Continued Development of OpenSHA/UCERFs in Support of OEF, Physics-Based Hazard Assessment, and Loss Modeling

Report for SCEC Award #20118
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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.)

Development in 2020 was focused on physics-based probabilistic seismic hazard analysis (PSHA), improving access to OpenSHA applications, and multi-fault rupture plausibility for the next Uniform California Earthquake Rupture Forecast (UCERF) model. The RSQSim-CyberShake model is the first of it's kind that combines a deterministic full-cycle physics-based earthquake simulator with physics-based ground motion simulations to perform fully nonergodic PSHA calculations. This achievement was made possible by building upon work from prior reporting years, and was recently published (Milner et al., 2021).

We launched a new OpenSHA website in 2020 with improved documentation (www.opensha.org). The new website is based on a wiki allowing for easy updating, and replaces an outdated drupal website that had become uneditable. We also formally re-released our applications on GitHub and started nightly builds of the applications and libraries from the git repositories.

Work has begun on the 2023 update to the USGS National Seismic Hazard Model. For this update, we will extend the UCERF3 methodology to the entire western US. Significant progress has been made on improving the plausibility filtering process by which the set of allowed multi-fault ruptures are determined. UCERF3 relied on simple azimuth change rules that are best suited for purely right-lateral fault systems. We have developed new filters using Coulomb stress transfer that improve upon the UCERF3 methodology and add more connectivity to the model.

We also made improvements to the UCERF3 Epidemic Type Aftershock Sequence (UCERF3-ETAS) model and continued to run the model after any M≥5 event in California.

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.

