Seismological Research Letters

Sensitivity Analysis of the Inter-frequency Correlation of Synthetic Ground Motions to Pseudo-dynamic Source Models --Manuscript Draft--

Manuscript Number:	SRL-D-20-00181R2
Full Title:	Sensitivity Analysis of the Inter-frequency Correlation of Synthetic Ground Motions to Pseudo-dynamic Source Models
Article Type:	Article - Regular Section
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Manuscript Region of Origin:	KOREA, REPUBLIC OF
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**Sensitivity Analysis of the Inter-frequency Correlation of Synthetic Ground Motions to
Pseudo-dynamic Source Models**

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ABSTRACT

Given the deficiency of recorded strong ground motion data, it is important to understand the effects of earthquake rupture processes on near-source ground motion characteristics and to develop physics-based ground motion simulation methods for advanced seismic hazard assessments. Recently, the inter-frequency correlation of ground motions has become an important element of ground motion predictions. We investigate the effect of pseudo-dynamic source models on the inter-frequency correlation of ground motions by simulating a number of ground motion waveforms for the 1994 Northridge, California, earthquake, using the Southern California Earthquake Center (SCEC) BroadBand Platform (BBP). We find that the cross-correlation between earthquake source parameters in pseudo-dynamic source models significantly affects the inter-frequency correlation of ground motions in the frequency around 0.5 Hz while its effect is not visible in the other frequency ranges. Our understanding of the effects of earthquake sources on the characteristics of near-source ground motions, particularly the inter-frequency correlation, may help to develop advanced physics-based ground motion simulation methods for advanced seismic hazard and risk assessments.

INTRODUCTION

Ground motion prediction is an important element of the assessment of seismic hazards. In particular, for advanced seismic hazard assessment endeavors, it is important to understand the near-source ground motion characteristics of large events. Empirical ground motion prediction equations (GMPEs) have been used extensively to predict ground motion intensity measures such as the peak ground acceleration (PGA) and pseudo-spectral acceleration (PSA) (e.g., Abrahamson et al., 2008). However, although ground motions have been recorded worldwide, the quantity of recorded strong ground motions is insufficient to investigate the near-source characteristics, i.e., the intensity and variability of ground motions near earthquake fault rupture (Chiou et al., 2008). Recently, physics-based ground motion simulation approaches, including both dynamic and pseudo-dynamic earthquake rupture models, have become more popular for evaluating the near-source ground motion characteristics such as the effect of rupture directivity and fault complexity (e.g., roughness), given the availability of advanced numerical modeling schemes and rapidly growing high-performance computing capabilities (Olsen et al., 2009; Graves et al., 2011; Shi and Day, 2013).

GMPEs predict both the mean and the standard deviation of ground motion intensity measures such as PGA and PSA, given a set of explanatory seismological parameters (magnitude, distance, site conditions, etc.). Recently, several research groups pioneered a method to investigate the inter-frequency (or inter-period) correlation characteristics of ground motions by analyzing recorded ground motion data (Baker and Cornell, 2006; Baker and Jayaram, 2008; Stafford, 2017; Bayless and Abrahamson, 2019a). The inter-frequency correlation characterizes the relative width (in the frequency domain) of the extrema in a ground motion spectrum. The widths of the peaks and troughs in ground motion spectra are significant in assessments

involving simulated ground motions because the variability in dynamic response analyses can be underestimated if simulated ground motions have an excessively low correlation (Bayless and Abrahamson, 2018).

It would be meaningful to investigate whether physics-based ground motion simulation models can produce the inter-frequency correlation of ground motions, consistent with empirical correlation models, obtained by analyzing recorded ground motion data. There have been several attempts to understand how well the physics-based ground motion simulation models reproduce the mean and the standard deviation of ground motion intensity measures, produced by empirical GMPEs (Cotton et al., 2013; Causse and Song, 2015; Imtiaz et al., 2015; Vyas et al., 2016; Crempien and Archuleta, 2017; Moschetti et al., 2017; Wirth et al., 2017). Recently, Wang et al. (2019) implemented an inter-frequency correlation model obtained by analyzing recorded ground motion data in their physics-based broadband ground motion simulation platform. In other words, they developed a post-processing method for their synthetic ground motion waveforms to mimic the inter-frequency correlation structure observed in the empirical model. However, we think that this study is a first attempt to understand the direct link between physics-based ground motion simulation models and the inter-frequency correlation of ground motions.

In this study, we adopted the pseudo-dynamic source modeling method, proposed by Song et al. (2014) and Song (2016), for physics-based ground motion simulations, which is implemented at the SCEC BBP. Pseudo-dynamic source modeling approaches maintain the computational efficiency of kinematic source modeling methods but emulate the essential physics of earthquake rupture dynamics by statistically analyzing a number of dynamic rupture models (Guatteri et al., 2004; Graves and Pitarka, 2010; Schmedes et al., 2013; Song et al., 2014). Fayjaloun et al. (2019) and Park et al. (2020) successfully investigated the effect of the

pseudo-dynamic source models, developed by Song et al. (2014) and Song (2016), on the mean and the standard deviation of ground motions. In this study, we investigated the effect of the pseudo-dynamic source models on the inter-frequency correlation of ground motions. We first performed a series of ground motion simulations for the 1994 Northridge, California, earthquake, using various sets of pseudo-dynamic source models. Then we investigated the sensitivity of the inter-frequency correlation of the simulated ground motions to those pseudo-dynamic source models.

