Preliminary Validation of a Spectral-Based Stochastic Ground Motion Model with a Non-Parametric Time-Modulating Function.

Marco Broccardo
Postdoctoral Fellow, Institute of Structural Engineering, ETH Zurich, Zurich, Switzerland

Mayssa Dabaghi
Assistant Professor, Dept. of Civil Engineering, American University of Beirut, Beirut, Lebanon

ABSTRACT: This study presents a site-based parameterized stochastic model for simulation of far-field synthetic ground motions. The model employs a modulated and filtered white-noise process defined via spectral representation. The modulating function is a recently proposed non-parametric function based on a monotonic cubic spline interpolation. As for the time-frequency modulating function, two slightly different versions are explored. The two versions of the model are fitted to a catalog of recorded ground motions and synthetic catalogs are generated using the fitted model parameters. To validate the model, some characteristics of the synthetic catalogs, namely the median, logarithmic standard deviations, and correlations of the elastic response spectra, are compared with those of the recorded catalog. These comparisons show that both versions of the model are able to adequately capture the spectral amplitudes, variability and correlations of recorded ground motions. The addition of a parameter to describe the rate of change of bandwidth with time does not result in any noticeable improvement and is therefore not warranted. Moreover, comparison with synthetic motions generated from the model by Rezaeian and Der Kiureghian (2010) shows that the proposed model results in an improved estimation of the correlations. Further studies are required to identify which feature(s) of our model are behind this improvement.

1. INTRODUCTION

In recent years, there has been growing interest in modeling earthquake ground motions and in developing methods for generation of synthetic ground motions, which can be used in performance-based earthquake engineering in addition to or in place of recorded motions.

One method to generate synthetic motions is using a site-based stochastic ground motion model, which directly describes the ground motion time-series recorded at a site. Recent examples of site-based stochastic ground motion models include the non-stationary filtered white-noise model for far-field ground motions Rezaeian and Der Kiureghian (2008, 2010), a wavelet-based model Yamamoto and Baker (2013), and a multi-modal non-stationary spectral model Vlachos et al. (2016). Extensions for near-fault ground motion includes Broccardo and Der Kiureghian (2014), and Dabaghi and Der Kiureghian (2017, 2018). All these models account for both temporal and spectral non-stationarity, which is an important characteristic of earthquake ground motions. Moreover, predictive relations for the model parameters were developed in terms of parameters describing the earthquake source and site characteristics. The predictive relations and stochastic model can then be used together to generate synthetic ground motions for any set of earthquake source and site characteristics of interest. Site-based stochastic models are attractive to design engineers because they have a simple formulation, require generally available input parameters, and are computationally efficient. Nonetheless, the resulting synthetic motions should be realistic and have characteristics that are consistent with recorded ground motions.

In this paper, we investigate a site-based parameterized stochastic model of broadband ground motion introduced by Broccardo and

Dabaghi (2017). Similar to the work of Rezaeian and Der Kiureghian (2008), our model employs a modulated and filtered white-noise process and has the key advantage of separating the temporal and spectral non-stationary characteristics of the process, thus simplifying the modeling and parameter estimation. However, our model differs from that of Rezaeian and Der Kiureghian. First, it is defined via spectral representation using by defining the Evolutionary Power Spectral Density (EPSD). Moreover, it uses a different time-modulating function, namely a recently proposed non-parametric function based on a monotonic cubic spline interpolation. As for the time-frequency modulating function, two slightly different versions are explored to describe the spectral non-stationarity. The first is the frequency domain counterpart of the function used in Rezaeian and Der Kiureghian (2007). It is defined by three parameters, namely the main frequency and bandwidth of the motion in the strong phase, and the rate of change of predominant frequency with time. The other version adds one parameter that describes the rate of change of the bandwidth with time. To ensure zero residual velocity and displacement, a high-pass filter is applied according to the evolutionary theory of Priestley (1965). This in conjunction with an energy correction factor eliminates a bias on the cumulative energy of the post-processed simulated motions, which is implicitly present in stochastic models of ground motion.

