three bullets in SCEC's mission statement is to "Integrate information into a comprehensive, physics-based understanding of earthquake phenomena." To that end, we computed the first probabilistic seismic hazard study using exclusively three-dimensional, physics-base models (RSQSim and CyberShake) in this reporting period. Validation efforts are underway to further evaluate the results, but we have demonstrated the feasibility of a fully-physics-based PSHA approach.

F. Broader Impacts

How does the project contribute to the broader impacts of SCEC as a whole? *For example: How well has the activity promoted or supported teaching, training, and learning at your institution or across SCEC? If your project included a SCEC intern, what was his/her contribution? How has your project broadened the participation of underrepresented groups? To what extent has the project enhanced the infrastructure for research and education (e.g., facilities, instrumentation, networks, and partnerships)? What are some possible benefits of the activity to society?*

OpenSHA, and it's implementation of the UCERF3 models, continues to be a valuable tool for the SCEC community. OpenSHA is used by engineers, researchers, and students. OpenSHA is also used in conjunction with CyberShake to generate seismic hazard maps and to generate data products for the UGMS project. We held two training sessions at the SCEC Annual Meeting on OpenSHA products. The first was part of the greater "SCEC Software Products Workshop" which was attended by 37 members of the SCEC community. We also redesigned, documented, and released a version of the UCERF3-ETAS model for wider use. This included a small workshop for 6 researchers at the SCEC AM who learned to use the model and run simulations on HPC resources.

G. Project Publications

All publications and presentations of the work funded must be entered in the SCEC Publications database. Log in at *http://www.scec.org/user/login* and select the Publications button to enter the SCEC Publications System. Please either (a) update a publication record you previously submitted or (b) add new publication record(s) as needed. If you have any problems, please email *web@scec.org* for assistance.

SCEC Contribution #8093:
Shaw, B. E., Milner, K. R., Field, E. H., Richards-Dinger, K., Gilchrist, J. J., Dieterich, J. H., & Jordan, T. H. (2018). A physics-based earthquake simulator replicates seismic hazard statistics across California. Science Advances, 4(8). doi: 10.1126/sciadv.aau0688.
SCEC Contribution #8033:
Field, E. H., & Milner, K. R. (2018). Candidate Products for Operational Earthquake Forecasting Illustrated Using the HayWired Planning Scenario, Including One Very Quick (and Not-So-Dirty) Hazard-Map Option. Seismological Research Letters, 89(4), 1420-1434. doi: 10.1785/0220170241.

II. Technical Report

The technical report should describe the project objectives, methodology, and results obtained and their significance. If this work is a continuation of a multi-year SCEC-funded project, please include major research findings for all previous years in the report. (Maximum 5 pages, 1-3 figures with captions, references and publications do not count against limit.)

A. Scientific and implementation Advances

We summarize our advances and contributions as follows:

