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Informing Rupture Directivity Modeling with SCEC CyberShake Simulations

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Abstract

In this study, a database of near-fault CyberShake simulations, consisting of many earthquake sources with multiple hypocenters and rupture realizations, is used to evaluate rupture directivity effects in the simulated ground motions, by taking these steps:

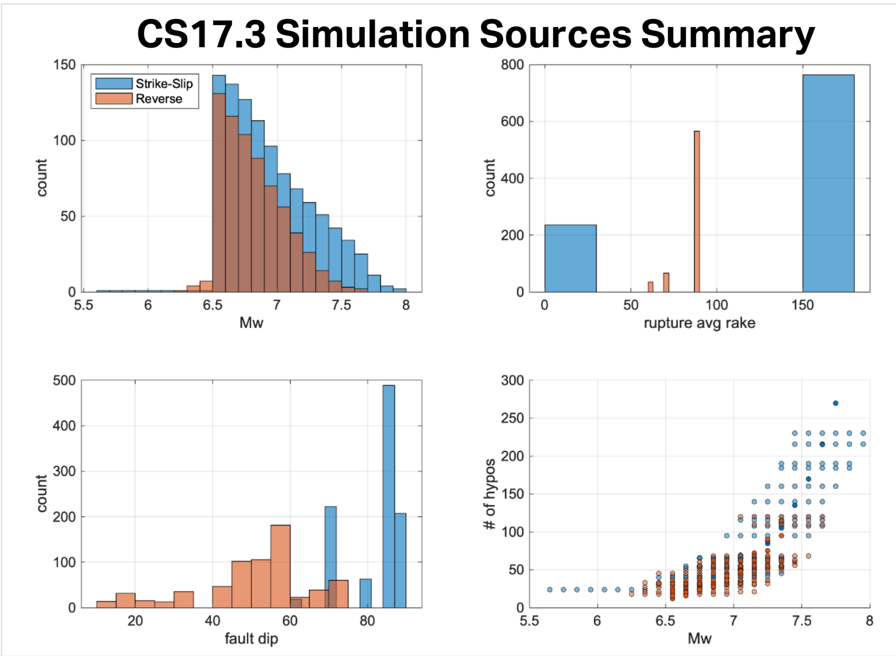
1. CyberShake ground motion residuals are calculated from the Meng et al. (2023; Mea23) ground motion model.
2. The residuals are used to evaluate the Bayless et al. (2020; Bea20) median directivity model.
3. These evaluations are both qualitative (subjective assessments of model performance) and quantitative (reductions in residual aleatory variability)

Results

- The overall performance of Bea20 as compared with the simulation residuals is promising, but wide-ranging. There are many instances of source and hypocenter location with residuals matching Bea20 quite well, and there are many instances which do not match as well.
- This is the same observation Bea20 made with respect to the recorded data used to develop their model.
- Peak amplitudes of mean simulation residuals are generally lower than the mean Bea20 predictions, and the variance of the simulation residuals are generally larger than Bea20.
- Nonetheless, significant modeling improvements gained by incorporating Bea20 are quantified through residual variance reductions.
- At T=5 sec, residual variance reductions of between 0.05 and 0.09 are found. This reduction is larger than the empirically derived reduction from Bea20, which is based on a relatively sparse dataset, and represents about a 12% reduction in one component of the aleatory variability, which is large enough to be impactful in seismic hazard applications.

(1) CyberShake Simulations

- The CS17.3 simulations for central California are selected for this study (both 1D and 3D versions). These sources are based on the UCERF2 model (Field et al., 2009) and use the Graves and Pitarka (2014) rupture generator.
- There are 1667 ruptures on 45 named faults with rupture extent completely within the footprint of the 438 sites. Each of these ruptures has multiple hypocenter location realizations, ranging from several dozens to several hundred of realizations depending on the rupture dimensions.
- 1034 of the 1667 ruptures are categorized as strike-slip based on average rake angle (absolute value of average rake less than 60 degrees or greater than 120 degrees).