In this paper, we start by introducing the proposed stochastic model. Next, the two versions of the model are fitted to a catalog of recorded far-field ground motions. The procedure used to fit the filter parameters differs from that used by Rezaeian and Der Kiureghian (2008, 2010). To validate the model, example synthetic motions are then generated using the fitted model parameters, and are compared with the corresponding recorded motions. The characteristics that are compared include the median and logarithmic standard deviation of the elastic response spectra and the correlations between spectral accelerations at different periods. Recent studies have highlighted that it is important for simulated ground motions used in PBEE applications to properly account for these correlations (Bayless and Abrahamson 2018). The results show that while the model of Rezaeian and Der Kiureghian (2007, 2010) overestimates correlations between spectral periods found in recorded ground motions, the proposed model is able to better capture them.

2. PROPOSED STOCHASTIC MODEL

2.1. Formulation and discretization in the frequency domain

A discrete spectral representation of a zero-mean stationary stochastic process can be written as a Fourier Series with random coefficients (Shinozuka, M., & Deodatis, G. (1991))

$$\bar{X}(t) = \sum_{k=0}^{K} \sigma_k [u_k \, sin(\omega_k t) + \, u_{K+k} \cos(\omega_k t)], \qquad (1)$$

where u_k and u_{K+k} are statistically independent standard normal random variables, $\sigma_k = \sqrt{2\hat{S}_{\bar{X}\bar{X}}(\omega_k)\Delta\omega}$, and $\hat{S}_{\bar{X}\bar{X}}(\omega_k) = \sum_k S_{\bar{X}\bar{X}}(\omega)\delta[\omega - \omega_k]$ [1] is the discretized version of the continuous two-sided Power Spectral Density (PSD) $S_{\bar{X}\bar{X}}(\omega)$. This formulation can be extended to simulate weakly non-stationary excitations, $X(t)$, (both in time and frequency domain) via Priestley's evolutionary theory of oscillating processes (1965). Specifically, in Eq. (1) σ_k is replaced with $\sigma_k(t) = \sqrt{2\hat{S}_{XX}(t,\omega_k)\Delta\omega}$, where $\hat{S}_{XX}(t,\omega_k) = \sum_k S_{XX}(t,\omega)\delta[\omega - \omega_k]$ is the continuous-time discrete-frequency version of the continuous-time-frequency EPSD $S_{XX}(t,\omega)$. The EPSD can be written as $S_{XX}(t,\omega) = |A(t,\omega)|^2 S_{\bar{X}\bar{X}}(\omega)$, where $A(t,\omega)$ is a time-frequency-modulating function. Without losing generalization, and selecting for convenience $S_{\bar{X}\bar{X}}(\omega) = 1$, $\sigma_k(t)$

[1] $\omega_k = k\Delta\omega$, and $\delta[x] = 1$ for $x = 0$ and $\delta[x] = 0$

can be written as $\sigma_k(t) = \sqrt{2\left|\hat{A}(t,\omega_k)\right|^2 \Delta\omega}$, where $\left|\hat{A}(t,\omega_k)\right|^2 = \sum_k |A(t,\omega)|^2 \delta[\omega - \omega_k]$. It is easy to show that $E[X^2(t)] = \sigma_X^2(t)$. A unit variance process ($\sigma_X^2(t) = 1$) with spectral non-stationarity is obtained by imposing

$$\left|\hat{A}(t,\omega)\right|^2 = \frac{\left|\hat{\phi}(t,\omega)\right|^2}{2\sum_{k=0}^{K}\left|\hat{\phi}(t,\omega_k)\right|^2 \Delta\omega}, \tag{2}$$

where $\phi(t,\omega)$ is a generic time-frequency modulating function, and $\hat{\phi}(t,\omega) = \sum_k \phi(t,\omega)\delta[\omega - \omega_k]$. A fully non-stationary process with separable time and frequency non-stationarity can be obtained by selecting

$$\left|\hat{A}(t,\omega)\right|^2 = q^2(t)\frac{\left|\hat{\phi}(t,\omega)\right|^2}{2\sum_{k=0}^{K}\left|\hat{\phi}(t,\omega_k)\right|^2 \Delta\omega}, \tag{3}$$

where $q(t)$ is a time-modulating function. It is a simple matter to show that the variance of the resulting process is $\sigma_X^2(t) = q^2(t)$.

