Synthetic Seismograms Using a Hybrid Broadband Ground-Motion Simulation Approach: Application to Central and Eastern United States

by Alireza Shahjouei and Shahram Pezeshk

Abstract Broadband synthetic time histories for central and eastern United States are generated using a proposed hybrid broadband simulation technique. The low-frequency (LF) portion of synthetics is calculated using kinematic source modeling and deterministic wave propagation. Using the COMPSYN software package (Spudich and Xu, 2003), a discrete wavenumber/finite-element method is implemented for the LF Green's functions generation. The procedure makes use of the reciprocity theorem and numerical techniques to assess the representation theorem integrals on a fault surface. Spatial random field models are employed to characterize the complexity of the slip distribution on the heterogeneous fault. In this study, the variability of some of the kinematic source modeling's parameters (e.g., hypocenter locations, slip distribution, source time function, and rupture propagation) is taken into account to produce multiple seismograms that contain a broader range of intensity measures such as peak ground motions and spectral accelerations. A stochastic finite-fault simulation model is employed to attain the high-frequency (HF) portion of synthetics. Combining HF and LF synthetics in a magnitude-dependent transition frequency, the broadband seismograms are constructed for $M_{5.5}$, $M_{6.5}$, and $M_{7.5}$ earthquakes in a distance range of 2–200 km.

Broadband synthetics will be compared with some of the existing ground-motion prediction equations for spectral accelerations at 0.2, 1.0, and 3.0 s, and the results will be discussed. A compatibility assessment of the stochastic point source and the finite source is performed. The generated seismograms could be implemented in engineering seismology applications such as structural seismic analysis/design and seismic-hazard analysis.

Introduction

Generation of accurate synthetic seismograms in the absence of the appropriate recorded strong ground motions has been a challenging issue in the fields of earthquake engineering and engineering seismology. According to the building codes, a number of either recorded and/or synthetic seismograms is needed for the seismic time history analysis of unique and irregular structures (Baker, 2011; Ghodrati et al., 2011). In addition, synthetic seismograms may be considered as a complement to the available earthquake catalog and can be used to develop ground-motion prediction equations (GMPEs), particularly in the regions with historical seismicity but insufficient recorded strong ground motions (Pezeshk et al., 2011). In general, these ground-motion models in well-recorded regions are empirically developed from the recorded earthquakes. Examples of such empirical GMPEs are ground-motion models for western North America developed by Graizer and Kalkan (2007) and Boore et al. (2014). The synthetic seismograms should include the specific underlying seismological features of a region and have characteristics of the frequency content, shaking duration, pulse-like character, and peak ground motions compatible with the recorded data at a site (Frankel, 2009).

In general, all main characteristics of an earthquake time history (amplitude, frequency content, and duration) significantly contribute to and have influence on the structural response values, the seismic risk analysis, and the seismic damage assessment (Hartzell et al., 1999). Although a precise prediction of future large earthquakes in time, location, and the time history—wiggle for wiggle—is not possible nowadays, some of the seismological and geological information could be implemented to characterize the earthquake source, the path effect, and the site characteristic and to determine the potential of future damaging earthquakes (Liu et al., 2006). All this information is the basis for the
development of empirical equations and is used in earthquake simulation techniques.

In the literature, a number of engineering-based, as well as seismological-based approaches have been proposed related to ground-motion simulation. Most engineering-based techniques have been focused on the ground-motion spectrum matching with a desired (design or target) spectrum (Suárez and Montesjo, 2007; Ghodrati et al., 2011; Malekmohammadi, 2013). The target spectrum may be derived from a probabilistic seismic-hazard analysis (Baker, 2011; Malekmohammadi, 2013). Seismological-based techniques, instead, construct the synthetics by either dynamic, kinematic, or stochastic modeling of the earthquake source.

The stochastic point-source simulation is a popular method for generating high-frequency (HF) ground motions (Boore, 1983). The stochastic approaches (either point source or finite source) generate seismograms by considering a random process for ground motions over almost all frequencies (Boore, 2003). The stochastic point-source techniques (such as the SMSIM software by Boore, 2005, 2012) and the stochastic finite-fault methods (such as the EXSIM software by Motazedian and Atkinson, 2005) are widely used to generate synthetic seismograms in both engineering and seismological applications. Atkinson et al. (2009) and Boore (2009) provided informative and detailed discussions on the comparison of the stochastic finite-source and the stochastic point-source models.