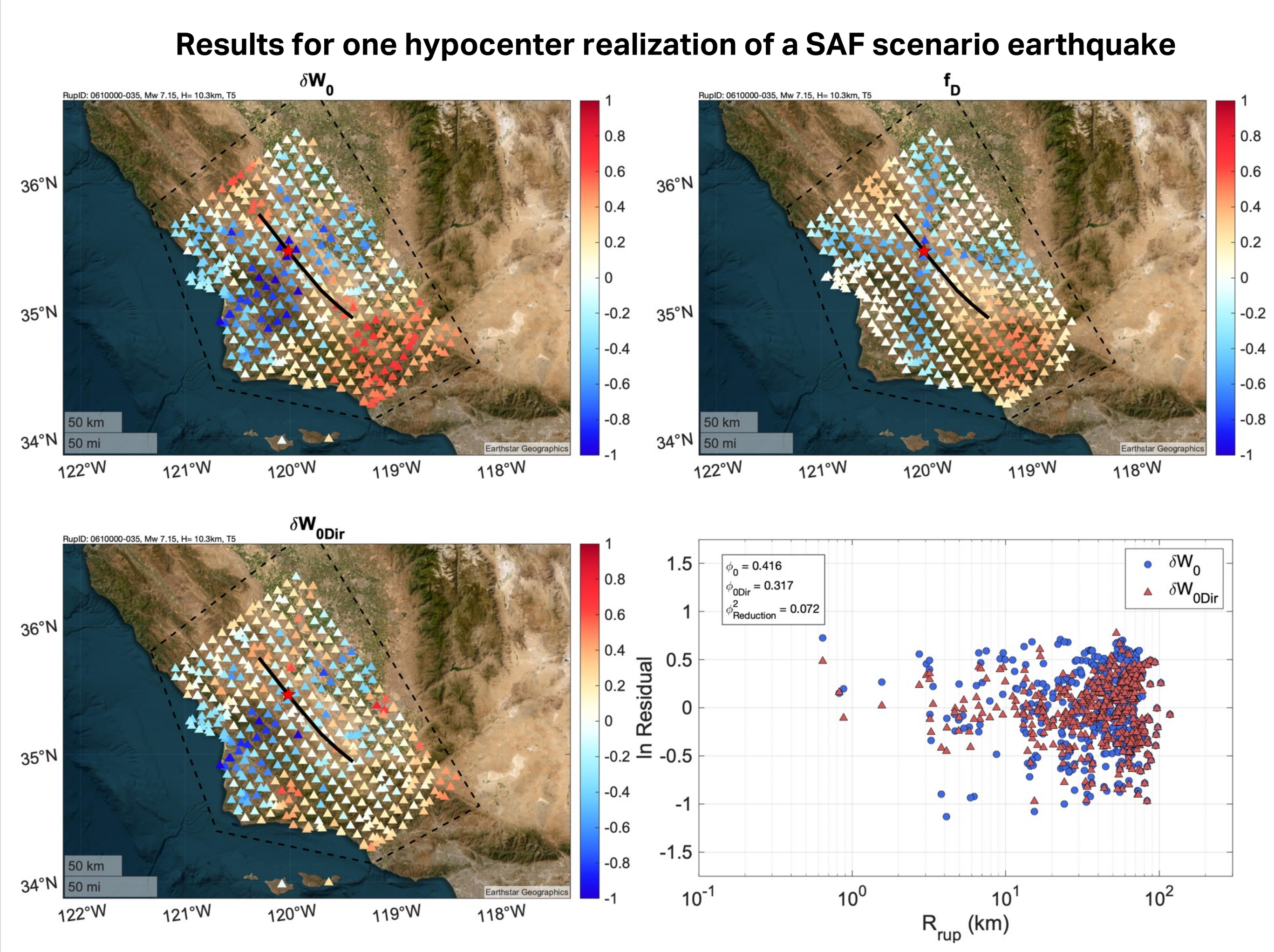


(2) Procedure

- δW_0 is the remaining CS17.3 residual (RotD50) after accounting for the median Mea23 ground motion model plus repeatable source, path, and site effects.
- f_D is the Bea20 directivity adjustment in natural log units (centered). Centering ensures the magnitude and distance scaling of the GMM is not altered.
- $\delta W_{0Dir} = (\delta W_0 - f_D)$ represents the the remaining residual after accounting for rupture directivity.
- The standard deviations of δW_0 and δW_{0Dir} are ϕ_0 and ϕ_{0Dir}, respectively.
- The reduction in aleatory variability due to incorporating the directivity model is represented as a difference in variances: $\phi^2_{Reduction} = \phi^2_0 - \phi^2_{0Dir}$

(3) Results: Individual Scenarios

- Individual scenario (defined as one earthquake and hypocenter realization) evaluations are used as a qualitative test of the Bea20 performance for median directivity.
- The figure at right compares maps of δW_0, f_D, and δW_{0Dir} (T=5 sec) for one hypocenter realization of one scenario earthquake.
- The δW_{0Dir} appear to have an improved fit to the simulation data, with less "hot" and "cold" areas on average than δW_0. This is especially apparent off the ends of the fault plane (forward directivity zones in a strike-slip earthquake).
- The residuals of this scenario have $\phi^2_{Reduction}$ = 0.072
- Overall Bea20 performance is wide-ranging (see abstract).

