Continued Development of OpenSHA/UCERFs in Support of OEF, Hazard and Risk Assessments, with a Focus on User Needs

Report for SCEC Award #21148
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Investigators: Christine A. Goulet (SCEC), 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.)

Development in 2021 was focused on preparations for the 2023 update to the USGS National Seismic Hazard Model (NSHM23). For this update, we improved upon the inversion-based methodology used in the Third Uniform California Earthquake Rupture Forecast (UCERF3), and extended it to the entire western US. We developed an updated plausibility filtering process by which the set of allowed multi-fault ruptures are determined. We also developed new filters using Coulomb stress transfer that improve the physical-consistency of the rupture set and add more connectivity to the model (Milner et al., 2022).

We retooled the simulated annealing algorithm used by UCERF3 to solve the inversion. We improved convergence by optimizing the java implementation of the algorithm and also switching to a new variable perturbation function that chooses random perturbations that are more likely to be kept in each annealing iteration. We also implemented a new set of uncertainty-weighted constraints where each constraint is evenly fit relative to its uncertainty.

To improve access to UCERF3 and future models, we greatly simplified and standardized file formats for storing model results for UCERF3, NSHM23, and similar models. We also released a beta version of a set of command line tools that allows end-users to build and modify UCERF3 and NSHM23 rupture sets and inversion solutions. These tools and improvements will increase accessibility and ease adoption of both current and future models.

We continued to support OpenSHA desktop applications, which were downloaded nearly 3,000 times in 2021.

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.

