SPECTRUM-COMPATIBLE SYNTHETIC TIME HISTORIES FOR CENTRAL AND EASTERN US USING A NEW HYBRID GROUND MOTION SIMULATION TECHNIQUE

Alireza Shahjouei$^1$ and Shahram Pezeshk$^2$

ABSTRACT

Synthetic ground motion generation is a proper approach for high seismicity regions such as Central and Eastern US (CEUS) while suitable real earthquake records in terms of magnitude, site characteristics, and distance are scarce. To perform time history analysis of structures, building and bridge design seismic provisions require at least three or seven recorded or synthetic earthquakes. In this study, we generate a suite of appropriate spectrum-compatible synthetics through a proposed hybrid broadband (HBB) simulation technique for CEUS.

In a proposed interdisciplinary engineering and seismological approach, we apply different kinematic parameters, which are correlated with different intensity measures in engineering application (such as peak ground acceleration, velocity, displacement: PGA, PGV, PGD, etc.) as well as a spatial random field model to characterize the complexity of the slip distribution on a non-homogeneous fault. Long period synthetics are obtained through a kinematic modeling of the source and deterministic wave propagation using a discrete wavenumber-finite element method. We use the point source stochastic method of Boore (2005) to generate high frequency portion of the time series. Finally, the broadband synthetics are obtained implementing a pair matched low-pass and high-pass Butterworth filters applied on the long and low frequency synthetics, respectively. A case study is presented and the results are shown for the predefined scenario of $M_w=6.5$. The proposed method is compared with the ground motion prediction equations proposed for the region.

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Spectrum-compatible synthetic time histories for Central and Eastern US using a new hybrid ground motion simulation technique

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Synthetic ground motion generation is a proper approach for high seismicity regions such as Central and Eastern US (CEUS) while suitable real earthquake records in terms of magnitude, site characteristics, and distance are scarce. To perform time history analysis of structures, building and bridge design seismic provisions require at least three or seven recorded or synthetic earthquakes. In this study, we generate a suite of appropriate spectrum-compatible synthetics through a proposed hybrid broadband (HBB) simulation technique for CEUS.

In a proposed interdisciplinary engineering and seismological approach, we apply different kinematic parameters, which are correlated with different intensity measures in engineering application (such as peak ground acceleration, velocity, displacement: PGA, PGV, PGD, etc.) as well as a spatial random field model to characterize the complexity of the slip distribution on a non-homogeneous fault. Long period synthetics are obtained through a kinematic modeling of the source and deterministic wave propagation using a discrete wavenumber-finite element method. We use the point source stochastic method of Boore (2005) to generate high frequency portion of the time series. Finally, the broadband synthetics are obtained implementing a pair matched low-pass and high-pass Butterworth filters applied on the long and low frequency synthetics, respectively. A case study is presented and the results are shown for the predefined scenario of $M_w=6.5$. The proposed method is compared with the ground motion prediction equations proposed for the region.

Introduction

There are few different engineering and seismological methods to generate synthetic seismograms. Synthetic ground motions are powerful tools in earthquake engineering for the time history analysis of structures due to the scarcity of sufficient and reliable recorded strong ground motions for a specific site. Furthermore, synthetic ground motions could be used as a supplement to the available catalog of recorded strong ground motions for developing ground motion prediction equations (GMPEs). Most engineering techniques have been focused on ground motion matching \cite{1,2}. Target spectrum may be obtained from a probabilistic seismic hazard analysis \cite{3}. Stochastic methods, either the point-source approach or the finite-fault procedure have been used for several years in both engineering and seismological applications \cite{4-6}. Other seismological models are hybrid broadband (HBB) in which low frequency portion of the synthetics are determined through more complex kinematic models \cite{7-9}. The high

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frequency part is obtained using the stochastic models having the specific underlying seismological spectral models [5]. Kinematic modeling requires additional seismological (and/or geological) information and their associated uncertainties. However, HBB models provide us with more realistic behavior of long period ground motions that are of interest for the analysis of low frequency structures such as long span bridges. Therefore, HBB methods depend strongly on the accuracy of ground motions parameters [10].

Central and Eastern US (CEUS) is considered as a high seismicity region with lack of recorded strong ground motion. Hwang et al. [11] applied a stochastic method for synthetic generation resulting from the large New Madrid earthquake. Olson [12] developed broadband synthetics for large earthquakes within the New Madrid seismic zone based on 1811-1812 events. In this study, a hybrid broadband model is proposed to generate the synthetics for CEUS. We generate synthetics for moment magnitudes of $M_w$ 5.5, 6.5, and 7.5 for the region considering numerical techniques of Spudich and Archuleta [13] by using the program COMPSYN [14]. To consider the complexity of the slip distribution, we use the random field model proposed by Mai and Beroza [15,16]. The synthetics’ high frequency portions are calculated using the computer program SMSIM, [17]. Spectrum-compatibility of the synthetics is shown to validate the proposed method. We generate synthetics for a moment magnitude of 6.5 and provide a detailed discussion of the procedure.