2.2. *Time-modulating function*

As was done in Broccardo and Dabaghi (2017), a non-parametric time-modulating function, $q(t;\boldsymbol{\theta}_q)$ is used in this study. Specifically, the time-modulating function is directly defined by preselected physically meaningful time-parameters that describe the buildup of the expected cumulative Arias intensity of the ground motion time series. The expected cumulative Arias intensity of the process $X(t)$ is expressed as $I_{a,q}(t;\boldsymbol{\theta}_q) = E\left[\frac{\pi}{2g}\int_0^t X^2(\tau)d\tau\right] = \frac{\pi}{2g}\int_0^t q^2(\tau;\boldsymbol{\theta}_q)d\tau$, while the empirical Arias intensity of a ground motion is defined as $I_{a,\ddot{u}_g} = \frac{\pi}{2g}\int_0^t \ddot{u}_g^2(t;\boldsymbol{\theta}_q)dt$. The empirical Arias intensity of a ground motion is a continuous and monotonically increasing function. Then, $q(t)$ completely defines the expected cumulative Arias intensity of $X(t)$ and is modeled with a smooth, continuous and monotone piecewise cubic interpolator (Fritsch, F. N., & Carlson, R. E., 1980). This function can easily be fitted to pass through any number of discrete points on the empirical cumulative Arias intensity of a recorded ground motion. The first derivative of the function is continuous and equal to $\frac{\pi}{2g}q^2(t;\boldsymbol{\theta}_q)$. In this study, seven points are selected ($n = 7$), namely $t_i = [t_0, t_{5\%,q}, t_{30\%,q}, t_{45\%,q}, t_{75\%,q}, t_{95\%,q}, t_f]$, where $t_{z\%,q}$ is the time at which z% of the total Arias intensity of the time-modulating function is reached. At these points, the monotone piecewise cubic interpolator is constrained to take the values $p_i = [0\ ,\ 0.05I_{a,\ddot{u}_g}\ ,\ 0.30I_{a,\ddot{u}_g}\ ,\ 0.45I_{a,\ddot{u}_g}\ ,\ 0.75I_{a,\ddot{u}_g},\ 0.95I_{a,\ddot{u}_g},\ I_{a,\ddot{u}_g}]$. The parameters $\boldsymbol{\theta}_q$ consist of the selected points in time (except t_0, which is arbitrary) and the total Arias intensity. Thus they are physically meaningful parameters that directly describe the buildup of cumulative energy of the ground motion.

2.3. *Time-frequency-modulating function*

The spectral non-stationarity of the process is defined by filter functions $\phi(\omega)$ with time-varying filter parameters $\boldsymbol{\theta}_\phi(t)$. It follows that $\phi(t,\omega;\boldsymbol{\theta}_\phi) = \phi(\omega;\boldsymbol{\theta}_\phi(t))$. Following Rezaeian and Der Kiureghian (2010), this study uses a second order filter that represents the pseudo-acceleration frequency response function of an underdamped linear-elastic single-degree-of-freedom oscillator, that is

$$\left|\phi(\omega;\boldsymbol{\theta}_\phi(t))\right|^2 = \frac{\omega_g^4(t)}{\left(\omega_g^2(t)-\omega^2\right)^2 + 4\zeta_g^2(t)\omega_g^2(t)\omega^2}, \tag{4}$$

where $\boldsymbol{\theta}_\phi(t) = [\omega_g(t)\ ,\ \zeta_g(t)]$, $\omega_g(t)$ is the predominant frequency of the filter, and $\zeta_g(t)$ is its bandwidth.