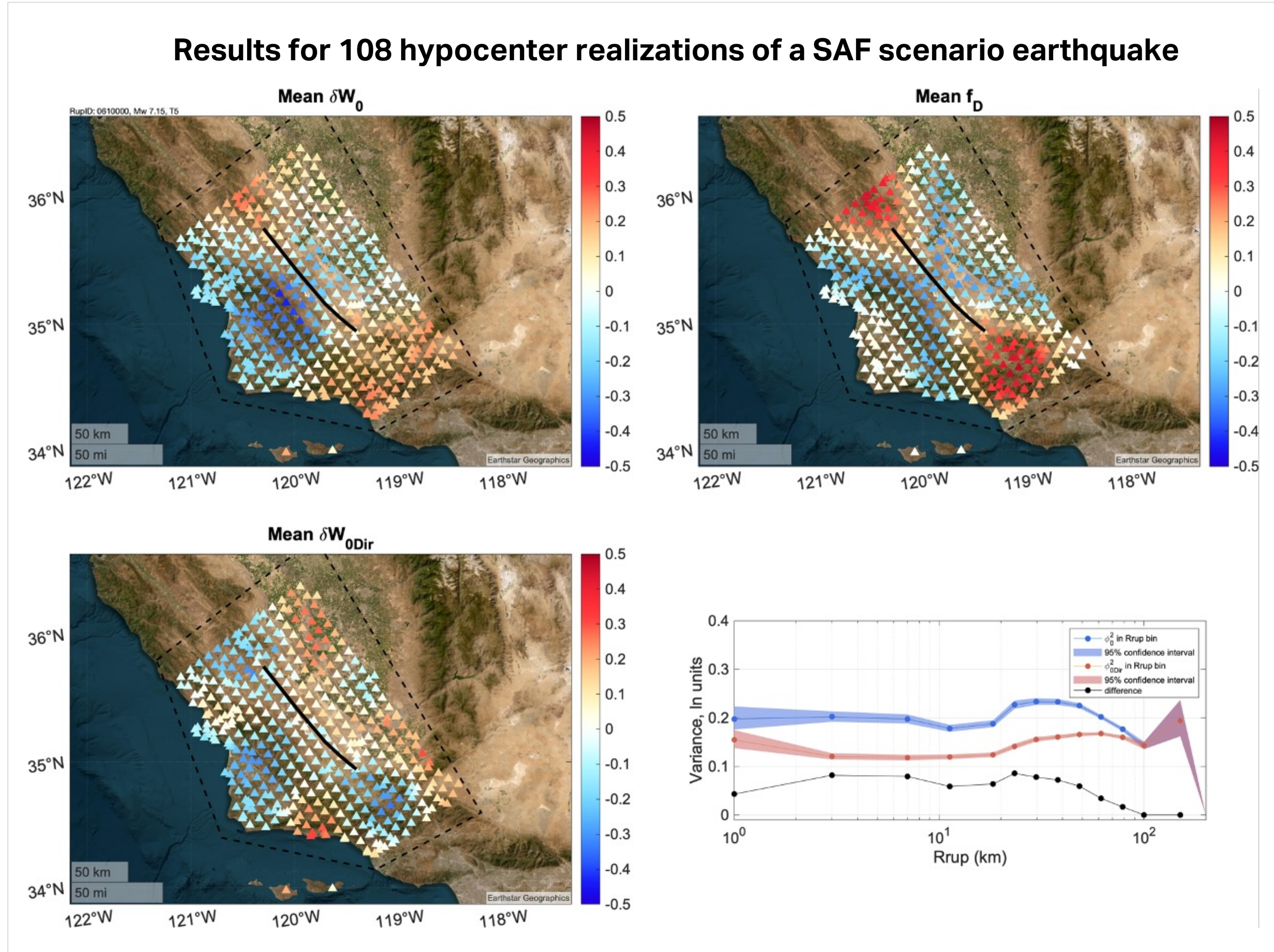


(4) Results: Considering Multiple Hypocenters

- The same maps as in Section 3, but using the mean results taken over 108 hypocenter realizations of the scenario.