GROUND MOTION SIMULATION

For this research, we adopted the broadband platform (BBP) developed by the Southern California Earthquake Center (SCEC) for synthetic ground motion simulations (see Data and Resources). Multiple research groups, including both earthquake scientists and engineers, have been involved in the SCEC BBP project (Goulet et al., 2015; Maechling et al., 2015). The BBP has been thoroughly validated against both actual ground motions recorded during past earthquakes and empirical GMPEs (Dreger et al., 2015; Goulet et al., 2015). The latest version of the BBP is released regularly; here, we used V. 16.5, which was released in May 2016. Multiple modeling schemes are provided in the platform; we chose the Song method, which uses pseudo-dynamic source models, based on the 1-point and 2-point statistics of earthquake source parameters (Song et al., 2014; Song, 2016). The Song method adopts the Graves and Pitarka (GP) method (Graves and Pitarka, 2010) for the simulation of high-frequency (> 1 Hz) ground motions as well as the low-frequency (< 1 Hz) seismic wave propagation. The GP method adopts the Green's function computation method developed by Zhu and Rivera (2002), given a 1-dimensional velocity model. In this study, we primarily aimed to investigate the inter-frequency

correlation of ground motions in the low-frequency range, i.e., between 0.1 and 1.0 Hz. Thus, we expect that the inter-frequency correlation is mainly affected by the pseudo-dynamic source models, implemented in ground motion simulations.

The SCEC BBP performed two types of validation (Goulet et al., 2015). The first validation (Part A) was against ground motion data recorded during past earthquakes in North America and Japan. The second (Part B) was against empirical GMPEs. Among the Part A validation events, we chose the 1994 Northridge, California, earthquake for our study. Detailed information about the fault plane geometry of the event is given in Table 1 and Figure 1. The Northridge event occurred in a highly populated area and produced well-recorded ground motions, as shown in Figure 1. For the details of the event simulation, we followed the procedure established by the SCEC BBP group (Goulet et al., 2015).

Given the fault geometry defined in Table 1, we prepared three sets of pseudo-dynamic rupture models for our sensitivity test, as summarized in Table 2. Furthermore, we employed the input source statistics models proposed by Song (2016), which are also summarized in Table 3. The basic set (Test Set I) in Table 2 is composed of two groups of pseudo-dynamic source models. One group contains correlated source models, while the other contains uncorrelated source models. The core element in the pseudo-dynamic source models proposed by Song et al. (2014) is the cross-correlation structure coupling the earthquake source parameters, such as the slip, rupture velocity, and peak slip velocity. For the group of uncorrelated source models, we simulated the pseudo-dynamic source models without a cross-correlation structure, as visualized in Figure 2. Several studies have been performed to understand the effects of the cross-correlation structure on near-source ground motions, particularly the mean and the standard

deviation of ground motion intensity measures such as the peak ground velocity (PGV) and PGA (Fayjaloun et al., 2019; Park et al., 2020).

However, whereas the authors of these studies perturbed each cross-correlation component individually for their sensitivity analysis, we focused on two cases, i.e., full cross-correlation (correlated) and no cross-correlation (uncorrelated) between the earthquake source parameters, as shown in Figure 2. For Test Set I in Table 2, we simulated 100 pseudo-dynamic source models, i.e., 50 correlated and 50 uncorrelated source models. Figure 3 shows the first three source models among the 50 models in the group of correlated source models, while Figure 4 shows the first three for the group of uncorrelated source models. In the correlated source models, the source parameters (such as the slip, rupture velocity, and peak slip velocity) are coupled together according to the cross-correlation structure in Figure 2a. Since the pseudo-dynamic source models are obtained by stochastic modeling, based on the covariance matrix constructed by the input source statistics models (Song et al., 2014), each source model exhibits unique randomness; nevertheless, we can observe correlations between the source parameters in Figure 3. In contrast, the distributions of the source parameters within the models depicted in Figure 4 display heterogeneity, controlled by the diagonal elements of Figure 2b, but no coupling between the source parameters is expected.

We also prepared two additional sets of pseudo-dynamic source models, i.e., Test Sets II and III in Table 2, for our sensitivity analysis. In Test Set II, we randomly perturbed the hypocenter of each source model. In the Part A validation, following Goulet et al. (2015), the hypocenter was fixed since the validation was performed for real past events. We adopted the same strategy for Test Set I. However, the hypocenter location may significantly affect the near-source ground motion characteristics. Therefore, since we aimed to investigate the sensitivity of

ground motions to various pseudo-dynamic source models rather than to validate our pseudo-dynamic source models against recorded ground motion data, we decided to test random hypocenter models in Test Set II as well.