2.4. *Parameterization of the time-varying filter parameters $\boldsymbol{\theta}_\phi(t)$*

2.4.1. *Version 1 (v1): linear variation of main frequency and bandwidth*

In this study, we implement a simple linear model to describe the evolution of the filter parameters with time, namely,

$$\boldsymbol{\theta}_\phi(t) = \boldsymbol{\theta}_{g,mid} + \boldsymbol{\theta}'_g(t - t_{mid}), \tag{5}$$

where t_{mid} is taken here as $t_{45\%}$. The set of four parameters $\boldsymbol{\theta}_{\phi,v1} = [\boldsymbol{\theta}_{g,mid}, \boldsymbol{\theta}'_g]$, where $\boldsymbol{\theta}_{g,mid} =$

$\left[\omega_{g,mid}, \zeta_{g,mid}\right]^T$, $\boldsymbol{\theta}_{g,mid} = \left[\omega'_g, \zeta'_g\right]^T$ completely defines the time variation of the filter parameters $\boldsymbol{\theta}_{\phi}(t)$. Moreover, for the selected filter function, $\boldsymbol{\theta}_{\phi,v1}$ also completely define the time-frequency-modulating function $\phi(\omega; \boldsymbol{\theta}_{\phi}(t))$.

2.4.2. Version 2 (v2): linear variation of main frequency and constant bandwidth

To compare with Rezaeian and Der Kiureghian (2010), we explore a slightly different version of the filter functions whereby the damping is assumed constant with time (i.e., $\zeta'_g = 0$ and $\zeta_g(t) = \zeta_{g,mid}$). In this version, time-frequency-modulating function is completely defined by the three parameters $\boldsymbol{\theta}_{\phi,v2} = [\omega_{g,mid}, \omega'_g, \zeta_{g,mid}]$.

2.5. High-pass filtering and energy correction

The process $X(t)$ is not integrable because $\left|\phi\left(0; \widetilde{\boldsymbol{\theta}}_{\phi}(t_n)\right)\right|^2 \neq 0$. Moreover its realizations do not have zero residual velocity and displacement. Usually, to overcome the first problem a high pass filter is used to modify the low frequency content and impose zero spectral values at $\omega = 0$. This modification was suggested by Clough and Penzien for stationary processes. The second problem is solved either by baseline correction or by applying a second high-pass filter to each simulation $x(t)$. Alternatively, as introduced in Broccardo and Dabaghi (2017), a single high-pass filter can be directly applied to the EPSD $S_{XX}(t, \omega)$ of the acceleration process $X(t)$ using the Priestley evolutionary theory. For example, a critically damped single-degree of freedom oscillator can be used as filter. Given its displacement impulse response function $h(t; \omega_f)$, where ω_f is the filter cutoff frequency, the ground displacement time series $u_g(t)$ in response to acceleration $x(t)$ is obtained as $u_g(t) = h(t; \omega_f) * x(t)$, where $*$ denotes convolution for $t \in [0, +\infty)$. It is easy to show that the EPSD of the high-pass filtered displacement process $U_g(t)$ is given by

$$S_{U_g U_g}(t, \omega) = \left|\int_0^t |A(t-\tau, \omega)|\, h(\tau; \omega_f) e^{i\omega t} d\tau\right|^2, \qquad (6)$$

which can be directly used to simulate $u_g(t)$ by using $\sigma_k(t) = \sqrt{2\hat{S}_{U_g U_g}(t, \omega_k)\Delta\omega}$. Then, the velocity, $\dot{u}_g(t)$, and the acceleration, $\ddot{u}_g(t)$, are obtained by differentiation. Note that this procedure yields velocity and acceleration processes that are integrable and with zero residual velocity and displacement. It is a simple matter to show that the EPSDs of the velocity and acceleration processes are given by $S_{\dot{U}_g \dot{U}_g}(t, \omega) = \left|\dot{M}(t, \omega) + i\omega M(t, \omega)\right|^2$, and $S_{\ddot{U}_g \ddot{U}_g}(t, \omega) = \left|\ddot{M}(t, \omega) + 2i\omega \dot{M}(t, \omega) - \omega^2 M(t, \omega)\right|^2$.

