# Continued Development of OpenSHA to Support Next-Generation Earthquake Rupture Forecasts and Facilitate User Adoption

Report for SCEC Award #25286

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## Contents

# 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 2025 focused on continued support and modernization of software tools for seismic hazard analysis, simulation, and visualization within the SCEC Community Modeling Environment. SCEC-VDO was updated with native Apple Silicon support, improving performance and cross-platform usability for 3D visualization of earthquake and fault data. The Quakeworx Science Gateway and UCERF3-ETAS application continued to be supported and enhanced, with improvements to user interface and performance enabling broader access to large-scale simulations through web-based workflows. OpenSHA development emphasized improved release practices and the implementation of the GetFile framework to support reliable access to large datasets such as UCERF3 and NSHM23, including support for the NSHM23 Western U.S. earthquake rupture forecast.

Additional efforts expanded usability and scientific capabilities within OpenSHA. Training materials were developed to support NSHM23 hazard calculations, and a new Intensity Measure Event Set Calculator was introduced for computing intensity measures across large sets of sites and earthquake ruptures. The OpenSHA-Jupyter project demonstrated the feasibility of Jupyter notebooks for interactive hazard analysis and reproducible workflows. CyberShake work continued traditional physics-based hazard calculations while introducing the ability to incorporate rupture directivity through user-defined rupture variation probabilities, enabling more flexible evaluation of its impact on hazard curves, maps, and disaggregation results.


## 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.

1. Research Computing (RC)
2. Earthquake Forecasting and Predictability (EFP)
3. Applied Science Implementation (ASI)

## 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.

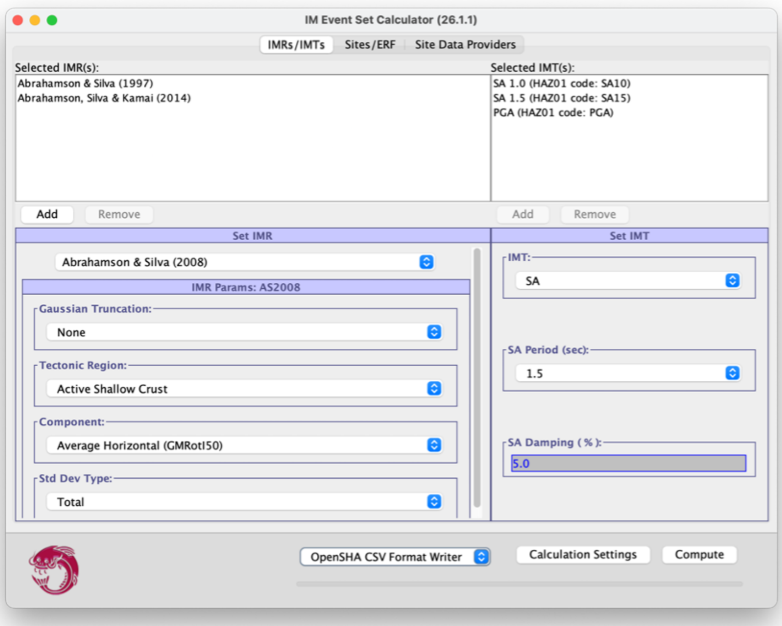


**Figure 1:** Intensity Measure Event Set Calculator v26.1.1.
New OpenSHA application for computing intensity measures (IMs) across large sets of sites and earthquake ruptures.

## D SCEC Science Milestones

Select all SCEC science milestones this project contributed to.

| |
|---|
| C1,2,3-1, C1-1, D2-1 |

## E SCEC Community Models

If relevant, choose all the SCEC Community Earth Models (CEMs) your project used.

| |
|---|
| CFM, CGM |

## F 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?
(Maximum 100 words.)

| |
|---|
| The work described in this report helps achieve SCEC's goal of integrating data and models into usable products that also support continued research. Specifically, it synthesized many studies conducted with SCEC support (e.g., fault slip rate studies, paleoseismic studies, and other research) into a high profile model: the 2023 update to the National Seismic Hazard Model. |

## G 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? (Maximum 100 words.)

OpenSHA is a primary vehicle for transforming the results of SCEC science into usable products (e.g., NSHM23 and CyberShake). OpenSHA not only benefits hazard and loss user communities, but also individual scientists and engineers by providing them with a suite of analysis tools and desktop applications for their research (e.g., viewing CyberShake results or computing hazard curves from NSHM23 and similar models) and as a PSHA teaching tool for professors. New tools and better documentation developed as part of this proposal will enable users to more easily interact with and customize NSHM23 and similar models.