In Test Set III, we perturbed the stress drop by increasing or decreasing the rupture dimension while holding the seismic moment constant. Since the stress drop directly affects the corner frequency and hence the shape of the Fourier amplitude spectrum (e.g., Causse and Song, 2015), the stress drop may also affect the inter-frequency correlation characteristics of ground motions. The static stress drop is proportional to the ratio of the mean slip to the characteristic rupture dimension ($\tilde{L}$), as given in the equation below (Kanamori and Anderson, 1975):

$$\Delta\tau \approx \frac{\mu_{slip}}{\tilde{L}} . \quad (1)$$

Models with larger stress drops were obtained by decreasing both the rupture length and the width by 30%, while models with smaller stress drops were obtained by increasing both the rupture length and the width by 30%. The input source statistics for each model are presented in Table 3. Figures 5 and 6 show one example each of the simulated pseudo-dynamic source models with larger and smaller stress drops, respectively. In Test Set III, there are 300 pseudo-dynamic source models, i.e., 150 correlated and 150 uncorrelated models, as indicated in Table 2. The 150 correlated source models contain 50 models with larger stress drops and 50 with smaller stress drops in addition to the 50 correlated source models from Test Set I.

Using the SCEC BBP (V. 16.5), we simulated three-component ground motion waveforms at the 133 stations illustrated in Figure 1 for each pseudo-dynamic source model. The Song method adopts a hybrid approach, i.e., pseudo-dynamic low-frequency (< 1 Hz; Song, 2016) and stochastic high-frequency (> 1 Hz; Graves and Pitarka, 2010) modeling schemes. For a systematic sensitivity analysis of the simulated ground motions with a single representative

metric for the ground motion intensity measures, we adopted the effective amplitude spectrum (EAS), computed with two horizontal-component ground motions as (Bayless and Abrahamson, 2018)

$$EAS(f) = \sqrt{\frac{1}{2}[FAS_{HC1}(f)^2 + FAS_{HC2}(f)^2]}, \quad (2)$$

where FAS_{HC1} and FAS_{HC2} are the Fourier amplitude spectra of the two orthogonal horizontal components of the three-component waveforms and f is the frequency in Hz. The EAS is independent of the orientation of the instrument. Using the average power of the two horizontal components (Eq. 2) leads to an amplitude spectrum that is compatible with the application of random vibration theory to convert the Fourier spectra into response spectra. The EAS is smoothed using the $\log_{10}$ -scale smoothing window of Konno and Ohmachi (1998) with the smoothing parameters described by Kottke et al. (2018).

Figure 7 shows examples of the EASs for the three selected stations plotted in red in Figure 1. For the near-source station (nwbp, $R_{rup} = 5.4$ km), the low- and high-frequency EASs do not differ considerably, but for the other two stations (gllp, $R_{rup} = 21.5$ km; schl, $R_{rup} = 40.4$ km), the two frequency bands, i.e., the low-frequency (< 1 Hz) and high-frequency (> 1 Hz) bands, show distinctive EAS patterns. Since we used the abovementioned hybrid approach, the low- and high-frequency ground motions may not behave consistently for all rupture scenarios and station locations. This issue may need to be investigated further for all hybrid ground motion simulation methods offered by the SCEC BBP. In this study, we aimed predominantly to analyze low-frequency (< 1 Hz) ground motions, which are affected by the cross-correlation structure of the input pseudo-dynamic source models, for the sensitivity analysis of inter-frequency correlations. We also added the mean and the standard deviation values predicted by the

empirical model (Bayless and Abrahamson, 2019b) to the figure for comparison purposes. The empirical model used in the study will be discussed in more details in the next section.

CORRELATION ANALYSIS

Bayless and Abrahamson (2019ab) developed both the inter-frequency correlation model and the GMPE using the Next Generation Attenuation-West2 (NGA-West2; Ancheta et al, 2014) database, which includes shallow crustal earthquakes in active tectonic regions. Their models adopt the effective amplitude spectrum (EAS), which is based on the Fourier Amplitude Spectra (FAS), in equation (2) as ground motion intensity measure. Bayless and Abrahamson (2019b) clearly described the benefit of using the EAS than response spectra in their paper. We adopted their EAS based GMPE and inter-frequency correlation model to compare with our synthetics since the Fourier spectra are more closely related to the physics-based simulations. Their empirical models also provide individual residual components for more detailed comparison. Residuals from empirical GMPEs are typically partitioned into between-event residual (δB), and within-event residuals (δW), following the notation of Al Atik et al., (2010). For large numbers of recordings per earthquake, the between-event residual is approximately the average difference in logarithmic-space between the observed Intensity Measure (IM) from a specific earthquake and the IM predicted by the GMPE. The within-event residual (δW) is the difference between the IM at a specific site for a given earthquake and the median IM predicted by the GMPE plus δB . By accounting for repeatable site effects, δW can further be partitioned into a site-to-site residual ($\delta S2S$) and the within-site residual (δWS). More detailed description about the residual partitioning, including the mathematical description of the inter-frequency correlation (both between- and within-event), is provided in Bayless and Abrahamson (2018).

Figure 8 shows the mean residuals on a natural logarithmic scale between the simulated EASs and the EASs predicted by the empirical GMPE (Bayless and Abrahamson, 2019b) for both the correlated and the uncorrelated models in Test Set I. We observed that the mean of the synthetic EASs underpredicts the mean of the GMPE at the low frequency, while the mean of the former overpredicts that of the latter at the high frequency. At the low frequency, the correlated models produce slightly higher EASs, as was also observed in previous studies (Song et al., 2014; Song, 2016; Fayjaloun et al., 2019; Park et al., 2020). Since we compared synthetic ground motions produced by simulating a specific earthquake, i.e., the Northridge event, and because we constructed the mean of the GMPE by using recorded ground motions from various events worldwide, the bias we observe in Figure 8 may be reasonable and may be considered part of the between-event variability (Al Atik et al., 2010). In addition, we aimed to investigate mainly the relative sensitivity of the inter-frequency correlation of our synthetic ground motions in this study rather than to reproduce the absolute level of ground motion intensities constrained by empirical GMPEs.