**Methodology**

**Long-Period Simulation**

In low frequencies portion of the HBB method, we use the numerical technique [13] in order to calculate the representation theorem integrals on a fault surface [14]. The Green’s functions have been calculated using the discrete wavenumber-finite element method for a set of observations and finite-sized fault in the space-frequency domain. Synthetics in the frequency domain are computed from a product of specified slip distribution on the fault and the Green’s functions. Finally, the long period synthetics in time domain are calculated using the inverse Fourier transform after applying two sided cosine taper filter.

To estimate the average of the slip on the fault, the following equation is used:

$$M_0 = \mu AD$$

where $M_0$ is the seismic moment, $\mu$ is the rigidity, $A$ is the faulting area, and $D$ is the average of the slip on the fault. To describe the heterogeneity of the slip distribution on the fault, different spatial random field models proposed by Mai and Beroza [16] are used. We have considered the Von Karman, which is one of the most common correlation functions. It is characterized in space by an auto correlation function (ACF), $C(r)$, or in the Fourier domain by a power spectral density (PSD), $P(k)$, as presented by the following equations:

$$C(r) = \frac{G_H(r)}{G_H(0)}$$

(2)
\[ P(k) = \frac{a_x a_z}{(1 + k^2)^{H+1}} \]

\[ G_H(r) = r^H K_H(r) \]

where \( H \) is the Hurst exponent, \( K_H \) is the modified Bessel function of first kind with order of \( H \), \( r \) is the distance, \( k \) is the wavenumber, \( k_x \) and \( k_z \) are the horizontal and the vertical wave number, respectively. The characteristic scales are symbolized by the correlation length in along the strike and downdip direction, \( a_x, a_z \), respectively. The distance and wave numbers are defined as the following:

\[ r = \sqrt{\left( \frac{x^2}{a_x^2} + \frac{z^2}{a_z^2} \right)} \]

\[ k = \sqrt{\left( a_x^2 k_x^2 + a_z^2 k_z^2 \right)} \]

where \( x \) and \( z \) are the distances along the strike and downdip, respectively. We have implemented three kinds of source time functions (STF) of boxcar, Brune [18] pulse shape, and SinCos proposed by Liu et al. [19] in different shaking scenarios. The modified empirical relation of Somerville et al. [20] proposed by Grave and Pitarka [21] is used for CEUS for the estimation of the rise time. It is represented by Eqs. 7 and 8. The local duration of slip rate function of each subfault is scaled to square root of the local slip to signify the trade off between constant slip velocity and constant rise time [22]. We have adjusted the local rise time applying a depth factor of two above 5 km and depth factor of one below 8 km (interpolation between 5-8 km) according to Grave and Pitarka [21].

\[ \tau = \alpha \times 2 \times 10^{-9} \times M_0^{1/3} \]

\[ \alpha = \begin{cases} 0.82 & \delta < 45^0 \\ 1.0 & \delta > 60^0 \end{cases} \]

where \( \alpha \) is the modification factor, \( \tau \) is the average of rise time, \( M_0 \) is the seismic moment, and \( \delta \) is the dip angle of the fault.

Rupture initiates at the hypothetical hypocenter and propagates with \( V_r = 0.8 \times V_s \), in which \( V_s \) is the shear velocity of the crustal model. We have used a rupture speed reduction factor of 70% above 5 km to represent the shallow week zone [21]. Rupture front arrival time in each subfault is computed using the local rupture velocity and a timing perturbation scale factor that scales rupture arrival time with the local slip.

**High-Frequency Simulation**

The high frequency portion of the HBB is computed based on the finite-fault simulation approach in which the point source stochastic simulations on each subfault are computed using the computer program SMSIM [17]. The total Fourier amplitude spectrum of displacement \( Y(M_0, R, f) \) for horizontal ground motions due to shear-wave propagation can be represented as:
\[ Y(M_0, R, f) = E(M_0, f) \times P(R, f) \times G(f) \times I(f) \]  

(9)

where \( E(M_0, f) \) is the point source spectrum term, \( P(R, f) \) is the path effect function, \( G(f) \) is the site response term, \( I(f) \) is the ground motion type, \( M_0 \) is the seismic moment (dyne-cm), \( R \) is the distance (km), and \( f \) is the frequency (Hz).