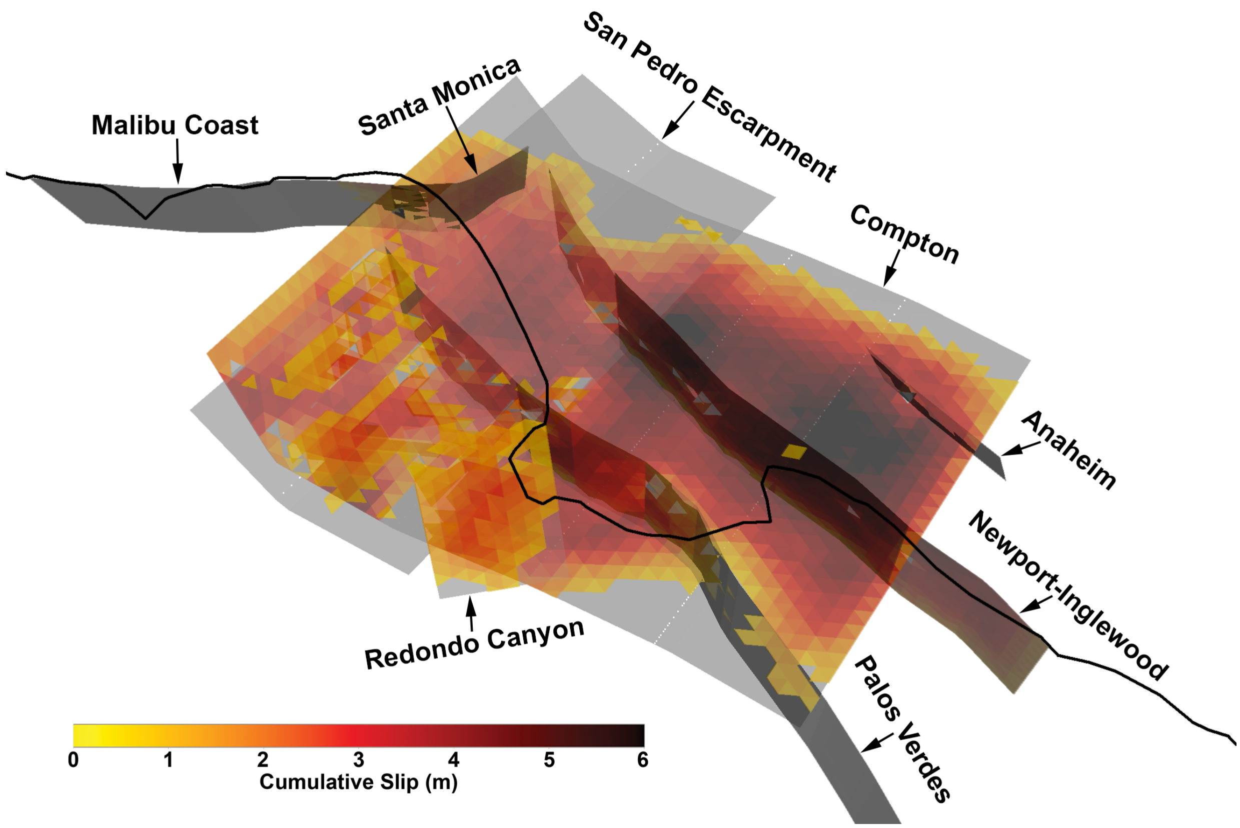


Figure 1
3D perspective view (looking north) of a complex synthetic **M** 7.8 RSQSim rupture in the Los Angeles basin. The rupture nucleates on the Compton fault and then spreads to the Newport–Inglewood, Palos Verdes, and other nearby faults. In total, 10 different UCERF3 fault sections participate, but the three aforementioned faults account for greater than 90% of the total seismic moment. Darker colors represent patches of larger total cumulative slip, and participating faults are labeled (the Elysian Park and San Pedro Basin faults also participate but are omitted as their contributions to the total seismic moment released are negligible).
Credit: from Milner et al. (2021)

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 developed the first probabilistic seismic hazard study using exclusively three-dimensional, physics-base models (RSQSim and CyberShake) in this reporting period. This has been published in Milner et al. (2021).

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. Our new website and improved application build process improves access to these models for the broader community. OpenSHA is also used in conjunction with CyberShake to generate seismic hazard maps and to generate data products for the UGMS project, which includes a public facing design response spectra tool for engineers (https://data2.scec.org/ugms-mcerGM-tool_v18.4/).

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 #10107:
Milner, K. R., Shaw, B. E., Goulet, C. A., Richards-Dinger, K. B., Callaghan, S., Jordan, T. H., Dieterich, J. H., & Field, E. H. (2021). Toward Physics-Based Nonergodic PSHA: A Prototype Fully Deterministic Seismic Hazard Model for Southern California. *Bulletin of the Seismological Society of America*. doi: https://doi.org/10.1785/0120200216.

SCEC Contribution #10630:
Milner, K. R., Shaw, B. E., & Jordan, T. H. (2020, 08). Multi-fault rupture plausibility inferences from a deterministic earthquake simulator. Poster Presentation at 2020 SCEC Annual Meeting.

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.)

