## 2025 SCEC progress report for Shaw

## "Statewide earthquake simulators: Exploring fault system geometry uncertainties and impacts on behavior and hazard"

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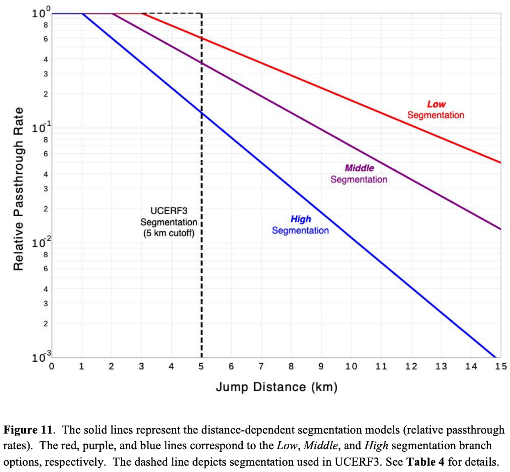
In the last year work relating to two NSHMs to which the PI contributed significantly, one the USGS NSHM and the other the New Zealand NSHM appeared in print. A substantial number of papers were published associated with these efforts, and other work. All have relevance to hazard. Below we mention 4 published papers, 3 concerning the hazard models, and one concerning ground motions arising from physics-based simulators.

## Published paper regarding 2023 Conterminous US NSHM

**" The USGS 2023 Conterminous U.S. Time-Independent Earthquake Rupture Forecast"** (*Field, et al, including Shaw, 2023*), *Bulletin of the Seismological Sociey of America*.

Multiple contributions to the earthquake rupture forecast came from our efforts. Figure 1a shows a figure from the paper regarding segmentation and an exponential dependence on jump distance, a result formulated from previous simulations (*Shaw and Dieterich*, 2007) and supported by results from UCERF3 fault system simulations as well. Figure 1b shows a figure from the paper regarding scaling that incorporates the work in *Shaw* (2023).

Figure 2 illustrates some of the ways the PI's research contributed to the NSHM. Figure 2a and 2b, from *Milner et al.* (2022), shows how we contributed to the NSHM effort by developing an improved set of ruptures for use in inversions for seismic hazard. Based on various robust statistical Coulomb measures, the new rules for constructing the rupture set were shown to be more compatible with simulator ruptures than the previous UCERF3 rules. Figure 2c from [*Field et al and Shaw, 2023*] shows the branch sensitivity to two other elements we contributed to, the scaling relations and segmentation model, with the segmentation model based on results from (*Shaw and Dieterich*, 2007) and newer work from the RSQSim simulator supporting this as well.

(a) 

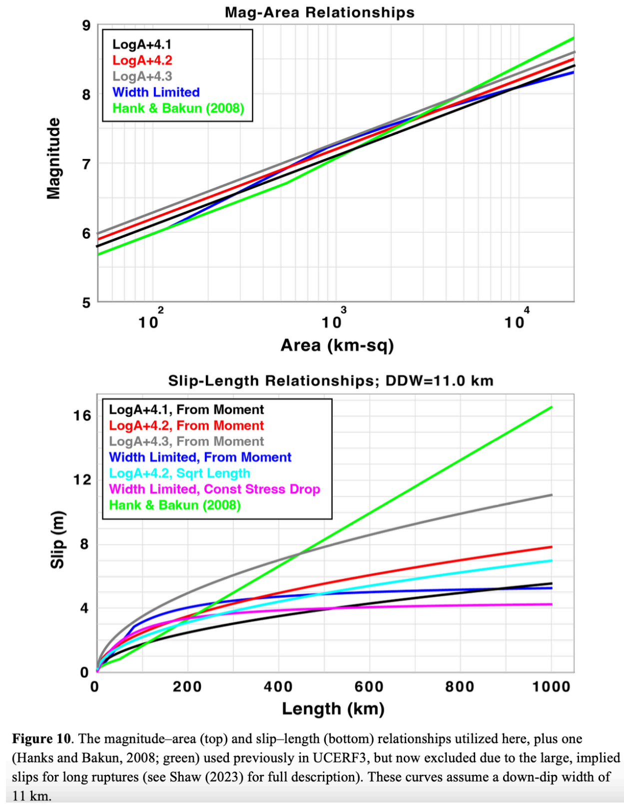

(b) 


Figure 1: (a) Aided NSHM effort with segmentation constraint. Figure from [*Field et al,*, 2023] showing segmentation constraints using an exponential of jump distance (*Shaw and Dieterich*, 2007). (b) Figure from [*Field et al,*, 2023] showing scaling contributions (*Shaw*, 2023).