Atkinson et al. [23] and Boore [24] provide great discussions on the finite-fault and the point source stochastic methods. High frequency synthetics for each subfault are multiplied by a stress-drop modification factor to conserve the total radiated energy over the entire fault. High frequency synthetics are summed and convolved with a source time function to ensure the acceleration spectral amplitude is constant for frequencies lower than the corner frequency [9]. We used the algorithm of Frankel [25] for this purpose.

Finally, the low frequency and high frequency synthetics are filtered implementing the matched second order low-pass and high-pass Butterworth filters, respectively and summed to make the hybrid broadband synthetics.

**Case Study**

In this section, we generate HBB synthetics for a specific scenario with a moment magnitude of \( M_w = 6.5 \) for a site located in CEUS (\( M_0 = 6.31 \times 10^{18} \text{N.m} \)). We used a crustal model proposed by Mooney [26] and provided in Table 1 (Personal communications with Mooney). We have adjusted the crustal structure model for \( Z \leq 1\text{km} \) based on Somerville et al. [27].

Using the empirical relation of Wells and Coppersmith [28] and Somerville [29], we estimated a vertical (dip=90) faulting area of 18.0 km by 12.0 km and extended the rupture zone from 3.0 km depth. The subevent (cell size) of 0.2 km by 0.2 km is chosen although the subfault dimension does not make a notable difference in acceleration spectra calculations [9]. A strike slip mechanism is considered for the scenario in this case study.

The correlation length is calculated as \( a_z = 2.42 \text{ km} \) and \( a_x = 11.04 \text{ km} \) and Hurst number \( H=0.83 \) is applied for calculation of PSD in Von Karman function (Eqs. 2 to 6). Fig. 1 shows the one and two dimensional power spectral density of the applied ACF.

The generated random field model is applied for distribution of the slip over the fault. Using Eq. 1, the average of the slip is about 90 cm and distributed on the fault. The hypothetical location of the hypocenter is set to be consistent with the observation in strike-slip earthquakes, which tend to nucleate in deeper section of the fault within or close to the regions of large slip [30]. The rise time and rupture propagation are modeled according to the previous discussion in the Methodology Section. Fig. 2 illustrates the slip distribution, rise time distribution, rupture front propagation, and the stress distribution used for the case study. The hypocenter is assumed to be at the middle of fault along the strike and 8.5 km downdip on the fault. It is symbolized with a star in Fig. 2.
Table 2 presents parameters used for the high frequency portion of the HBB synthetics. We used 250 Bars for the root mean square value of the stress drop over the fault. We used a transition frequency of 1.0 Hz between the deterministic and stochastic seismograms for this study following observations of Frankel [9].

**Generated HBB time histories and validation**

For the previously discussed scenario, we used stations with the closest distance to the fault ($R_{jb}$) of 2.0-200.0 km. The location of stations is shown in the Fig. 3. Stations are set in a way that they have approximately equal distance from each other in any given closest distance to the fault. The synthetics are generated for a total of 192 stations in both fault normal and fault parallel.

HBB synthetics are generated for the stations depicted in the Fig. 3 according to the methodology and the parameters described earlier. As an example, Fig. 4 shows the fault normal components of the synthetics generated for the stations along the strike from the distances of 2.0 to 200.0 km considering the origin time from the initiation of the rupture at the hypocenter. The near field effects and the forward directivity are captured and easily visible in the generated seismograms.

We compare the results of our case study through the spectrum compatibility of the synthetics and ground motion prediction equations (GMPEs) developed for the region at the desired period. Building codes focus on 0.2 and 1.0 second spectral periods. So, the acceleration spectrum-compatibilities for the periods of 0.2, and 1.0 sec. are shown in the Fig. 5. Data obtained from the case study is compared with GMPEs proposed by Pezeshk et al. [31] and Atkinson and Boore [32] [see Fig.5]. At large distances, GMPEs are comparable with the case study; however, for short distances of less than 10 km, both GMPEs models overestimate results of the case study. Note that the Fig. 5 shows spectrum comparison of just a specific predefined shaking scenario (in case study) while GMPEs are assumed to be backbone curves for all possible scenarios; therefore, we do not expect to see a comprehensive compatibility in all the distances. Applying different shaking scenarios (hypocenter location, slip distribution, rupture propagation, etc.) and the varying other parameters could have a significant affect on the long period portion of the synthetics and should be considered in the validation process. For the future work, we will apply further shaking scenarios to compare with the GMPEs.

**Conclusions**

Hybrid broadband synthetics have been generated for CEUS with the most updated seismological parameters. One of the features of the HBB synthetics is capturing the near-field effects such as the directivity that is crucial in earthquake engineering for the analysis of the long period structures. We used the discrete wavenumber-finite element method for calculating the Green’s function in low frequency components. Heterogeneity of the slip is considered in the kinematic modeling of the fault. The Von Karman auto correlation function in space and frequency domain is used in the kinematic modeling of the faulting. The high frequency portion is generated using a finite-fault stochastic model. To conserve the radiated energy on the entire fault, a stress-scaling factor is multiplied on the subfault’s stochastic seismograms before summation on the fault. Finally, the HBB synthetics are achieved from summation of the low
and high frequency synthetics after passing the matched Butterworth filters.