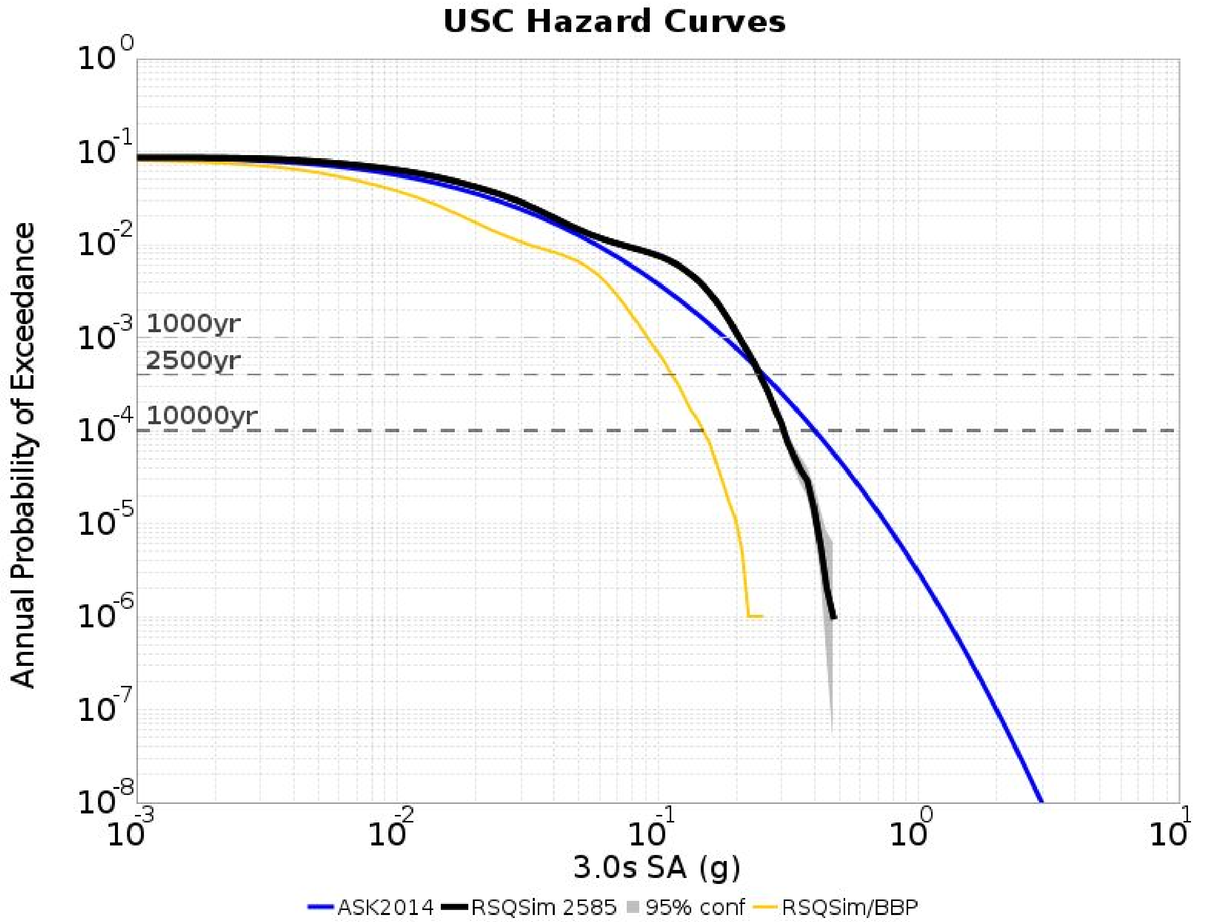
- Published of a suite of example Operational Earthquake Forecasting data products for the USGS HayWired scenario earthquake in SRL (Field & Milner 2018).
- Finalized CyberShake web delivery system for the SCEC Utilization of Ground Motion

Simulations (UGMS) committee, which was released in April 2018 for use by the engineering community: https://data2.scec.org/ugms-mcerGM-tool_v18.4 (collaborators: C. B. Crouse, Edric Pauk, and the UGMS committee). The work is documented in a paper published for the 11th National Conference in Earthquake Engineering (Crouse et al., 2018).