## Published paper regarding 2023 USGS NSHM

**" The 2023 U.S. 50-State National Seismic Hazard Model: Overview and Implications"** (*Petersen, et al, including Shaw, 2023*), *Earthquake Spectra*.

The US National Seismic Hazard Model (NSHM) was updated in 2023 for all 50 states using new science on seismicity, fault ruptures, ground motions, and probabilistic techniques to produce a standard of practice for public policy and other engineering applications (defined for return periods greater than ;475 or less than ;10,000 years). Changes in 2023 time-independent seismic hazard (both increases and decreases compared to previous NSHMs) are substantial because the new model considers more data and updated earthquake rupture forecasts and ground-motion components. In developing the 2023 model, we tried to apply best available or applicable science based on advice of co-authors, more than 50 reviewers, and hundreds of hazard scientists and end-users, who attended public workshops and provided technical inputs. The hazard assessment incorporates new catalogs, declustering algorithms, gridded seismicity models, magnitude-scaling equations, fault-based structural and deformation models, multi-fault earthquake rupture forecast models, semi-empirical and simulation- based ground-motion models, and site amplification models conditioned on shear- wave velocities of the upper 30 m of soil and deeper sedimentary basin structures. Seismic hazard calculations yield hazard curves at hundreds of thousands of sites, ground-motion maps, uniform-hazard response spectra, and disaggregations developed for pseudo-spectral accelerations at 21 oscillator periods and two peak parameters, Modified Mercalli Intensity, and 8 site classes required by building codes and other public policy applications. Tests

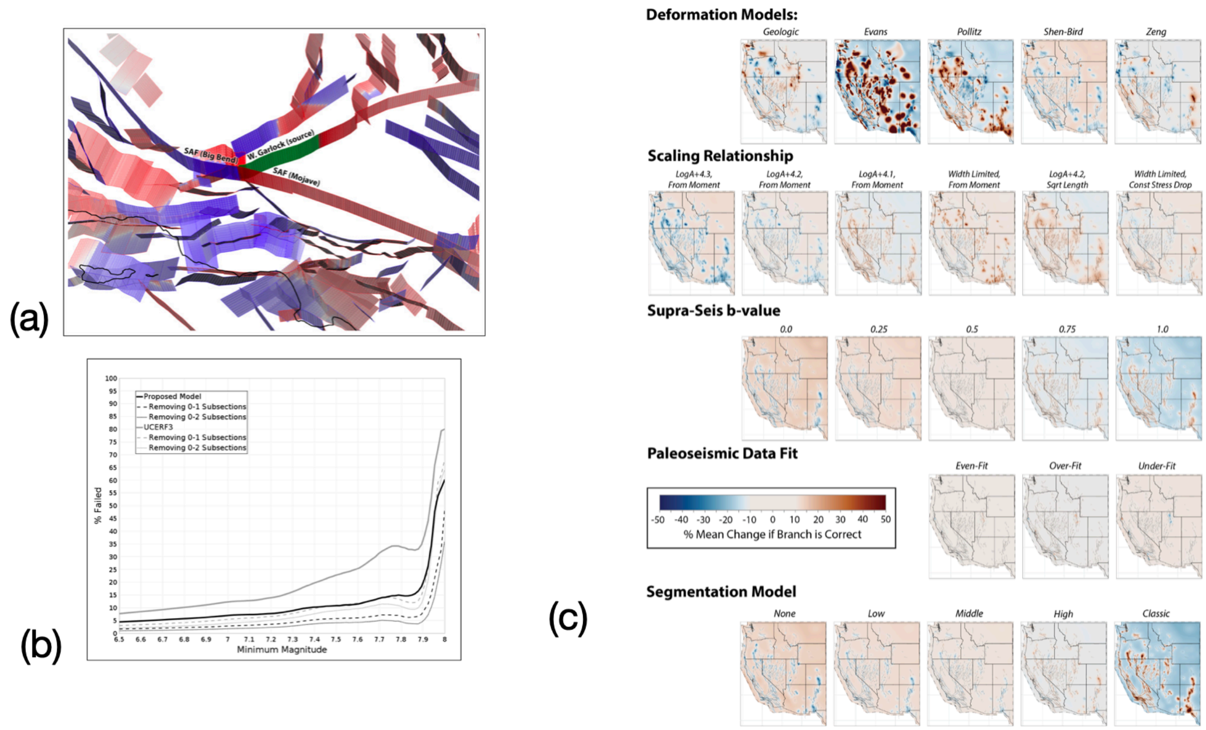



Figure 2: Aided USGS NSHM 2023 in multiple ways. This figure illustrates three ways the PI's research contributed to the hazard estimates. One is by developing improved rules for rupture sets used in hazard inversions, which (a) and (b) illustrate from [*Milner, Shaw, and Field*,, 2022].. A second is from the scaling relations (*Shaw*, 2023), which (c) also illustrates. A third is from the segmentation formulation, which (c) illustrates From [*Field et al and Shaw*, 2023]