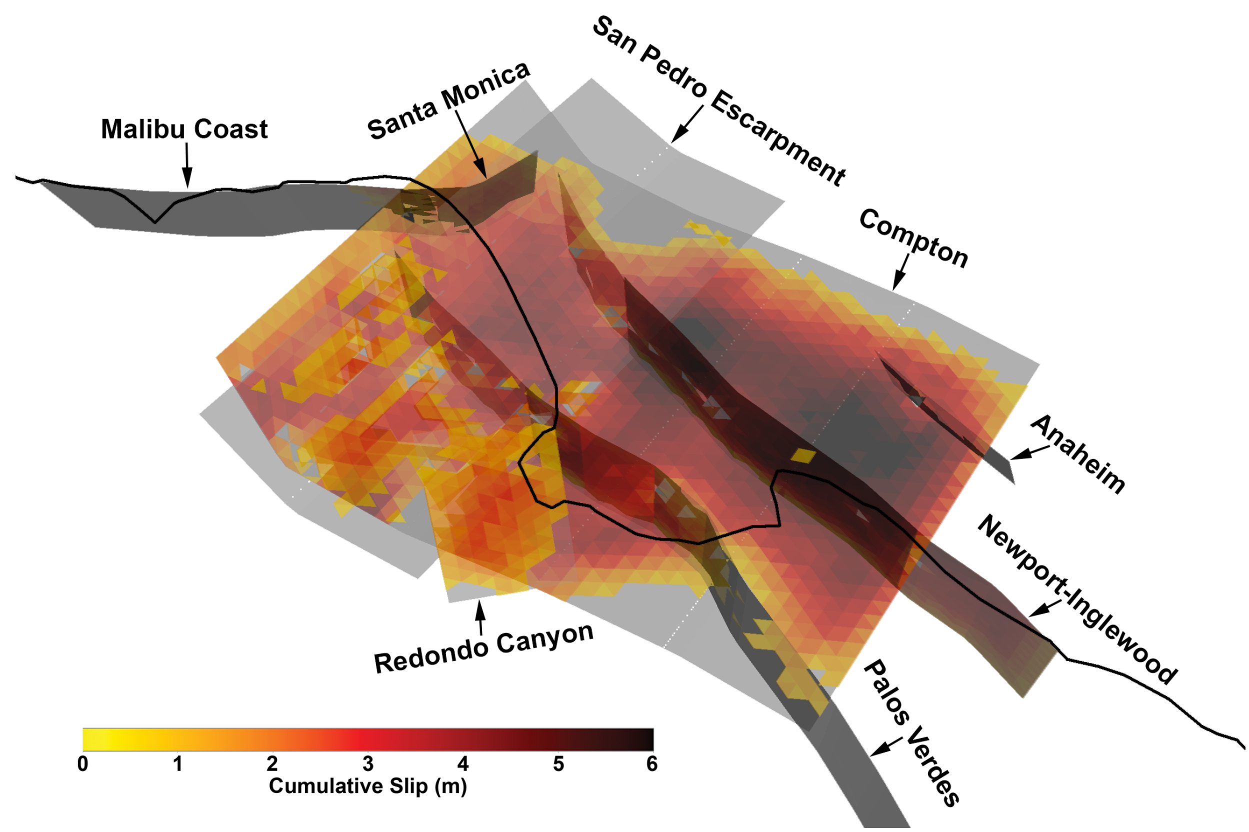
A. Scientific and implementation Advances

Our project spanned multiple aspects of PSHA-related research conducted at SCEC. We have made substantial contributions and advances that are summarized in the following bullet points.

- Developed a new and more flexible framework to represent and build permutations of complex multi-fault ruptures for UCERF4. In UCERF3, ruptures were represented as an ordered list of fault 'subsections' (~7km long portions of a named fault section) that participate in a rupture. The new "Cluster Rupture" representation treats multi-fault ruptures as a *m*-ary tree where vertices are clusters of contiguous subsections on a single named fault section, and edges are jumps between the closest points of two clusters. The benefits of this new representation include:
    - Flexibility to accurately represent complex real-world or RSQSim ruptures that include splays (and thus did not fit into the UCERF3 representation). This allows for fairer comparisons of arbitrarily complex ruptures with UCERF3 rupture plausibility criteria.
    - Ability to build rupture sets with splays.
    - Support for new and flexible "cluster permutation strategies" that allow for coarse discretization of large ruptures. In UCERF3, a rupture of *N* subsections would be accompanied by ruptures consisting of all contiguous subsets of those *N* subsections (subject to passing other plausibility criteria). The new rupture building algorithm allows for coarser permutations as a function of rupture length.
    - Support for a number of new plausibility filters that replace the azimuth change rules used in UCERF3, better match RSQSim catalogs, and allow more connectivity.
- Implemented Okada (1992) stiffness calculations in OpenSHA (modified from the RSQSim implementation) for on-the-fly Coulomb calculations between pair-wise UCERF subsections. UCERF3's Coulomb plausibility criterion used precomputed Coulomb calculations (Parsons et al., 2012) at assumed fault jumps (based on closest distance), but did not incorporate Coulomb interactions between the rest of rupture on either side of each jump This new capability allows for more sophisticated whole-rupture Coulomb plausibility criteria, removing the need for prior assumptions.
- Ran 10,000 UCERF3-ETAS simulations retrospectively for every week from 1985-present for four different model variants. This large dataset will be used as an input to the newly developed tests within the Collaboratory for the Study of Earthquake Predictability to allow us to check for any systematic biases in the model, and test performance of the full UCERF3-ETAS model and its variants against a simpler ETAS model that ignores known faults. Initial observations from these datasets show that, even with the new aleatory productivity branch implemented in the prior year, more variability is needed to capture quiescent periods in the data: ~20% of observations of one-week