Applying the high-pass filter eliminates part of the low frequency content of the process and decreases its total energy. To account for this effect, an energy correction factor K is introduced (Broccardo and Dabaghi, 2017),

$$K = \frac{\int_0^t \ddot{u}_g^2(t) dt}{\int_0^{t_f} \sum_{k=0}^{K} 2\hat{S}_{\ddot{U}_g \ddot{U}_g}(t, \omega_k)\Delta\omega}. \qquad (7)$$

Then, we can define the EPSDs of the energy consistent ground motion processes as $S^C_{U_g U_g}(t, \omega) = K S_{U_g U_g}(t, \omega)$, $S^C_{\dot{U}_g \dot{U}_g}(t, \omega) = K S_{\dot{U}_g \dot{U}_g}(t, \omega)$, and $S^C_{\ddot{U}_g \ddot{U}_g}(t, \omega) = K S_{\ddot{U}_g \ddot{U}_g}(t, \omega)$.

3. FITTING TO RECORDED CATALOG

3.1. Recorded Catalog

The two versions of the model investigated in this study are fitted to a dataset of recorded motions taken from the PEER NGA-West2 database. In particular, 71 ground motions recorded at a range of distances (10-90 km) and site conditions from reverse earthquakes with magnitude between 6 and 7.6 are used. Similar to Rezaeian and Der Kiureghian (2012), the two horizontal components of each record are rotated into the major and intermediate principal directions. Only the major component is fitted in this study.

3.2. Fitting time-modulating function parameters

As mentioned earlier, the parameters $\boldsymbol{\theta}_q$ of the time modulating function are fitted by matching points on the cumulative Arias intensity function of $q(t)$, $I_{a,q}(t)$, with points on the cumulative Arias intensity function of a target recorded ground motion $\ddot{u}_g(t)$, $I_{a,\ddot{u}_g}(t)$. Given $t_{0,\ddot{u}_g}$, the physically meaningful parameters are $\boldsymbol{\theta_q} = [I_{a,\ddot{u}_g}, t_{5\%,\ddot{u}_g}, t_{30\%,\ddot{u}_g}, t_{45\%,\ddot{u}_g}, t_{75\%,\ddot{u}_g}, t_{95\%,\ddot{u}_g}, t_{f,\ddot{u}_g}]$. For more details about the fitting procedure, see Broccardo and Dabaghi (2017).

3.3. Fitting filter function parameters

Given a target recorded ground motion, the set of parameters $\boldsymbol{\theta}_\phi$ is estimated such that $\phi(\omega; \hat{\theta}_\phi(t))$ "best fits" an empirical discrete EPSD $\tilde{S}_{XX}(t_n, \omega)$ of the recorded motion, with $n \in [0, \ldots N]$ and $t_n = n\Delta t$. First, $\tilde{S}_{XX}(t_n, \omega)$ is computed with the short-time Thomson's multiple-window (STTMW) spectrum estimation technique (Conte and Peng, 1997). The main advantage of STTMW is that it is not limited by the usual trade-off between variance and spectral leakage. Then, at each instant of time t_n, the set of parameters $\widetilde{\boldsymbol{\theta}}_\phi(t_n)$ is estimated by minimizing the square difference between the normalized empirical EPSD, $\tilde{\phi}(t_n, \omega) = \tilde{S}_{XX}(t_n, \omega) / Z_{\tilde{S}_{XX}}(t_n)$, and $\left|\phi\left(\omega; \widetilde{\boldsymbol{\theta}}_\phi(t_n)\right)\right|^2$, where $Z_{\tilde{S}_{XX}}(t_n)$ is a normalizing constant. It follows that

$$\hat{\hat{\boldsymbol{\theta}}}_\phi(t_n) = \underset{\widetilde{\boldsymbol{\theta}}_\phi(t_n), \phi_0(t_n)}{\operatorname{argmin}} \sum_{k=0}^{K} \left[\hat{\phi}\left(t_n, \omega_k; \widetilde{\boldsymbol{\theta}}_\phi(t_n)\right)\phi_0(t_n) - \left(\sum_{m=-\frac{M}{2}}^{\frac{M}{2}} \pi(m)\tilde{\phi}(t_{n+m}, \omega_k)\right)\right]^2, \quad (8)$$