Dynamic models and kinematic models are two approaches for modeling of an earthquake source to predict more precise ground motions having the underlying physical mechanism. The kinematic source model assumes a specific slip distribution as well as a source time function (STF), whereas in the dynamic model an explicit frictional failure law (e.g., slip-weakening model) is specified (Trugman and Dunham, 2014). As the computational problem of the rupture process in dynamic models is nonlinear, such models are computationally more intensive than kinematic models. The pseudodynamic (PD) model is an alternative to the dynamic model in which the main physical characteristics of the rupture simulation are related to the kinematic model to develop dynamically consistent kinematic source models that are computationally more efficient. Examples of incorporating PD source models in ground-motion simulations may be found in studies by Guatteri et al. (2004), Song and Somerville (2010), Mena et al. (2012), Schmedes et al. (2013), Song et al. (2014), and Trugman and Dunham (2014).

The deterministic simulation of the ground motion using dynamic, pseudodynamic, and kinematic approaches in a broad frequency range of engineering interest (0–10 Hz) is still computationally expensive (Schmedes et al., 2013). Hybrid broadband (HBB) simulation techniques have been developed in which the deterministically generated long-period synthetics are combined with HF motions to produce broadband synthetics for the entire frequency band of interest. Some of the broadband methods (e.g., Zeng et al., 1994; Hartzell et al., 2005; Mai et al., 2010) use the physics of wave scattering to simulate the HF ground motion (frequency > 1.0 Hz), whereas some other methods incorporate stochastic approaches to generate the HF portion of seismograms (e.g., Graves and Pitarka, 2004, 2010; Liu et al., 2006; Frankel, 2009). In the first group, Zeng et al. (1994) proposed a HBB composite source model, which uses scattering functions for HF coda waves. Hartzell et al. (2005) calculated broadband time histories using kinematic and dynamic models and compared the results with the 1994 Northridge earthquake. Mai et al. (2010) combined the low-frequency (LF) deterministic seismograms (frequency < 1.0 Hz) with the HF S-to-S backscattering seismograms. Mena et al. (2010) updated Mai et al. (2010) by accounting for finite-fault effects in HF wave computation, as well as applying dynamically consistent STFs in the simulation. In the latter methods, Liu et al. (2006) generated the broadband ground-motion synthetics using a frequency method with correlation random source parameters. Frankel (2009) proposed a constant stress-drop model to generate HBB synthetic seismograms. He also used a static stress drop for HF synthetics and dynamic stress drop for LF synthetics in his simulations. Graves and Pitarka (2010) updated the hybrid simulation approach of Graves and Pitarka (2004) by incorporating spatial heterogeneity in slip, rupture speed, and rise time in the kinematic rupture fault modeling.

The central and eastern United States (CEUS) is considered a high seismic area where recorded strong ground motions are scarce. Hwang et al. (2001) generated synthetic seismograms from the large New Madrid earthquake using a stochastic method. Somerville et al. (2001) generated broadband synthetics to develop GMPEs for CEUS. Olsen (2012) implemented 3D broadband simulations to predict ground motions in the New Madrid Seismic Zone (NMSZ) for 1811–1812 events with the moment magnitudes M 7.4–7.7 earthquakes. Synthetic simulations are also performed in the studies of Frankel et al. (1996), Toro (2002), Campbell (2003), Tavakoli and Pezeshk (2005), Atkinson and Boore (2006), and Pezeshk et al. (2011) to develop ground-motion models in central and eastern North America.

The objective of this study is to generate synthetic seismograms that are consistent with the overall characteristic of ground motions expected to observe in CEUS. Applying the proposed broadband approach, seismograms are produced from different shaking scenarios for this region. The key feature of this study is implementing the discrete wavenumber/finite-element (DWFE) technique of the COMPsyn package (Spudich and Xu, 2003) to compute LF synthetics in the proposed broadband simulation approach for CEUS. In addition, the most recently updated geological and seismological parameters (of both kinematic and stochastic source modeling) and techniques that are proposed in the literature and are compatible with CEUS are incorporated in earthquake simulations. The HF synthetics are computed through the stochastic finite-fault method applying identical fault planes defined and implemented in LF simulations. We used the updated seismological parameters in
CEUS in HF synthetic simulations. The LF and HF synthetics are combined in a magnitude-dependent transition frequency to construct the broadband synthetics. The simulation approach is implemented to generate synthetics for three moment magnitudes of $M_{5.5}$, $M_{6.5}$, and $M_{7.5}$ at the source–station distance range of 2–200 km for hard-rock conditions in CEUS. Spectrum compatibility of the synthetics is presented to validate the method. The response spectral amplitudes from the synthetics are compared with those obtained from some of the recent GMPEs for CEUS.