- For this earthquake, the mean δW_0 has positive valued lobes off the ends of the fault, and regions of negative values between the fault ends; broadly consistent with Bea20.

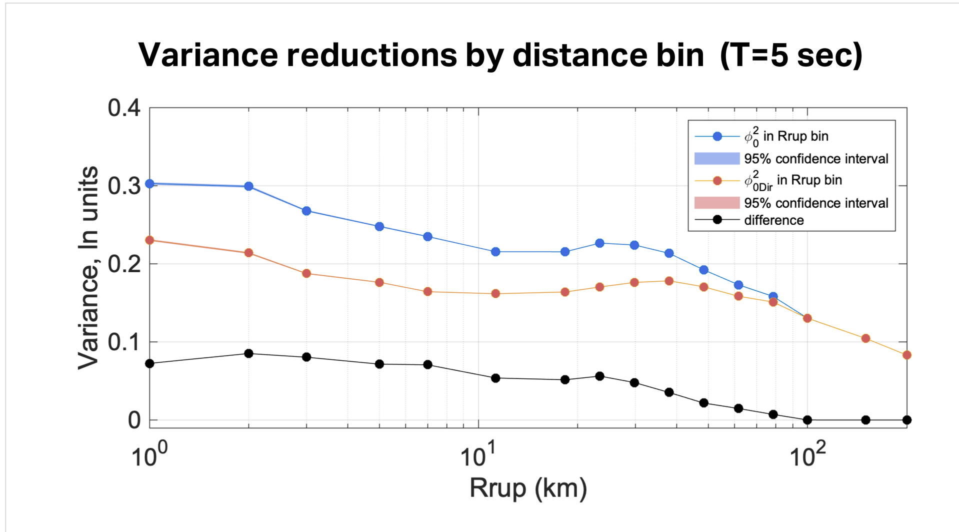
Overall observations:

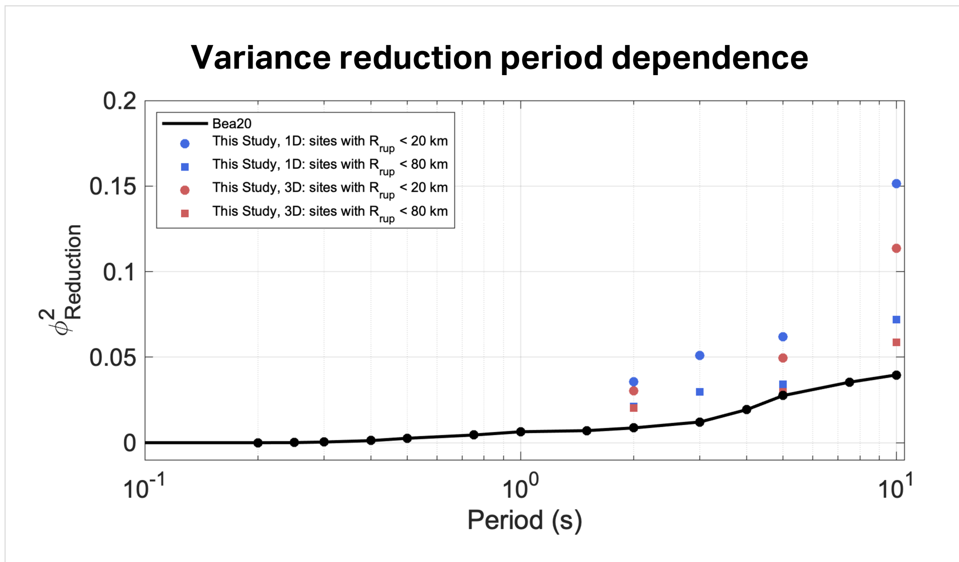
- The peak amplitudes of mean δW_0 are lower than the mean f_D.
- The variance δW_0 is larger than the variance of f_D.
- The Bea20 median adjustment may be too large, and the model variability may be low.
- Even considering these factors, the variability reductions are significant.



(5) Results: Aggregate (All Scenarios, All Hypocenters)

- The residuals from the 1034 strike-slip scenarios are pooled together to estimate the total variance reductions which result from including the Bea20 model.
- Within each distance bin, the variance is of the residuals from all scenarios and hypocenters.
- The $\phi^2_{Reduction}$ is between 0.05 and 0.09 for distances less than about 30 km, and then decreases to zero at 80 km distance and greater.
- Using example values of ϕ^2_0 = 0.30 and $\phi^2_{Reduction}$ = 0.07, the corresponding standard deviations are ϕ_0 = 0.548 and ϕ_{0Dir} = 0.480, which is a 12% reduction in the ϕ component of the aleatory variability. This is enough to be impactful in PSHA.
- The Bea20 model for $\phi^2_{Reduction}$ is shown at right. The Bea20 reduction was determined empirically from recordings of 22 NGA-West2 earthquakes, using sites within 80 km rupture distance. There was not sufficient data in Bea20 to determine distance dependence.





(6) Summary

- The overall performance of Bea20 as compared with the CS17.3 δW_0 is promising, but wide-ranging. There are many instances of source and hypocenter location with residuals patterns and amplitudes matching Bea20 quite well; these correspond to improved median predictions and variability reductions. There are also many instances which do not match as well. This is the same observation Bea20 made with respect to the recorded data used to develop their model.
- Generally better model performance occurs when the hypocenters are located near the ends of the faults. In these scenarios, the residuals have clearly defined areas of strong forward and backward directivity effects. When hypocenters are located closer to the middle of the fault plane, directivity effects in the residuals tend to be weaker than the Bea20 predictions. Instances of poorer match can correspond to the absence of apparent directivity effects in the δW_0 or to unexpected azimuthal patterns.
- Considering the multiple hypocenter realizations of any given scenario earthquake, two observations are made: The peak amplitudes of mean δW_0 are generally lower than the mean f_D, and the variance δW_0 is generally larger than the variance of f_D. These observations indicate that the Bea20 median adjustment may be too large, and the model variability may be low.
- Nonetheless, aleatory variance reductions ($\phi^2_{Reduction}$) resulting from incorporation of Bea20 into the residual analysis are significant. At T=5 sec, residual variance reductions are between 0.05 and 0.09 for sites with rupture distances less than about 30 km. This reduction is larger than the empirically derived reduction from Bea20, which is based on a relatively sparse dataset. A $\phi^2_{Reduction}$ value of 0.07 represents about a 12% reduction in the ϕ component of the aleatory variability, which is large enough to be impactful in PSHA.
- A future paper will describe the total aleatory variability adjustment that is appropriate with Bea20 in PSHA.

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