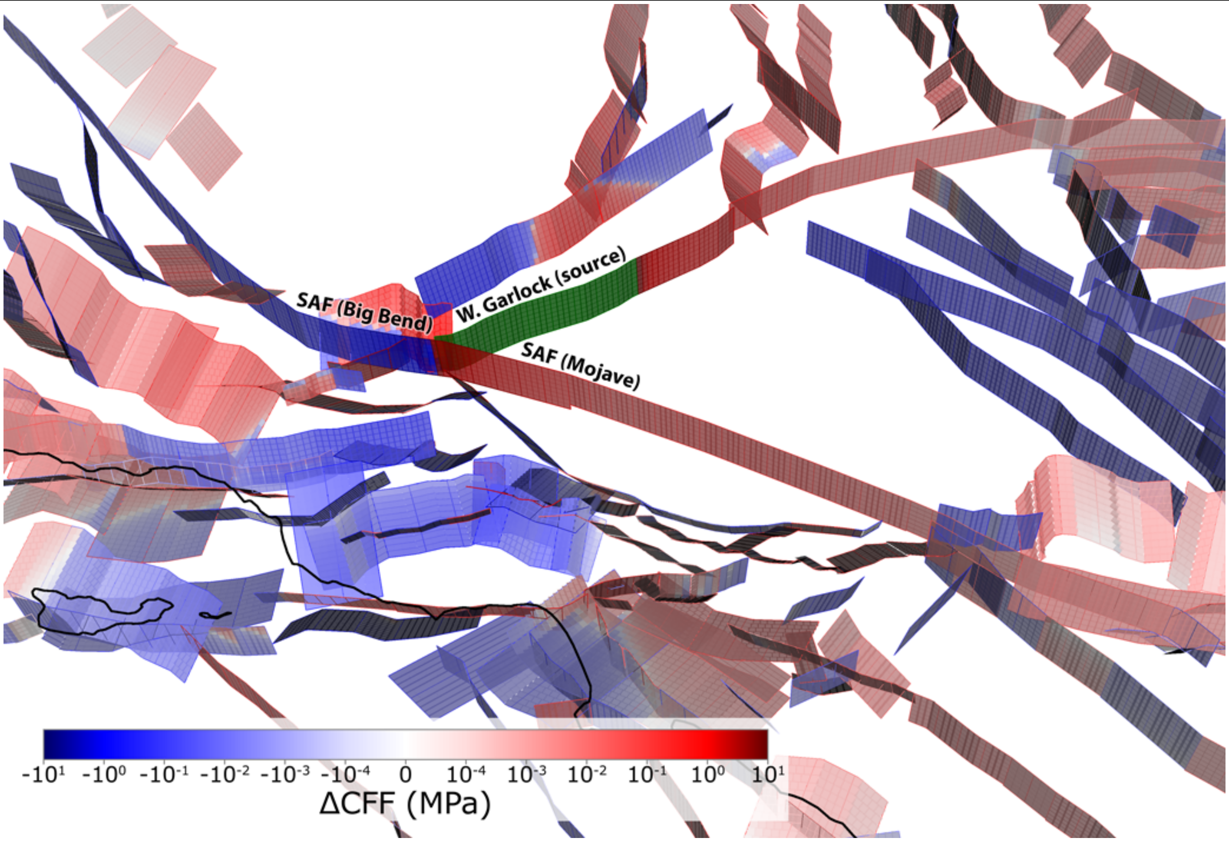


Figure 1
3D view looking north of faults model 3.1 from the Third Uniform California Earthquake Rupture Forecast (UCERF3) model discretized into 2 km x 2 km patches for Coulomb calculations. In this example, eight subsections of the Garlock fault are used as sources (green) with 1 m displacement and Coulomb stress changes are computed to all other patches (with contributions summed across all source patches). Receiver patches are colored by their sign with darker colors indicating greater amplitude, and subsection outlines are colored by the sum across all receiver patches (red is positive, blue negative). This shows the Coulomb-preferred co-rupture direction of the left-lateral Garlock Fault connecting to the Mojave section of the right-lateral San Andreas Fault (SAF). Coastlines are overlaid in black.
Credit: from Milner et al. (2022)

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?*

The work described in this report helps achieve SCEC's goal of integrating data and models into usable products that also support continued research. It improves upon previous approaches in multiple ways, including a more physically consistent set multi-fault ruptures, better inversion convergence and data fits than prior models, and better acknowledgement and sampling of model uncertainties. These innovations have been or will be published in peer-reviewed journals, as well as internally within the USGS.

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 its implementation of the UCERF3 models, continues to be a valuable tool for the SCEC community. OpenSHA is used by engineers, researchers, and students, and was downloaded nearly 3,000 times in 2021.

The work on the 2023 update to the national seismic hazard model (NSHM23) will help to synthesize data from a number of different SCEC-funded projects (e.g., fault slip rate and paleoseismic studies) into useful and widely used models for the community. We also led a training session in 2021 to demonstrate new tools for building, modifying, and interacting with UCERF3 and NSHM23 results.

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 #11760:
Milner, K. R., Shaw, B. E., & Field, E. H. (2022). Enumerating Plausible Multifault Ruptures in Complex Fault Systems with Physical Constraints. *Bulletin of the Seismological Society of America*.
SCEC Contribution #11859:
Field, E. H., Milner, K. R., & Page, M. T. (2020). Generalizing the Inversion-Based PSHA Source Model for an Interconnected Fault System. *Bulletin of the Seismological Society of America*, 111(1), 371-390. doi: 10.1785/0120200219.
SCEC Contribution #11351:
Milner, K. R., & Field, E. H. (2021, 08). OpenSHA: New tools and file formats for building and analyzing UCERF3-style rupture sets and running inversions. Poster Presentation at 2021 SCEC Annual Meeting.
SCEC Contribution #11677:
Field, E. H., Milner, K. R., Page, M. T., Savran, W. H., & van der Elst, N. J. (2021). Improvements to the Third Uniform California Earthquake Rupture Forecast ETAS Model (UCERF3-ETAS). *The Seismic Record*, 1(2), 117-125. doi: 10.1785/0320210017.
SCEC Contribution #11111:
Field, E. H., Milner, K. R., & Luco, N. (2021). The Seismic Hazard Implications of Declustering and Poisson Assumptions Inferred from a Fully Time-Dependent Model. *Bulletin of the Seismological Society of America*, 112(1), 527-537. doi: 10.1785/0120210027.