- Developed a new generalized UCERF3-ETAS-Launcher to allow other researchers to run UCERF3-ETAS simulations for custom scenario events. Held a training session for six researchers at the 2018 SCEC Annual Meeting. Developed extensive documentation which is available, along with the code, on GitHub: https://github.com/opensha/ucerf3-etas-launcher).
- Developed preliminary implementation of algorithms to automatically map finite fault surfaces from observed earthquakes to UCERF3 subsections for elastic rebound calculations in UCERF3-ETAS. This is a required step towards operationalization of the UCERF3-ETAS model.
- Initial retrospective tests of UCERF3-ETAS have begun in CSEP in the Fall of 2018, in collaboration with CSEP Developer Bill Savran.
- Released a beta version of ETAS-based operational aftershock forecast (OAF) application ("Fast-ETAS") at a special workshop at the 2018 Seismology of the Americas meeting in Miami, as an alternative to Reasenberg and Jones (1989) which will soon be fully operational on the USGS event web pages (also built with OpenSHA). This new ETAS model utilizes OpenSHA to compute a spatial ground motion forecast, and will eventually replace the Reasenberg and Jones (1989) model on the USGS event pages (collaborators: Nicholas van der Elst, Morgan Page, both at the USGS).
- Published comparisons of hazard maps generated with RSQSim catalogs on the UCERF3 fault model with maps computed from UCERF3 directly (Shaw et al. 2018). Strong agreement between the two models at hazard levels of design interest was found, which increases confidence in both approaches.
- Initiated testing of the UCERF3 rupture plausibility criteria against RSQSim catalogs. Large agreement found with more than 80% of RSQSim M>6.5 ruptures passing the UCERF3 criteria. The Coulomb plausibility criterion was the most inconsistent with RSQSim, failing on 17.5% of RSQSim M>6.5 ruptures. This result needs further investigation which is planned for the UCERF4 project (in development).
- Developed pathway to use RSQSim as a source model in CyberShake for end-to-end physics-based PSHA. Initial RSQSim & CyberShake hazard curves were computed for two catalogs at a total of 16 sites. Completed extensive comparisons with empirical ground motion models (GMMs) in both 1-D (with SCEC BBP) and 3-D (collaborators: Bruce Shaw, Jacqui Gilchrist, Keith Richards-Dinger, Jim Dieterich).
- Reproduced SCEC BBP "Part B" validation exercise (from Goulet et. al. 2015) with RSQSim source model: comparisons against GMMs for M6.6 strike-slip and reverse

events at distances of 20 and 50 km (collaborators: Christine Goulet, Fabio Silva, Bruce Shaw)

- Added support for new variable slip speed version of RSQSim where patch slip speed is computed from the shear impedance relationship at failure and updated throughout a slip event. This improvement in RSQSim was motivated by OpenSHA analysis of low RSQSim rupture propagation velocities (collaborators: Keith Richards-Dinger, Jim Dieterich, Bruce Shaw).
- Implemented a new N-dimensional hazard interpolation scheme for efficient computation of PSHA maps for point source ETAS catalogs when each grid node has a Gutenberg-Richter magnitude-frequency distribution with the same b-value. Achieved approximately 100x speedup compared to traditional PSHA calculations, which allows for rapid spatial ground motion forecasts in the Fast-ETAS OAF application.
- Continued access to CyberShake's 3D-waveform-based hazard data set. Produced hazard map and curve products for CyberShake Study 18.8, a Northern California study (collaborators: Philip Maechling, Rob Graves, Scott Callaghan, Christine Goulet).
- Submitted paper on "Assessing the Value of Removing Earthquake Hazard-Related Epistemic Uncertainties, Exemplified Using Average Annual Loss in California" to Earthquake Spectra. For this research, we computed annual losses for all UCERF3-TD and ground motion model logic tree branches, and assess the value of removing each branch (collaborators: Ned Field, Keith Porter)



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B. Technical Advances

- Completely re-wrote the code for configuring and running UCERF3-ETAS simulations to increase flexibility, expose parameters, and allow external groups to run the model. Simulation parameters and input ruptures now specified in JSON configuration files, extensive documentation and scripts for running on personal computers and on HPC resources. https://github.com/opensha/ucerf3-etas-launcher
- Continued development of the new VTK-based version of SCEC-VDO 3D visualization platform which uses OpenSHA components and visualises OpenSHA models (collaborators: John Yu, 2018 SCEC UseIT Interns).
- Improved I/O performance of SCEC-BBP simulations on RSQSim ruptures through

OpenSHA to allow for processing of larger catalogs in parallel without degrading performance of HPC filesystems. Results are written to node-local storage and only final results are consolidated to persistent network storage asynchronously during simulations, greatly reducing filesystem load at USC HPC and TACC Stampede2.

- Wrote parsers for CyberShake file formats in OpenSHA: PSA, RotD, Seismograms, and Duration
- Began rewrite and modernization of OpenSHA-CyberShake database accessor code to reduce code redundancy and allow for non-UCERF2 ERFs, which was required for RSQSim-based CyberShake calculations.
- Continued rectification of core OpenSHA code with a forked version tailored specifically to the needs of the NSHMP (NSHMP-haz) (collaborators: Peter Powers)