## H Project Participants

What individuals have worked on the project? What organizations have been involved as partners? Were other collaborators or contacts involved? If so, please provide details. (Maximum 100 words.)

Project Co-PIs: Philip Maechling, Kevin Milner, and Ned Field

USGS Researchers: Kevin Milner and Ned Field

SCEC Software Developer: Akash Bhatthal

## I Project Publications

All publications and presentations of the work funded must be entered in the SCEC Publications database. If you have any problems, please email scec-web@usc.edu for assistance.

- ☑ I confirm I have added to the SCEC Publications database by
    - a) updating publication records previously submitted and/or
    - b) adding new publications related to this SCEC project.
- ☐ There are no publications related to this SCEC project at this time.

# 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 SCEC-VDO

Researchers and interns at the Statewide California Earthquake Center (SCEC) have built a seismic data visualization software tool called the SCEC Virtual Display of Objects (SCEC-VDO). Written in Java with the Swing GUI toolkit to create interactive menus and the Visualization Toolkit (VTK) to render 3D content, SCEC-VDO allows for the visualization of 3D earthquake and fault objects on maps and the creation of images and movies for analysis, presentation, and publication. With software release v24.11.0, native architecture support is provided for the new Apple Silicon Macs with significantly improved performance, documentation, and cross-platform packaging.

## B Quakeworx / UCERF3-ETAS

The Quakeworx Science Gateway supports many applications and pipelines for execution on HPC and cloud systems to support seismic simulations. One such application, UCERF3-ETAS, forecasts earthquakes in California and combines long-term rupture forecasts with short-term aftershock modeling to simulate seismic activity on and off faults. Collaborations with Fabio Silva have greatly improved the UI and performance of this application on Quakeworx.

UCERF3-ETAS simulations continue to be supported for use after significant California earthquakes on multiple computing systems and by multiple users. This includes SCEC hardware housed at USC, and allocations at the San Diego Supercomputing Center and the Texas Advanced Computing Center. The Quakeworx Science Gateway UCERF3-ETAS application enables users to leverage Expanse for UCERF3-ETAS simulations directly from a web browser without requiring a complex terminal-based workflow.

## C OpenSHA

OpenSHA is an open-source, Java-based platform for conducting Seismic Hazard Analysis (SHA). Many applications are built on this platform and distributed via GitHub software releases. We've improved the release process with rigorous beta testing periods prior to release, along with detailed release notes and email announcements leveraging the new OpenSHA mail list and the existing SCEC mail list.

The increasing size of geospatial datasets for earthquake models is rapidly exceeding the 100 MB file-size limits imposed by GitHub. The GetFile framework provides a robust mechanism for retrieving hazard models directly from USC and Amazon servers, ensuring reliable access to the datasets required for OpenSHA analyses. This ensures UCERF3 and NSHM23 models are up to date for use across OpenSHA applications. The NSHM23 Western U.S. ERF is supported via GetFile for OpenSHA applications.