Finally, the parameters $\widehat{\boldsymbol{\theta}}_{\phi,v1}$ or $\widehat{\boldsymbol{\theta}}_{\phi,v2}$ are fitted using weighted least squares minimization of the difference between $\widehat{\boldsymbol{\theta}}_\phi(t)$ from Eq. (5) and $\hat{\hat{\boldsymbol{\theta}}}_\phi(t_n)$ from Eq. (6) (for more details, see Broccardo and Dabaghi, 2017).

4. COMPARISON OF SYNTHETIC AND RECORDED CATALOGS

To validate a ground motion simulation model, the characteristics of the resulting synthetic ground motions should be compared with those of recorded ground motions [e.g., (Burks and Baker 2014)]. In this study, we compare the statistics of the response spectra of the three catalogs, namely the mean and median levels, the variability (standard deviations), and the correlations between spectral ordinates.

4.1. Elastic response spectra

For each ground motion in the recorded catalog, the parameters of the two stochastic models (v1 and v2) are fitted. Then, each model is used with its corresponding fitted model parameters to generate one synthetic motion for each recorded motion. Note that for each recorded motion, a single white noise process is generated and used in both simulation models. Therefore, the resulting two simulated motions only differ in the definition of their EPSD. This simulation procedure results in two synthetic catalogs each consisting of 71 ground motion time series.

Figure 1 shows the 5% damped elastic pseudo-acceleration, pseudo-velocity, and displacement response spectra of the simulated motions. The mean, median and 95$^{\text{th}}$ percentile levels of the recorded motions are compared with those of the synthetic catalogs generated using models v1 (light red) and v2 (dark red). The comparison shows that both models result in response spectra that are almost identical and are both able to adequately represent the ground motion levels of the recorded motions.

Figure 2 shows the lognormal standard deviation of the 5% damped elastic response spectral ordinates of the recorded and simulated catalogs. The figures show that both models v1 and v2 able to adequately represent the ground motion variability of the recorded motions up to periods around 4-5s. At longer periods, the synthetic catalogs tend to underestimate the variability found in the recorded catalog. This could be caused by the high-pass filtering procedure used; modifications will be later explored to check if they can correct this underestimation of variability at the longer periods.

4.2. Correlations between spectral periods

Figure 3 shows the correlations between the 5% damped elastic pseudo-acceleration response spectra at different periods for the recorded

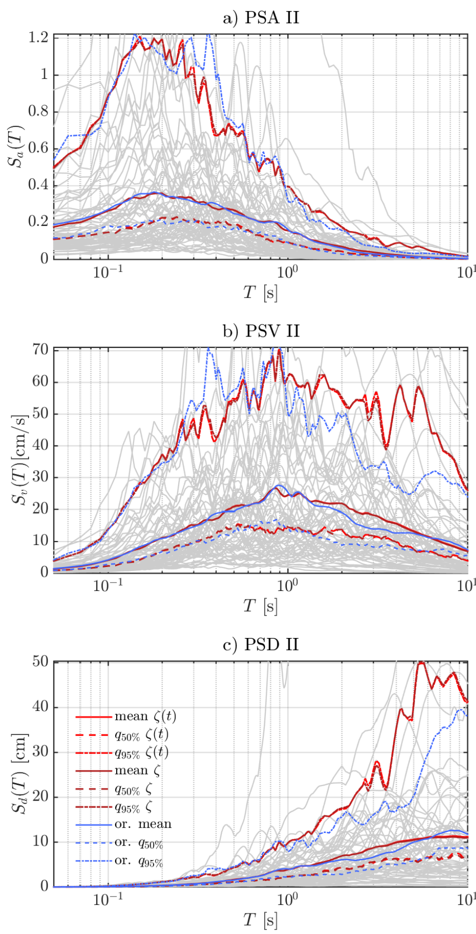

Figure 1: Statistics of 5% damped elastic response spectra of recorded motions (blue) and corresponding motions simulated using fitted model parameters with models v1 (light red) and v2 (dark red): (a) pseudo-acceleration; (b) pseudo-velocity; and (c) displacement spectra