statewide M≥2.5 earthquake counts lie outside the simulated 95% bounds, with the majority of those below the lower 2.5% bound. Collaborator: Bill Savran.

- Completed RSQSim-CyberShake hazard and variability calculations (Figure 1) for a physics-based nonergodic hazard paper (Milner et al., 2021). Collaborators: Bruce Shaw, Tom Jordan, Scott Callaghan, Keith Richards-Dinger, Jim Dieterich.
- Continued to improve access to CyberShake's 3D-waveform-based hazard data set. Added capabilities to integrate background seismicity ground motions computed with empirical models with CyberShake data products (hazard curves, maps). Collaborators: Philip Maechling, Rob Graves, Scott Callaghan.



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Credit: from Milner et al. (2021)

B. Technical Advances

Key technical advances are summarized below:

- Transitioned OpenSHA website (https://opensha.org) to a wiki-based solution hosted by

GitHub. This allows OpenSHA collaborators to more easily update content, and replaces an aging and outdated website that was no longer editable. The documentation has also been updated to provide better user support.

- Transitioned OpenSHA application builds to GitHub (see https://opensha.org/Applications) and formally re-released applications. Set up nightly builds to allow advanced users to try new features before broad release. Integrated GitHub issue submission with applications such that when an error occurs, a user can click a button to raise a pre-populated issue description on the OpenSHA GitHub page.
- Parallelized UCERF rupture building algorithm to more quickly build large and complex rupture sets (see new “Cluster Rupture” description above in section 2). The UCERF3 rupture set can now be reproduced in ~30 seconds on a 4-core laptop, and larger rupture sets with millions of ruptures are tractable in ~10 minutes.
- Redesigned UCERF inversion constraint implementations into new flexible object-oriented framework. This allows for unit testing of individual constraints (basic tests implemented for all UCERF3 constraints), and for investigators to more easily add and test new constraints.
- Added UCERF3 Epistemic List ERF to OpenSHA applications which allows investigators to compute hazard curves/spectra across the entire UCERF3 time-independent logic tree. Collaborators: Jon Stewart, Timothy O’Donnell.
- Created ‘event reports’ capability to generate html pages when given a USGS event ID. These pages include mainshock and sequence details (e.g., spatial and temporal distributions of aftershocks), with capabilities to include a UCERF3-ETAS forecast when one has been pre-computed. Edric Pauk added these as an internal capability for authorized users (not for public consumption) on scec.org to view sequence information and preliminary forecasts. Collaborators: Yehuda Ben-Zion and Edric Pauk.

References

Milner, K. R., Shaw, B. E., Goulet, C. A., Richards-Dinger, K. B., Callaghan, S. Jordan, T. H., Dieterich, J. H., & Field, E. H. (in press). Toward Physics-Based Nonergodic PSHA: A Prototype Fully Deterministic Seismic Hazard Model For Southern California. *Bulletin of the Seismological Society of America*.

Okada, Y. (1992). Internal deformation due to shear and tensile faults in a half-space. *Bulletin of the Seismological Society of America*, 82(2), 1018-1040.

Parsons, T., Field, E. H., Page, M. T., & Milner, K. (2012). Possible Earthquake Rupture Connections on Mapped California Faults Ranked by Calculated Coulomb Linking StressesPossible Earthquake Rupture Connections on Mapped California Faults. *Bulletin of the Seismological Society of America*, 102(6), 2667-2676.