The variability (e.g., standard deviation) of ground motions is an important consideration in ground motion prediction (Abrahamson et al., 2008; Cotton et al., 2013; Causse and Song, 2015; Imtiaz et al., 2015; Vyas et al., 2016; Crempien and Archuleta, 2017; Withers et al., 2019ab). Figure 9 shows the standard deviations for both the between-event and the within-event components of the EAS residuals from the three sets of model tests. The between-event term is calculated from various realizations of the source within each test set. First, little difference is noted between the ground motions obtained from the correlated and uncorrelated pseudo-dynamic source models. In other words, the cross-correlations between the earthquake source parameters in Figure 2 do not significantly affect both the between-event and the within-event

standard deviations in our simulations. Crempien and Archuleta (2017) found that the longer correlation (i.e., autocorrelation) of earthquake slip increases both the between- and within-event standard deviations of ground motions. The cross-correlation of pseudo-dynamic source models does not seem to play a significant role in determining the standard deviation in our simulations, but may need to be further investigated in subsequent studies to confirm its behavior.

Note that the between-event standard deviation for Test Set II (random hypocenter) is much larger than that for the other two test sets. Since Test Set II introduces randomly located hypocenters, this discrepancy implies that randomizing the hypocenter has a greater effect on the between-event variability than does the stress drop perturbation. It is also noticeable that the random hypocenter models reduce the within-event standard deviation significantly as shown in Figure 9b. We also compared them with the standard deviations from the empirical GMPE (Bayless and Abrahamson, 2019b) as indicated in black lines. Regarding the between-event standard deviation, the empirical model is consistent with the synthetic ground motions with the random hypocenter models. Regarding the within-event standard deviation, in general synthetic ground motions produce larger values. For the random hypocenter model in Figure 9b, the difference is minimized. However, if we consider only the within-site (δWS) standard deviation without the between-site ($\delta S2S$) term since the site effect was not included in our simulations, the synthetics still produce larger standard deviations. Note that we restricted our analysis to the low frequency below 1 Hz although we show the results up to 10 Hz for reference in the figure.

The main goal of this study was to investigate the effect of cross-correlations between earthquake source parameters, such as the slip, rupture velocity, and peak slip velocity, in pseudo-dynamic source models on the inter-frequency correlation of ground motions. Figure 10 shows the between-event inter-frequency correlations of the synthetic EASs for the three sets of

model tests in the low-frequency band (0.1 – 1.0 Hz) with those from an empirical model (Bayless and Abrahamson, 2019a). Interestingly, the between-event inter-frequency correlations for the fixed-hypocenter models decay much faster than those for the empirical model as the frequency deviates from the reference frequencies (0.2, 0.3, 0.4, 0.5, and 1.0 Hz), while the random hypocenter models produce inter-frequency correlations that are compatible with those from the empirical model. More remarkably, we found distinctive features between the correlated and uncorrelated models at approximately 0.5 Hz (2 s) when the reference frequencies were 0.4 Hz (Test Set II) or 0.5 Hz (Test Sets I and III): the correlated source models (in red) produced higher inter-frequency correlations than the uncorrelated source models (in blue) for all three test sets at approximately 0.5 Hz, although the difference was not significant at the other reference frequencies. In this analysis, we focus more on the correlation near each reference frequency, i.e., initial decay pattern from each reference frequency. Thus we show correlations only between 0.6 and 1.0 in Figure 10. The correlation at the far distance in the spectral domain may need to be analyzed further in subsequent studies. This observation, however, may imply that the cross-correlation between earthquake source parameters in pseudo-dynamic source models affects the initial decay pattern of the inter-frequency correlation of ground motions in a certain frequency range, as depicted with solid red and blue traces in Figure 10.

Within-event residuals represent the variability in the path effects and directivity effects for a given event at various stations. Figure 11 indicates that the inter-frequency correlations of simulated ground motions systematically exceed those of the empirical model. And we do not observe significant differences between correlated and uncorrelated pseudo-dynamic source models. It is not clear yet why the synthetic ground motions produce broader inter-frequency correlation structure than the empirical model. Based on Bayless and Abrahamson (2018), the

fully stochastic ground motion simulation method (e.g., Atkinson and Assatourians, 2015) produce the within-event inter-frequency correlations compatible with the empirical model (figure 10b of Bayless and Abrahamson (2018)) while the physics-based ground motion simulation methods produce the correlations, which are broader than the empirical model (figures 11b, 12b, 13b and 14b of Bayless and Abrahamson (2018)). It is still puzzling why the physics-based methods, which more explicitly handle wave propagation effects such as directivity, produce the within-event correlations inconsistent with the empirical model. Although we aim to focus more on the effect of earthquake source on the inter-frequency correlations, i.e., between-event, the inconsistency observed in the within-event correlation may need to be investigated further in subsequent studies.