**Hybrid Broadband Simulation Method**

In the proposed hybrid simulation technique, HF and LF ground-motion synthetics are separately calculated and then combined to produce broadband time histories. A transition frequency between HF and LF portions in many studies is presumed to be around 1.0 Hz. Frankel (2009) proposed a magnitude-dependent transition frequency based on his observation of the magnitude dependency of the transition of frequency between coherent and incoherent summation in recorded earthquakes. Following Frankel (2009), we implemented transition (crossover) frequencies of 0.8, 2.4, and 3.0 Hz in our simulations for moment magnitudes ($M$) of 7.5, 6.5, and 5.5, respectively.

The LF and HF synthetics are combined after passing matched filters. To combine two portions of synthetics at each station, HF synthetic (generated in frequencies greater than transition frequency) is synchronized with LF synthetics (generated in frequencies lower than transition frequency) applying the real arrival time computed in LF simulations. Second-order low-pass and high-pass Butterworth filters are implemented to the deterministic LF and stochastic HF synthetics, respectively. These phaseless filters have similar fall-offs and corner frequencies and do not vary the phase of the synthetics (Hartzell et al., 1999). Figure 1 illustrates the flowchart of the simulation approach. Detailed discussions are provided in the next few sections.

![Flowchart](image) - Flowchart of the method used to compute hybrid broadband (HBB) synthetics. The color version of this figure is available only in the electronic edition.

**Low-Frequency Simulation**

Low-frequency synthetics are constructed using the kinematic source modeling of the earthquake fault and the deterministic wave propagation approach. The detailed source characterizations and the wave propagation are described next.

**Kinematic Source Characteristics.** A kinematic earthquake source model is implemented to generate LF synthetics. The main input parameters are the fault geometry (length, width, dip, and strike) and the location, a desired magnitude (moment magnitude or seismic moment), a hypothetical rupture initiation point on the fault surface (the hypothetical hypocenter), the slip direction (rake), and the crustal model of the earth at the vicinity of the fault. The average of slip on the fault, $D$, is estimated by

$$D = \frac{M_0}{\mu A}, \quad (1)$$

in which $M_0$ is the seismic moment, $\mu$ is the rigidity, and $A$ is the rupturing area. The shear modulus $\mu = 3.3 \times 10^{10}$ N/m$^2$ is used in this study. A random slip distribution on the fault with a wavenumber-squared spectral decay ($k^2$) is assumed (Somerville et al., 1999; Graves and Pitarka, 2010). The heterogeneity of the slip distribution on the fault is modeled using different spatial random fields proposed by Mai and Beroza (2002) and Frankel (2009). We used the von Karman autocorrelation function (ACF) of Mai and Beroza (2002). The detailed description of this function is also briefly described in the Appendix. The slip distribution is scaled to match the desired moment for the entire faulting rupture, which is calculated using equation (1).

Assuming a hypothetical hypocenter on a fault, the rupture arrival time on each point of the fault is determined following modifications of Graves and Pitarka (2010). The procedure includes calculation of a background rupture speed distribution and local slip-dependent scaling steps. In the first step, a general ratio of the rupture velocity ($V_R$) to the local shear velocity ($V_S$), (i.e., $V_R/V_S$) is assumed to be
0.8 on the deeper part of the fault (Somerville et al., 1999), and a 70% reduction on the shallower part (i.e., \( V_R = 0.56 \, V_s \)) is applied to represent the shallow weak zone in the surface-rupture events (Pitarka et al., 2009). The background rupture velocity distribution is given by equation (2). The linear interpolation is used between the depth \( z \) of 5 and 8 km. Equation (2) is used to calculate the initial rupture front arrival time, \( T_{RF-i} \) at any individual subfault, \( i \) (Graves and Pitarka, 2004, 2010):

\[
V_R = \begin{cases} 
0.8 \times V_s & z > 8 \text{ km} \\
0.56 \times V_s & z < 5 \text{ km}
\end{cases}
\]  

(2)

The final rupture arrival time \( T_{RF-i} \) at each subfault, \( i \), after scaling is determined as

\[
T_{RF-i} = T_{RO-i} - \Delta t \left( \log(s_i) - \log(s_A) \right),
\]  

(3)

in which \( S_i \) and \( S_A \) are the average and the maximum slip on the fault, respectively. \( S_i \) is the local slip at subfault, \( i \). The scaling factor \( \Delta t = 1.8 \times 10^{-9} \times M_0^{1/3} \) is applied following Graves and Pitarka (2010). We added a small component (no more than 5%) to the final rupture front values \( T_{RF-i} \).