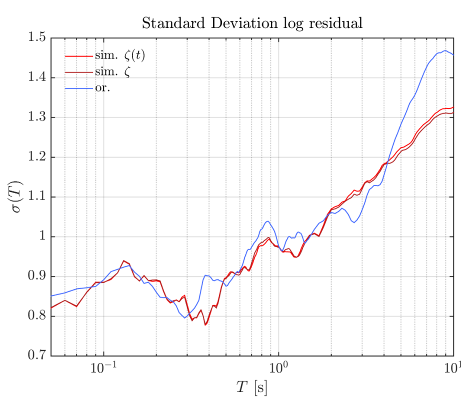

Figure 2: Lognormal standard deviation of 5% damped elastic response spectral ordinates of recorded ground motions (blue) and corresponding motions simulated using fitted model parameters with models v1 (light red) and v2 (dark red)

motions and the motions in the synthetic catalogs generated using v1 and v2.

Figure 4 shows the correlation map between response spectral ordinates for the two model and the original ground motions. The figures show that the correlations of the simulated motions from both models are almost identical. Moreover, the simulations tend to overestimate the correlations between spectral ordinates compared to recorded ground motions. These comparisons show that both versions v1 and v2 of the model are able to adequately capture the spectral amplitudes, variability and correlations of recorded ground motions. The addition of a parameter ζ' to describe the rate of change of bandwidth with time does not result in any noticeable improvement and is therefore not warranted.

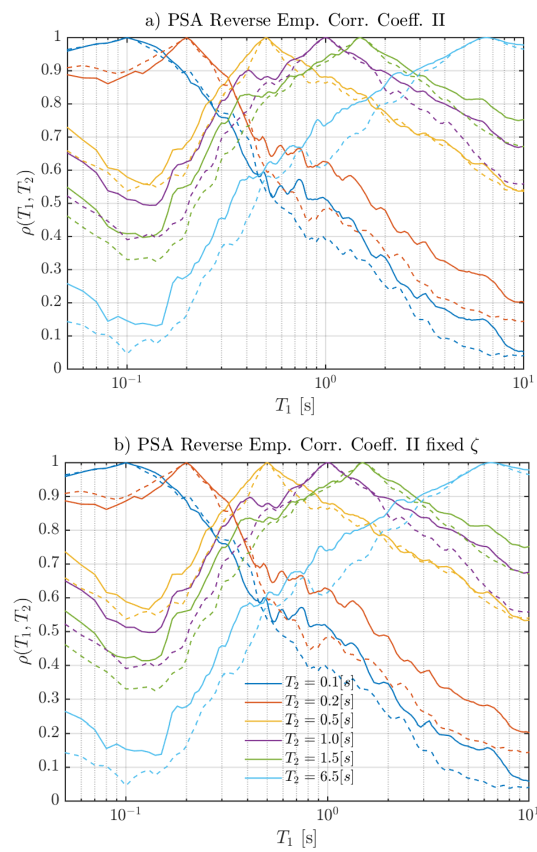

Figure 3: Correlations between response spectral ordinates for recorded ground motions (dashed lines) and corresponding motions simulated using fitted model parameters (solid lines)with models v1 (a) and v2 (b)