DISCUSSION

In Figure 10, the cross-correlation in the pseudo-dynamic source models affects the between-event inter-frequency correlation of ground motions in a specific frequency range, i.e., approximately 0.5 Hz. However, it is not yet clear why the frequency range centered at approximately 0.5 Hz is strongly affected by the cross-correlation of pseudo-dynamic source models for the Northridge, California, earthquake. It is also surprising that there are almost no differences in the other frequency ranges. This phenomenon may be linked to the magnitude of the simulated event or the event type. The reason may become clearer if we perform more sensitivity analyses over a wide range of magnitudes and event types in subsequent studies. Moreover, the number and positions of stations used in the analyses may also affect the outcomes. Test Sets II and III clearly indicate that the inter-frequency correlation can be affected by randomized hypocenter locations and stress drop perturbations more significantly than by

input source statistics perturbations, as shown in Table 3. Hence, we need to carefully consider these source parameters, such as the hypocenter and stress drop, even when we focus on investigating the effects of the detailed input source statistics in Table 3 on the characteristics of ground motions. Finally, our sensitivity analyses clearly indicate that the cross-correlation structure in the pseudo-dynamic source models affects the inter-frequency correlation more significantly than the standard deviation of the ground motions. We may also employ the empirical inter-frequency correlation model (Bayless and Abrahamson, 2019a) to constrain the cross-correlation structure of pseudo-dynamic source models.

There have been several attempts to investigate the effects of pseudo-dynamic source models on the mean and standard deviation of ground motions (Song et al., 2014; Song, 2016; Fayjaloun et al., 2019; Park et al., 2020). However, this study is the first attempt to investigate the effect of pseudo-dynamic source models on the inter-frequency correlation of ground motions. Interestingly, we found that the cross-correlation structure, which is a core element of the pseudo-dynamic source modeling approach proposed by Song et al. (2014), may significantly affect the inter-frequency correlation of ground motions, at least in a specific frequency range. Nevertheless, we may need more comprehensive sensitivity analyses to understand the link between pseudo-dynamic source models and the inter-frequency correlation of ground motions in greater detail. However, we believe that this pilot study already shows the potential of physics-based ground motion simulation methods provided by the SCEC BBP for studying the inter-frequency correlation characteristics of ground motions.

CONCLUSIONS

In this study, we investigated the effect of pseudo-dynamic source models, particularly their cross-correlation structure between earthquake source parameters, on the inter-frequency correlation of ground motions by simulating a number of ground motions for the 1994 Northridge, California, earthquake using the SCEC BBP. We found that the cross-correlation of pseudo-dynamic source models significantly affects the between-event inter-frequency correlation at a specific frequency range (at approximately 0.5 Hz), while the effect on the standard deviation of ground motions is not significant. It is important to understand the inter-frequency correlation characteristics of ground motions in ground motion predictions. This type of study may help to understand the relation between physics-based earthquake source models and the inter-frequency correlation of ground motions and consequently to develop physics-based ground motion simulation methods for advanced seismic hazard and risk assessments.

DATA AND RESOURCES

We simulated synthetic 3-component ground motion waveforms using the SCEC BBP (V. 16.5), which is available online (http://scec.usc.edu/scecpedia/Broadband_Platform, last accessed April 2020). The stand-alone version of the pseudo-dynamic rupture model generator, used in the study, is also available online (<http://www.github.com/sgsong1017/SongRMG>, last accessed July 2020).

ACKNOWLEDGMENTS

We appreciate the editor's and three anonymous reviewers' comments, which helped to improve the paper significantly. We would like to thank F. Silva, P. Maechling, C. Goulet, and R.W. Graves for their kind technical and scientific support regarding the SCEC BBP. This study was

354 supported by a See-At Project funded by the Korea Meteorological Administration (KMA)
355 (KMI2018-01810) and by a Basic Research Project of the Korea Institute of Geoscience and
356 Mineral Resources (KIGAM), funded by the Ministry of Science and ICT (MSIT, Korea)
357 (GP2020-027).

REFERENCES

- Abrahamson, N., G. Atkinson, D. Boore, Y. Bozorgnia, K. Campbell, B. Chiou, I. M. Idriss, W. Silva, and R. Youngs (2008). Comparisons of the NGA ground-motion relations, *Earthquake Spectra* **24** 45-66.
- Al Atik, L., N. Abrahamson, J. J. Bommer, F. Scherbaum, F. Cotton, and N. Kuehn (2010). The variability of ground-motion prediction models and its components, *Seismol. Res. Lett.* **81** 794-801.
- Ancheta, T. D., R. B. Darragh, J. P. Stewart, E. Seyhan, W. J. Silva, B. S.-J. Chiou, K. E. Wooddell, R. W. Graves, A. R. Kottke, D. M. Boore, et al. (2014). NGA-West2 database, *Earthquake Spectra* **30**, 989–1005.
- Atkinson, G. M., and K. Assatourians (2015). Implementation and validation of EXSIM (A stochastic finite-fault ground-motion simulation algorithm) on the SCEC broadband platform, *Seismol. Res. Lett.* **86** 48-60.
- Baker, J. W., and C. A. Cornell (2006). Correlation of response spectral values for multicomponent ground motions, *Bull. Seismol. Soc. Am.* **96** 215-227.
- Baker, J. W., and N. Jayaram (2008). Correlation of spectral acceleration values from nga ground motion models, *Earthquake Spectra* **24** 299-317.
- Bayless, J., and N. A. Abrahamson (2018). Evaluation of the interperiod correlation of ground-motion simulations, *Bull. Seismol. Soc. Am.* **108** 3413-3430.
- Bayless, J., and N. A. Abrahamson (2019a). An empirical model for the interfrequency correlation of epsilon for fourier amplitude spectra, *Bull. Seismol. Soc. Am.* **109** 1058-1070.
- Bayless, J., and N. A. Abrahamson (2019b). Summary of the BA18 ground-motion model for

381 fourier amplitude spectra for crustal earthquakes in California, *Bull. Seismol. Soc. Am.*
 382 **109** 2088-2105.