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.)

Development in 2021 was focused primarily on the 2023 update to the USGS National Seismic Hazard Model (NSHM23). Considerable progress was made on the OpenSHA software itself to improve the performance of the fault system inversion approach, and new methods were developed to improve fits to observed data while respecting and quantifying uncertainties. We also finalized a paper (Milner et al, 2022) on a multifault rupture plausibility model used as input to the inversion. and greatly improved our file formats and user tools for interacting with models.

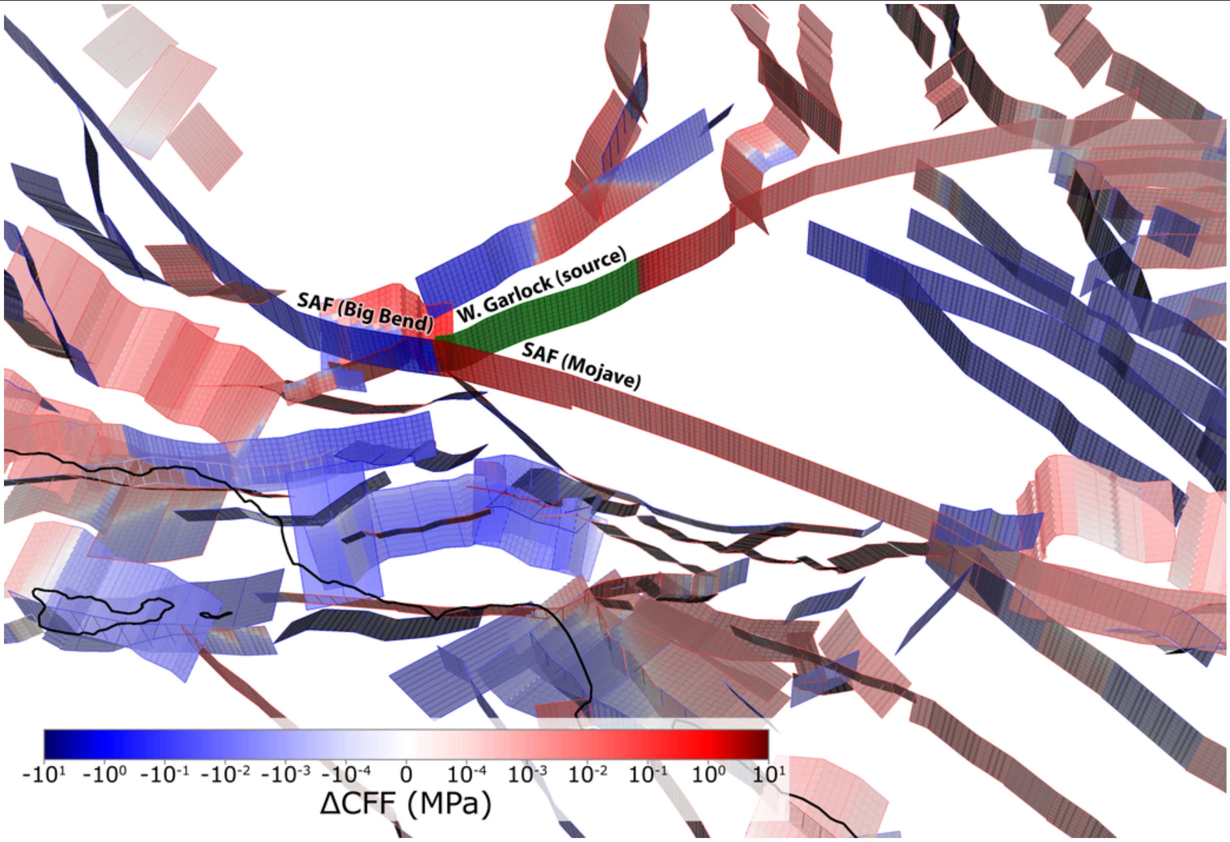
Details on these and other activities are summarized in the following bullet points, broken down into separate sections for scientific advances (methods & implementation), and technical (software) advances.