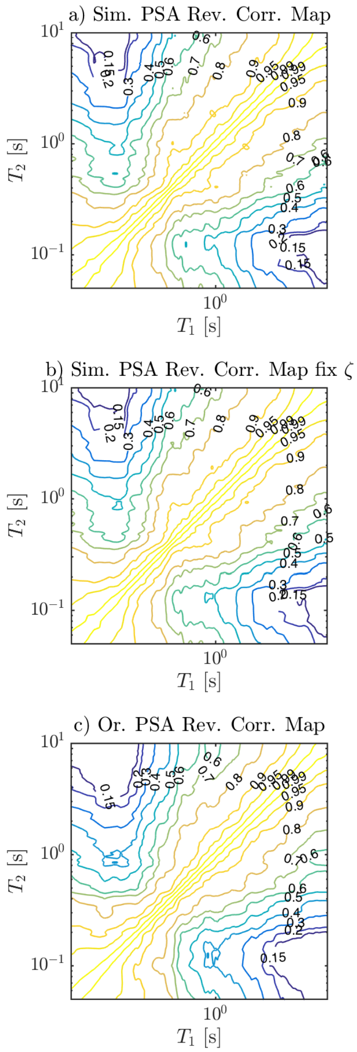

Figure 4 Correlations map between response spectral ordinates for the ground motion catalogs: (a) simulations using model v1; (b) simulations using model v2; and (c) recorded motions

These results are also compared with synthetic catalogs generated using the stochastic ground motion model proposed by Rezaeian and Der Kiureghian (2010), which is formulated in the time domain. Figure 5 shows the correlations between the 5% damped elastic pseudo-acceleration response spectra at different periods for a synthetic catalog generated using the Rezaeian and Der Kiureghian (2010) model and for the recorded catalog to which the model was fitted. As illustrated in Figure 5, their model produces synthetic ground motions that exhibit correlations between spectral periods that are a lot higher than those of recorded ground motions.

Comparing Figure 3 and Figure 5 shows that our model results in an improved estimation of the correlations compared with that of Rezaeian and Der Kiureghian (2010). This improvement should then be explained by one (or more) of the differences between the two models. The differences include: (1) a formulation in the frequency domain; (2) a more flexible time-modulating function; (3) post-processing applied directly in the frequency domain; (4) energy correction similar to Dabaghi and Der Kiureghian (2017, 2018). Further investigation is required to identify the main cause of the improvement.

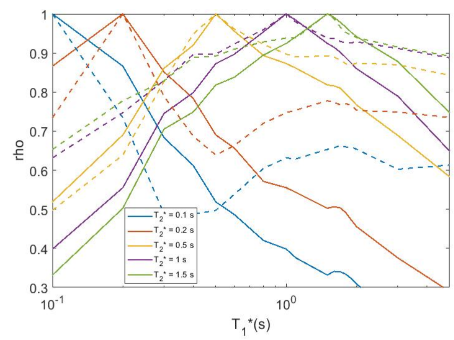

Figure 5: Correlations between response spectral ordinates for recorded motions (solid lines) and corresponding motions simulated using the model by Rezaeian and Der Kiureghian (2010) (dashed lines)

5. SUMMARY AND CONCLUSIONS

In summary, a recently proposed site-based parameterized stochastic ground motion model is described and validated in this paper. The model is defined via spectral representation and uses a recently proposed non-parametric function based on a monotonic cubic spline interpolation. As for the time-frequency modulating function, two slightly different versions are explored. The first is defined by three parameters, namely the main frequency and bandwidth of the motion in the strong phase, and the rate of change of predominant frequency with time. The other version adds one parameter that describes the rate of change of the bandwidth with time. The two versions of the model are fitted to a catalog of recorded far-field ground motions and synthetic catalogs are generated using the fitted model parameters. Some characteristics of the synthetic catalogs, namely the median, logarithmic standard deviations, and correlations of the elastic response spectra, are compared with those of the recorded catalog. These comparisons show that both versions of the model are able to adequately capture the spectral amplitudes, variability and correlations of recorded ground motions. The addition of a parameter ζ' to describe the rate of change of bandwidth with time does not result in any noticeable improvement and is therefore not warranted. Moreover, comparison with synthetic motions generated from the model by Rezaeian and Der Kiureghian (2010) shows that the proposed model results in an improved estimation of the correlations. Further studies are required to asses which feature(s) are behind this improvement.

6. ACKNOWLEDGEMENTS

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