383 Causse, M., and S. G. Song (2015). Are stress drop and rupture velocity of earthquakes
 384 independent? Insight from observed ground motion variability, *Geophys. Res. Lett.* **42**
 385 7383-7389.

386 Chiou, B., R. Darragh, N. Gregor, and W. Silva (2008). NGA project strong-motion database,
 387 *Earthquake Spectra* **24** 23-44.

388 Cotton, F., R. Archuleta, and M. Causse (2013). What is sigma of the stress drop?, *Seismol. Res.*
 389 *Lett.* **84** 42-48.

390 Crempien, J. G. F., and R. J. Archuleta (2017). Within-event and between-events ground motion
 391 variability from earthquake rupture scenarios, *Pure Appl. Geophys.* **174** 3451-3465.

392 Dreger, D. S., G. C. Beroza, S. M. Day, C. A. Goulet, T. H. Jordan, P. A. Spudich, and J. P.
 393 Stewart (2015). Validation of the SCEC broadband platform V14.3 simulation methods
 394 using pseudospectral acceleration data, *Seismol. Res. Lett.* **86** 39-47.

395 Fayjaloun, R., M. Causse, C. Cornou, C. Voisin, and S. G. Song (2019). Sensitivity of high-
 396 frequency ground motion to kinematic source parameters, *Pure Appl. Geophys.* doi:
 397 10.1007/s00024-019-02195-3

398 Goulet, C. A., N. A. Abrahamson, P. G. Somerville, and K. E. Wooddell (2015). The SCEC
 399 broadband platform validation exercise: methodology for code validation in the context
 400 of seismic-hazard analyses, *Seismol. Res. Lett.* **86** 17-26.

401 Graves, R., T. H. Jordan, S. Callaghan, E. Deelman, E. Field, G. Juve, C. Kesselman, P.
 402 Maechling, G. Mehta, K. Milner, D. Okaya, P. Small, and K. Vahi (2011). Cybershake: a
 403 physics-based seismic hazard model for Southern California, *Pure Appl. Geophys.* **168**

404 367-381.

405 Graves, R. W., and A. Pitarka (2010). Broadband ground-motion simulation using a hybrid
 406 approach, *Bull. Seismol. Soc. Am.* **100** 2095-2123.

407 Guatteri, M., P.M. Mai, and G.C. Beroza (2004). A pseudo-dynamic approximation to dynamic
 408 rupture models for strong ground motion prediction, *Bull. Seismol. Soc. Am.* **94** 2051-
 409 2063.

410 Imtiaz, A., M. Causse, E. Chaljub, and F. Cotton (2015). Is ground-motion variability distance
 411 dependent? Insight from finite-source rupture simulations, *Bull. Seismol. Soc. Am.* **105**
 412 950-962.

413 Kanamori, H., and D. L. Anderson (1975). Theoretical basis of some empirical relations in
 414 seismology, *Bull. Seismol. Soc. Am.* **65** 1073-1095.

415 Konno, K., and T. Ohmachi (1998). Ground-motion characteristics estimated from spectral ratio
 416 between horizontal and vertical components of microtremor, *Bull. Seismol. Soc. Am.* **88**
 417 228-241.

418 Kottke, A., E. Rathje, D. M. Boore, E. Thompson, J. Hollenback, N. Kuehn, C. A. Goulet, N. A.
 419 Abrahamson, Y. Bozorgnia, and A. D. Kiureghian (2018). *Selection of random vibration*
 420 *procedures for the NGA east project, PEER Rept. No. 2018/05*. Pacific Earthquake
 421 Engineering Research Center, University of California, Berkeley, California.

422 Maechling, P. J., F. Silva, S. Callaghan, and T. H. Jordan (2015). SCEC broadband platform:
 423 system architecture and software implementation, *Seismol. Res. Lett.* **86** 27-38.

424 Moschetti, M. P., S. Hartzell, L. Ramírez-Guzmán, A. D. Frankel, S. J. Angster, and W. J.
 425 Stephenson (2017). 3D ground-motion simulations of Mw 7 earthquakes on the salt lake
 426 city segment of the wasatch fault zone: variability of long-period ($T \geq 1$ s) ground

427 motions and sensitivity to kinematic rupture parameters, *Bull. Seismol. Soc. Am.* **107**
 428 1704-1723.