A. Scientific and implementation Advances

- Created a draft multi-fault rupture plausibility model for NSHM23, implemented in OpenSHA. We improved upon the rules used in UCERF3 to increase connectivity (in response to Page, 2021) and the physical consistency of ruptures. We replaced UCERF3's simple azimuth change rules with new Coulomb favorability metrics and increased the maximum jump distance to 15 km. The UCERF3 rules were appropriate for faults with similar rakes, but the new Coulomb calculations inherently encode preferred orientations between faults of different rakes. The new rules are designed to be insensitive to discretization details and are generally more permissive than their UCERF3 counterparts; they allow more than twice the connectivity compared to UCERF3, yet heavily penalize long ruptures that take multiple improbable jumps. A draft manuscript summarizing the updated plausibility filters is nearly ready for submission (Milner et al., in pres.).
- Improved the simulated annealing algorithm (SAA) used for UCERF3 inversions and to be used for NSHM23. The SAA is iterative, randomly perturbing the rate of a rupture in each iteration. UCERF3 used a random perturbation function (p=[rand()-0.5]*0.001) that was too large, making it difficult to sample the small rates that are expected for largest ruptures and slow-moving faults (e.g., those with P<1e-5). We improve this by first determining a baseline rate, b_r, for each rupture from a regional Gutenberg-Richter magnitude frequency distribution. We then randomly sample perturbations in log10-space, plus and minus two orders of magnitude around b_r: p=[rand()-0.5]*10^[2+b_r -[4*rand()]]. This change speeds up inversion convergence by ~4x.
- Modified SAA inversion constraints used in UCERF3 and proposed for use in NSHM23 to weigh each constraint relative to their uncertainties. This was used in UCERF3 for paleoseismic data, but not for slip rate and magnitude-frequency distribution constraints. This allows for easier interpretation of inversion misfits, including the degree of under/overfitting relative to the range of uncertainties.
- Created a draft segmentation constraint to control the number of multi-fault ruptures in

the inversion. This constraint is applied as a proxy slip-rate constraint between faults (as proposed in Field et al., 2021), and uses a jump-distance-dependent formulation from Shaw and Dieterich (2007) which is consistent with RSQSim calculations performed on the UCERF3 fault system.

- Implemented a simpler (than UCERF3) way of determining on-fault supra-seismogenic target magnitude frequency distribution for a region for use in NSHM23 inversions. This new method takes only a supra-seismogenic b-value and deformation model moment rates as input to construct and then sum fault magnitude-frequency distributions.
- Published fully physics-based PSHA paper based on RSQSim-CyberShake calculations performed in prior years (Milner et al., 2021). Collaborators: Bruce Shaw, Tom Jordan, Scott Callaghan, Keith Richards-Dinger, Jim Dieterich.
- Continued access to CyberShake's 3D-waveform-based hazard data set.
  - Supported research by Yajie Lee and Zhenghui Hu, who used an OpenSHA tool to calculate CyberShake scenario ShakeMaps and compute hazard to the Los Angeles Department of Water and Power's underground water pipeline network. They found that CyberShake simulations imply lower hazard at long return periods than empirical ground motion models (GMMs).
  - Added capability to compute scenario shakemap realizations for CyberShake simulations interpolated onto an empirical GMM basemap with random spatially-correlated ground motions; correlations implemented following the methodology of Loth and Baker (2013). Collaborators: Philip Maechling, Rob Graves, Scott Callaghan, Kim Olsen.
- Published a paper using UCERF3-ETAS to study the hazard implications of declustering and Poisson assumptions (Field, Milner, and Luco 2021). A key finding was that it is better to keep all earthquakes (including aftershocks) in PSHA studies and treat their recurrence as following a Poisson process.
- Published a paper on improvements to UCERF3-ETAS that were implemented in prior proposal years: random variability in productivity parameter, and random finite-fault selection of off-modeled-fault ruptures (Field et al., 2021).