The response spectrum of the synthetics at periods of 0.2 and 1.0 second are shown for a specific predefined shaking scenario with the moment magnitude $M_w = 6.5$. We compared the generated seismograms with GMPEs of Pezeshk et al. [31] and Atkinson and Boore [32]. Comparison shows good spectrum-compatibilities for distances greater than 10 km. To reach a general conclusion further modeling of shaking scenarios and varying multiple kinematic parameters will be performed in the future work.

Acknowledgments

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Table 1. Velocity model used in synthetic generations

<table>
<thead>
<tr>
<th>$Z$ (km)</th>
<th>$V_p$ (km/s)</th>
<th>$V_s$ (km/s)</th>
<th>$\rho$ (g/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>4.9</td>
<td>2.83</td>
<td>2.52</td>
</tr>
<tr>
<td>1.0</td>
<td>6.1</td>
<td>3.52</td>
<td>2.74</td>
</tr>
<tr>
<td>10.0</td>
<td>6.5</td>
<td>3.75</td>
<td>2.83</td>
</tr>
<tr>
<td>20.0</td>
<td>6.7</td>
<td>3.87</td>
<td>2.88</td>
</tr>
<tr>
<td>40.0</td>
<td>8.1</td>
<td>4.68</td>
<td>3.33</td>
</tr>
</tbody>
</table>

Table 2. Median Parameter Values Used with the Stochastic Method in ENA (Pezeshk et al., 2011)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CEUS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source spectrum model</td>
<td>Single-corner-frequency $\omega R^2$</td>
</tr>
<tr>
<td>Stress parameter, $\Delta \sigma$ (bars)</td>
<td>250</td>
</tr>
<tr>
<td>Shear-wave velocity at source depth, $\beta_s$ (km/s)</td>
<td>3.7</td>
</tr>
<tr>
<td>Density at source depth, $\rho_s$ (gm/cc)</td>
<td>2.8</td>
</tr>
<tr>
<td>Geometric spreading, $Z(R)$</td>
<td>$R^{-1.3}; R &lt; 70$ km</td>
</tr>
<tr>
<td></td>
<td>$R^{0.2}; 70 \leq R &lt; 140$ km</td>
</tr>
<tr>
<td></td>
<td>$R^{-0.5}; R \geq 140$ km</td>
</tr>
<tr>
<td>Quality factor, $Q$</td>
<td>$\max(1000, 893 f^{0.32})$</td>
</tr>
<tr>
<td>Source duration, $T_s$ (sec)</td>
<td>$1/f_a$</td>
</tr>
<tr>
<td></td>
<td>$0$; $R \leq 10$ km</td>
</tr>
<tr>
<td></td>
<td>$+0.16 R$; $10 &lt; R &lt; 70$ km</td>
</tr>
<tr>
<td>Path duration, $T_p$ (sec)</td>
<td>$-0.03 R$; $70 &lt; R \leq 130$ km</td>
</tr>
<tr>
<td></td>
<td>$+0.04 R$; $R &gt; 130$ km</td>
</tr>
<tr>
<td>Site amplification, $A(f)$</td>
<td>Atkinson and Boore (2006)</td>
</tr>
<tr>
<td>Kappa, $k_0$ (sec)</td>
<td>0.005</td>
</tr>
</tbody>
</table>
Figure 1. Random field parameters for $M_w=6.5$: Power spectral density along the strike and downdip (left), 1D spectra and correlation length (right).

Figure 2. Fault modeling for $M_w=6.5$ used in the case study. Slip distribution (top left), duration of slip velocity (top right), stress distribution (bottom left) and the rupture front (bottom right). The star depicts the hypocenter location.
Figure 3. Set of stations for $M_w = 6.5$ simulations. The stations (circles) have approximately equal distances from each other in any given closest distance (in km) to the fault ($R_{jb}$).

Figure 4. Fault normal components of the synthetic acceleration time histories for the set of stations along the strike with $R_{jb} = 2.0-200$ km for the scenario $M_w = 6.5$ simulations. The origin time starts from the initiation of rupture at hypocenter.
Figure 5. Spectral acceleration (SAs) at 0.2 sec (left) and at 1.0 sec (right) from the synthetics in all 192 stations and their comparison with GMPEs by Pezeshk et al. [31], and Atkinson and Boore [32]. The median plus and minus one standard deviation are shown for the Pezeshk et al. [31].

References