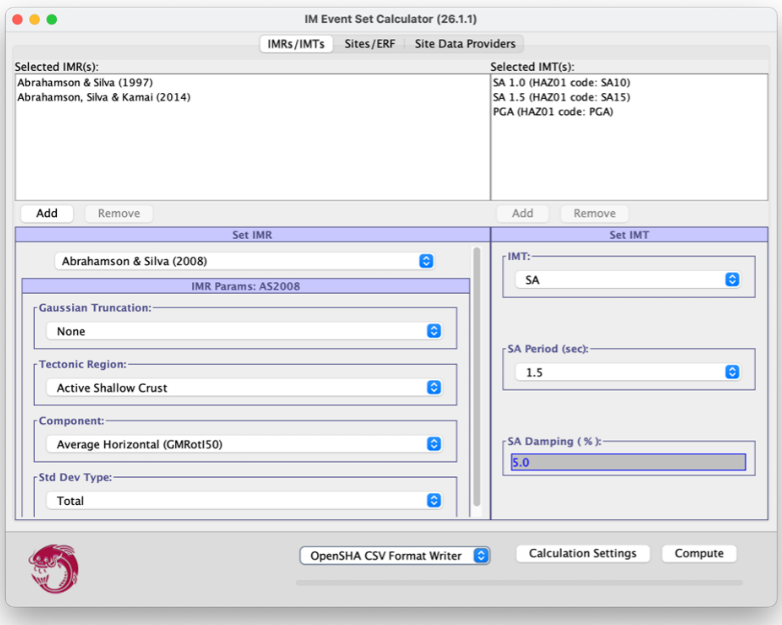


**Figure 1:** Intensity Measure Event Set Calculator v26.1.1.
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Training documentation and walkthroughs on hazard calculations with the NSHM23 model build directly on the existing OpenSHA tutorials and follow a standard PSHA workflow. Users select the NSHM23 Western U.S. branch-averaged earthquake rupture forecast, choose appropriate ground motion models such as the NSHM23 Active Crustal models, define the intensity measure, and compute hazard curves through the OpenSHA interface or APIs. The tutorials at https://opensha.org/Tutorials demonstrate how to generate and interpret hazard curves, adjust calculation parameters, and compare results across models. The NSHM23 model introduces an expanded fault database and inversionbased rupture modeling that includes more faults and complex multi-fault ruptures, which leads to differences in hazard results compared to earlier models. The walkthrough connects these calculations to downstream products such as hazard maps and disaggregation, enabling users to reproduce standard hazard workflows while leveraging the updated physics and data in NSHM23.

The OpenSHA-Jupyter project demonstrates that Jupyter notebooks are a viable and effective environment for OpenSHA and other Java-based applications by providing a portable, Dockerized JupyterLab setup with the OpenSHA framework preloaded. This approach enables users to execute Java code interactively within notebooks, combining code, documentation, and results in a single environment. It replaces the traditional workflow of running scattered example classes in an IDE with a more accessible, REPL-style interface where demonstrations are organized and easily navigable. The system also supports debugging and rapid testing of hazard workflows, showing that Jupyter can successfully facilitate interactive training, development, and reproducible analysis for OpenSHA and related Java tools.

## D CyberShake

CyberShake is a physics-based probabilistic seismic hazard analysis (PSHA) platform that uses large-scale earthquake simulations to compute ground motions at specific sites. Instead of relying on empirical models, it generates synthetic seismograms for many possible earthquake ruptures and stores the results in a database. These simulations are then used to calculate hazard curves, which describe the probability of exceeding different shaking levels. These curves can be combined into hazard maps and further analyzed through disaggregation to identify the dominant contributing earthquakes.

Continuing traditional CyberShake calculations means extending this workflow as new sites are added by populating the database with simulation results and recomputing hazard products. Recent work shows how the process can be improved by incorporating rupture directivity into hazard calculations. The key change is to move beyond assuming all rupture variations are equally likely. Instead, CyberShake and OpenSHA allow users to assign custom probabilities to each rupture variation, defined by source, rupture, and hypocenter location, using an input file. These probabilities can reflect preferred rupture directions and are used directly in hazard curve computations. The results show that hazard curves can change depending on whether rupture direction is treated as random or biased. Comparing these cases helps determine whether directivity significantly affects hazard estimates or averages out across scenarios. In practice, the workflow still produces the same downstream products such as hazard curves, maps, and disaggregation, but with improved flexibility to represent more realistic earthquake behavior.

# References

Field, Edward H., Kevin R. Milner, Jeanne L. Hardebeck, et al. (2017). "A Spatiotemporal Clustering Model for the Third Uniform California Earthquake Rupture Forecast (UCERF3-ETAS): Toward an Operational Earthquake Forecast". In: *Bulletin of the Seismological Society of America* 107.3, pp. 1049–1081. DOI: 10.1785/0120160173.

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