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3D view looking north of faults model 3.1 from the Third Uniform California Earthquake Rupture Forecast (UCERF3) model broken up into 2 km x 2 km patches for Coulomb calculations. In this example, eight subsections of the Garlock fault are used as sources (green) with 1 m displacement and Coulomb stress changes are computed to all other patches (with contributions summed across all source patches). Receiver patches are colored by their sign with darker colors indicating greater amplitude, and subsection outlines are colored by the sum across all receiver patches (red is positive, blue negative). This shows the Coulomb-preferred co-rupture direction of the left-lateral Garlock Fault connecting to the Mojave section of the right-lateral San Andreas Fault (SAF). Coastlines are overlaid in black.

B. Technical Advances

Key technical advances are summarized below:

- Created a suite of command-line tools that allow users to build UCERF3-like rupture sets and run their own inversions. These tools were demonstrated as a poster presentation at the 2021 SCEC Annual Meeting, and live at the European Seismological Commission Fault2SHA working group's "Hands-on fault based PSHA" meeting in September, 2021. Currently available tools allow users to build rupture sets for their own fault systems following the UCERF3 and proposed NSHM23 multi-fault rupture plausibility algorithms, and run simple inversions to fit slip rate and magnitude-frequency distribution constraints: https://github.com/opensha/opensha-fault-sys-tools
- Published original UCERF3 data files (in the original legacy file format) on Zenodo for posterity and citability. These files were previously only stored on USC disks and web

servers: https://zenodo.org/record/5519802

- Added support for reading and writing region, location, and fault data in GeoJSON, a widely accepted standard used by common GIS packages. See: https://opensha.org/Geospatial-File-Formats
- Created better and more user-friendly file formats for storing UCERF3-like rupture sets and inversion results. The previous custom binary formats were space-efficient but were difficult to interact with for end-users. The new file formats are simple zip files backed by human-readable and editable CSV and JSON files. See: https://opensha.org/Modular-Fault-System-Solution
The new fault system rupture set/inversion solution file format corresponds with larger refactoring of the codebase to allow for modular hot-swapping of model components used to build and constrain rupture sets/inversion. This allows model developers to easily and cleanly (from a class hierarchy perspective) mix and match model components (e.g., scaling relationships, gridded seismicity implementations, inversion targets, etc.) from UCERF3 with newer replacement implementations.
- Improved the performance of the UCERF3 inversion algorithm. More efficient calculation and tracking of inversion misfits during inversion led to a ~50x speedup in the number of SAA iterations per wall-clock time. UCERF3 inversions that were run over the course of 5 hours can now be reproduced (with the same iteration count) in <10 minutes. Additionally, a new averaging scheme between multiple thread pools on a compute node leads to more stable results and more efficiently uses all available processors on a compute node: one inversion with the new approach on a machine with 20 cores available is similar to the average of five independently run prior inversions, further reducing the overall computational burden.
- Simplified git project structure, merging production code that existed in multiple sub-projects into a single primary repository (https://github.com/opensha/opensha).
- Implemented automated building and testing on every push and pull request through GitHub actions. Created additional test that runs every 6 hours to ensure that web services are operational, and added badges to show current test, build, and server status to all repositories and the opensha.org website.
- Transitioned Working Group on California Earthquake Probabilities (WGCEP) website (https://wgcep.org) to a wiki-based solution hosted by GitHub. Migrated and updated old UCERF3 model and data documentation that previously existed on an external wiki to the new website. Both the old WGCEP website and wiki were outdated and no longer editable.

References

Field, E. H., Milner, K. R., & Page, M. T. (2021). Generalizing the Inversion‐Based PSHA Source Model for an Interconnected Fault System. Bulletin of the Seismological Society of America, 111(1), 371-390.

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