429 Olsen, K. B., S. M. Day, L. A. Dalguer, J. Mayhew, Y. Cui, J. Zhu, V. M. Cruz-Atienza, D.
 430 Roten, P. Maechling, T. H. Jordan, D. Okaya, and A. Chourasia (2009). ShakeOut-D:
 431 ground motion estimates using an ensemble of large earthquakes on the southern San
 432 Andreas fault with spontaneous rupture propagation, *Geophys. Res. Lett.* **36** L04303.

433 Park, D., S. G. Song, and J. Rhie (2020). Sensitivity analysis of near-source ground motions to
 434 pseudo-dynamic source models derived with 1-point and 2-point statistics of earthquake
 435 source parameters, *J. Seismol.* doi: 10.1007/s10950-020-09905-8

436 Schmedes, J., R. J. Archuleta, and D. Lavallée (2013). A kinematic rupture model generator
 437 incorporating spatial interdependency of earthquake source parameters, *Geophys. J. Int.*
 438 **192** 1116-1131.

439 Shi, Z., and S. M. Day (2013). Rupture dynamics and ground motion from 3-D rough-fault
 440 simulations, *J. Geophys. Res. Solid Earth* **118** 1122-1141.

441 Song, S. G. (2016). Developing a generalized pseudo-dynamic source model of Mw6.5–7.0 to
 442 simulate strong ground motions, *Geophys. J. Int.* **204** 1254-1265.

443 Song, S. G., L. A. Dalguer, and P. M. Mai (2014). Pseudo-dynamic source modelling with 1-
 444 point and 2-point statistics of earthquake source parameters, *Geophys. J. Int.* **196** 1770-
 445 1786.

446 Stafford, P. J. (2017). Interfrequency correlations among fourier spectral ordinates and
 447 implications for stochastic ground-motion simulation, *Bull. Seismol. Soc. Am.* **107** 2774-
 448 2791.

449 Vyas, J. C., P. M. Mai, and M. Galis (2016). Distance and azimuthal dependence of ground-

450 motion variability for unilateral strike-slip ruptures, *Bull. Seismol. Soc. Am.* **106** 1584-
 451 1599.

452 Wang, N., R. Takedatsu, K. B. Olsen, and S. M. Day (2019). Broadband ground-motion
 453 simulation with interfrequency correlations, *Bull. Seismol. Soc. Am.* **109** 2437-2446.

454 Wirth, E. A., A. D. Frankel, and J. E. Vidale (2017). Evaluating a kinematic method for
 455 generating broadband ground motions for great subduction zone earthquakes: application
 456 to the 2003 M w 8.3 Tokachi-Oki Earthquake, *Bull. Seismol. Soc. Am.* **107** 1737-1753.

457 Withers, K.W., K.B. Olsen, Z. Shi, and S.M. Day (2019a). Ground motion and intra-event
 458 variability from 3-D deterministic broadband (0-7.5 Hz) simulations along a non-planar
 459 strike-slip fault, *Bull. Seismol. Soc. Am.* **109** 212-228.

460 Withers, K.W., K.B. Olsen, Z. Shi, and S.M. Day (2019b). Validation of deterministic broadband
 461 ground motion and variability from dynamic rupture simulations of buried thrust
 462 earthquakes, *Bull. Seismol. Soc. Am.* **109** 229-250.

463 Zhu, L.P., and L.A. Rivera (2002). A note on the dynamic and static displacements from a point
 464 source in multilayered media, *Geophys. J. Int.* **148** 619-627.

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486 **TABLES**

487 **Table 1.** Fault geometry of the Northridge earthquake

Magnitude	6.73
Strike, dip, rake	122°, 40°, 105°
Length, width	20 km, 27 km
HTop ¹⁾	5 km
Top center ²⁾ (latitude, longitude)	34.344°, -118.515°
Hypocenter (shyp ³⁾ , dhyp ⁴⁾	6.0 km, 19.4 km

488 ¹⁾ Depth to the top of the fault plane

489 ²⁾ Geographical location of the center of the top fault plane boundary

490 ³⁾ Hypocenter location in the along-strike direction (distance from the top center of the fault
491 plane)

492 ⁴⁾ Hypocenter location in the along-dip direction (distance from the top center of the fault plane)

493

494 **Table 2.** Three sets of model tests

	Number of pseudo-dynamic source models	Description
Test Set I (Basic)	100 (50 + 50)	- 50 correlated and 50 uncorrelated source models
Test Set II (Random hypocenter)	100 (50 + 50)	- Same as Test Set I except that the hypocenter is randomly perturbed
Test Set III (Stress drop perturbation)	300 (150 + 150)	- 150 correlated and 150 uncorrelated source models: the 150 correlated source models are composed of 50 models from Test Set I, 50 models with a larger stress drop, and 50 models with a smaller stress drop; the 150 uncorrelated source models are produced the same way