show the new model is consistent with past ShakeMap intensity observations. Sensitivity and uncertainty assessments ensure resulting ground motions are compatible with known hazard information and highlight the range and causes of variability in ground motions. We produce several impact products including building seismic design criteria, intensity maps, planning scenarios, and engineering risk assessments showing the potential physical and social impacts. These applications provide a basis for assessing, planning, and mitigating the effects of future earthquakes.

Multiple contributions to the earthquake rupture forecast came from our efforts. The previous discussion of the [Field, et al, 2023] paper lists a number of them.

## Published paper regarding 2022 New Zealand NSHM

**"The Seismicity Rate Model for the 2022 New Zealand National Seismic Hazard Model"** (*Gerstenberger, et al, including Shaw, 2024*), *Bulletin of the Seismological Sociey of America*.

A seismicity rate model (SRM) has been developed as part of the 2022 Aotearoa New Zealand National Seismic Hazard Model revision. The SRM consists of many component models, each of which falls into one of two classes: (1) inversion fault model (IFM); or (2) distributed seismicity model (DSM). Here we provide an overview of the SRM and a brief description of each of the component models. The upper plate IFM forecasts the occurrence rate for hundreds of thousands of potential ruptures derived from the New Zealand Community Fault Model version 1.0 and utilizing either geologic- or geodetic- based fault-slip rates. These ruptures are typically less than a couple of hundred kilometers long, but can exceed 1500 km and extend along most of the length of the country (albeit with very low probabilities of exceedance [PoE]). We have also applied the IFM method to the two subduction zones of New Zealand and forecast earthquake magnitudes of up to Mw 9.4, again with very low PoE. The DSM combines a hybrid model developed using multiple datasets with a non-Poisson uniform rate zone model for lower seismicity regions of New Zealand. Forecasts for 100 yr are derived that account for overdispersion of the rate variability when compared with Poisson. Finally, the epistemic uncertainty has been modeled via the range of models and parameters implemented in an SRM logic tree. Results are presented, which indicate the sensitivity of hazard results to the logic tree branches and that were used to reduce the overall complexity of the logic tree.

Multiple contributions to the seismicity rate model came from our efforts. A productive synergistic collaboration across the US and NZ efforts, which went in parallel, helped improve a number of inputs, including scaling and rupture plausibility filter development.

## Published paper regarding Ground Motions reproduced by Physics-Based Simulators

**"Deterministic physics-based earthquake sequence simulators match empirical ground-motion models and enable extrapolation to data-poor regimes: Application to multifault multimechanism ruptures". Seismological Research Letters. " (Shaw, Milner, and Goulet, 2025) Seismological Research Letters, doi: 10.1785/0220240141.**

We use the deterministic earthquake simulator RSQSim to generate complex sequences of ruptures on fault systems used for hazard assessment. We show that the source motions combined with a wave propagation code create surface ground motions that fall within the range of epistemic uncertainties for the Next Generation Attenuation- West2 set of empirical models. We show the model is well calibrated where there are good data constraints, and has good correspondence in regions with fewer data con- straints. We show magnitude, distance, and mechanism dependence all arising naturally from the same underlying friction. The deterministic physics-based approach provides an opportunity for better understanding the physical origins of ground motions. For exam- ple, we find that reduced stress drops in shallow layers relative to constant stress drop with depth lead to peak ground velocities in the near field that better match empirical models. The simulators may also provide better extrapolations into regimes that are poorly empirically constrained by data because physics, rather than surface shaking data parameterizations, is underlying the extrapolations. Having shown the model is credible, we apply it to a problem where observations are lacking. We examine the case of crustal faults above a shallow subduction interface seen to break coseismically in simulations of the New Zealand fault system. These types of events were left out of consideration in the most recent New Zealand national seismic hazard model due to the modeling complexity and lack of observational data to constrain ground-motion models (GMMs). Here, we show that in the model, by breaking up the coseismic crustal and interface rupturing fault motions into two separate subevents, and then recombining the resulting ground-motion measures in a square-root-of-sum-of-squares incoherent manner, we reproduce well the ground-motion measures from the full event rupture. This provides a new method for extrapolating GMMs to more complex multifault ruptures.

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