495

496 **Table 3.** Input source statistics model

Model Parameters		Description	Basic	Larger Stress Drop	Smaller Stress Drop
1-Point Statistics	μ_{slip}	Mean slip (cm)	78.36	159.08	46.50
	μ_{V_r}	Mean rupture velocity (km/s)	3.27	3.30	3.26
	$\mu_{V_{max}}$	Mean peak slip velocity (cm/s)	114.93	158.24	97.84
	σ_{slip}	Standard deviation of slip (cm)	45.15	90.83	27.11
	σ_{V_r}	Standard deviation of rupture velocity (km/s)	1.08	1.17	1.04
	$\sigma_{V_{max}}$	Standard deviation of peak slip velocity (cm/s)	89.00	125.64	74.54
2-Point Statistics	a_x	Correlation length in the along-strike direction (km) (slip vs. slip, slip vs. V_r , slip vs. V_{max} , V_r vs. V_r , V_r vs. V_{max} , and V_{max} vs. V_{max})	$\begin{pmatrix} 3.9 & 2.7 & 2.4 \\ & 1.3 & 5.6 \\ & & 6.2 \end{pmatrix}$	$\begin{pmatrix} 3.5 & 2.6 & 1.7 \\ & 1.3 & 4.9 \\ & & 4.7 \end{pmatrix}$	$\begin{pmatrix} 4.1 & 2.7 & 2.7 \\ & 1.3 & 5.9 \\ & & 7.0 \end{pmatrix}$
	a_z	Correlation length in the along-dip direction (km) (slip vs. slip, slip vs. V_r , slip vs. V_{max} , V_r vs. V_r , V_r vs. V_{max} , and V_{max} vs. V_{max})	$\begin{pmatrix} 5.6 & 2.0 & 1.6 \\ & 3.6 & 1.4 \\ & & 1.9 \end{pmatrix}$	$\begin{pmatrix} 13.3 & 4.0 & 3.9 \\ & 4.2 & 1.9 \\ & & 2.4 \end{pmatrix}$	$\begin{pmatrix} 4.0 & 1.5 & 1.1 \\ & 3.4 & 1.3 \\ & & 1.8 \end{pmatrix}$
	ρ_{max}	Maximum correlation coefficient (slip vs. V_r , slip vs. V_{max} , and V_r vs. V_{max})	$\begin{pmatrix} 1 & 0.72 & 0.94 \\ & 1 & 0.64 \\ & & 1 \end{pmatrix}$	$\begin{pmatrix} 1 & 0.81 & 0.89 \\ & 1 & 0.69 \\ & & 1 \end{pmatrix}$	$\begin{pmatrix} 1 & 0.68 & 0.96 \\ & 1 & 0.62 \\ & & 1 \end{pmatrix}$

LIST OF FIGURE CAPTIONS

Figure 1. Fault geometry and station locations for the 1994 Northridge, California, earthquake.

The black box indicates the ground surface projection of the fault plane; i.e., the top of the fault plane is depicted by a solid line, and the rest of the fault plane is delineated with dashed lines. Triangles show the locations of the 133 stations used in the simulation, including the three selected stations in red.

Figure 2. Input correlation model (Test Set I). (a) Correlated, (b) uncorrelated, i.e., without a cross-correlation structure.

Figure 3. Correlated pseudo-dynamic source models. The contour lines in the middle panels indicate rupture time distributions. The hypocenter is located at the bottom right corner of the rupture area.

Figure 4. Uncorrelated pseudo-dynamic source models. The contour lines in the middle panels indicate rupture time distributions. The hypocenter is located at the bottom right corner of the rupture area.

Figure 5. Pseudo-dynamic source models with a larger stress drop. (a) Correlated, (b) uncorrelated. The contour lines in the middle panels indicate rupture time distributions. The hypocenter is located at the bottom right corner of the rupture area.

Figure 6. Pseudo-dynamic source models with a smaller stress drop. (a) Correlated, (b) uncorrelated. The contour lines in the middle panels indicate rupture time distributions. The hypocenter is located at the bottom right corner of the rupture area.

Figure 7. EASs obtained from Test Set I for the three stations plotted in red in Figure 1. Fifty EAS values are plotted in cyan for each panel. The 50th EAS is added in red as an example. [left] EASs obtained from the correlated pseudo-dynamic source models; [right] EASs obtained from

the uncorrelated source models. Both mean and standard deviation from the empirical GMPE model (Bayless and Abrahamson, 2019b) are presented for comparison purposes.

Figure 8. Mean residuals between the simulated EASs and those predicted by the empirical GMPE (Bayless and Abrahamson, 2018b). (a) Test Set I (basic), (b) Test Set II (random hypocenter), and (c) Test Set III (stress drop perturbation).

Figure 9. Standard deviations (τ : between-event, ϕ : within-event, and ϕ_0 : within-site) of the EAS residuals in (a) Test Set I (basic), (b) Test Set II (random hypocenter), and (c) Test Set III (stress drop perturbation). For the within-event standard deviation from the empirical model, both the within-event (i.e., within-site and between-site terms) and only the within-site standard deviations are presented for the comparison purposes.

Figure 10. Inter-frequency correlations (between-event) with 5 reference frequencies (0.2, 0.3, 0.4, 0.5, and 1.0 Hz) in (a) Test Set I (basic), (b) Test Set II (random hypocenter), and (c) Test Set III (stress drop perturbation).

Figure 11. Inter-frequency correlations (within-event) with 5 reference frequencies (0.2, 0.3, 0.4, 0.5, and 1.0 Hz) in (a) Test Set I (basic), (b) Test Set II (random hypocenter), and (c) Test Set III (stress drop perturbation).

543 **FIGURES**

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Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

(a) EAS (nwHP)

(b) EAS (gllp)

(c) EAS (schl)

Figure 8

Figure 9a

Figure 9b

Figure 9c

Figure 10

Figure 11