One of the assumption requirements in the kinematic earthquake source model is defining the time history of the finite slip duration during the rupture propagation. Tinti et al. (2005) performed a broad study on the STFs, and they proposed a kinematic regularized Yoffe slip rate function compatible with earthquake dynamics. Liu et al. (2006) proposed a trigonometric slip velocity function. Figure A1 shows the comparison of a number of kinematic slip rate functions in both time and frequency domains. In this study, we employed boxcar, triangle, and the Liu et al. (2006) STFs in different simulations. Graves and Pitarka (2010) proposed a function to heterogeneously distribute the rise time (duration of slip rate function) over the fault. The function is given in equation (4) with a linear transition between depths of 5 and 8 km. It incorporates the effect of reductions in peak slip rates in the shallower depth of surface-rupturing events (by applying factor 2 in \( z < 5 \text{ km} \)) and represents the trade-off between using constant rise time and constant slip velocity—by applying \( S^{0.5} \):

\[
T_{R-i} = \begin{cases} 
k \times S_i^{0.5} & z > 8 \text{ km} \\
2 \times k \times S_i^{0.5} & z < 5 \text{ km}
\end{cases}
\]  

(Aagaard et al., 2008), in which \( T_{R-i} \) and \( S_i \) are the local rise time and the local slip at subfault \( i \). We calculated the constant \( k \) such that the average rise time in the asperity regions over the fault is equal to the suggested value for the region. Somerville et al. (1999, 2009) proposed an average rise time for CEUS. A dip-dependent modification factor on the average rise time was proposed by Graves and Pitarka (2010). This modification reduces the rise time by decreasing the fault dip. The resultant relation for the CEUS region is given in equations (5) and (6):

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

(5)

where \( \alpha_t \) is the average rise time, \( \alpha_t \) is the scale that is a function of fault dip, \( \delta \), and the seismic moment, \( M_0 \), has dyn-cm unit. A linear transition is applied between dips 45° and 60°. The \( \alpha_t \) modification is consistent with observations for thrust- and reverse-faulting events (Hartzell et al., 2005) and should not be used on the normal-faulting scenarios (Graves and Pitarka, 2010):

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

(6)

We added a random component to equation (5) and constrained the average rise time not to vary more than 5% of the average value.

**Deterministic Wave Propagations.** The complete long-period Green’s functions for the wave propagation through a layered crustal velocity model are calculated using the DWFE method of Olson et al. (1984), applying the COMPSYN codes by Spudich and Xu (2003). The COMPSYN package has been widely used in the literature for earthquake simulation applications (e.g., Ameri et al., 2008; Ripperger et al., 2008; Wang et al., 2009; Mena et al., 2012). To evaluate the representation theorem integrals on the fault surface, the package uses the numerical techniques of Spudich and Archuleta (1987). In this package, the earth is assumed in a 3D Cartesian space with a free surface at \( z = 0 \). The application adopts the crustal structure as a 1D layered elastic medium; therefore, anelastic attenuation and 3D basin effects is not considered in the computation. Because the anelastic attenuation effect at near distances is not significant, this approximation does not notably affect the results (Ameri et al., 2008).

A midcontinental crustal model suggested for CEUS by Mooney et al. (2012) and W. Mooney (personal comm., 2013) was used in the study. We incorporated the crustal velocity model at shallow depths (to a depth of 1 km) following Somerville et al. (2001). Table 1 summarizes the crustal structure model used in this study.

<table>
<thead>
<tr>
<th>( Z ) (km)</th>
<th>( V_p ) (km/s)</th>
<th>( V_S ) (km/s)</th>
<th>( \rho ) (g/cm³)</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>

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

where \( \tau \) is the average rise time, \( \alpha_t \) is the scale that is a function of fault dip, \( \delta \), and the seismic moment, \( M_0 \), has dyn-cm unit. A linear transition is applied between dips 45° and 60°. The \( \alpha_t \) modification is consistent with observations for thrust- and reverse-faulting events (Hartzell et al., 2005) and should not be used on the normal-faulting scenarios (Graves and Pitarka, 2010):

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Long-period synthetic seismograms are generated computationally fairly quickly compared with the 3D codes and include the complete response of the earth structure (i.e., P and S waves, surface waves, leaky modes, and near-field
terms; Spudich and Xu, 2003). COMPSYN generates LF Green’s functions at receiver locations in the form of tractions on a fault plane by taking advantage of reciprocity theorem. The kinematic source characteristics (e.g., slip and slip velocity) are employed to convolve with the Green’s functions to develop ground-motion spectra at the receiver’s location. The Green’s function calculation is performed in the frequency/wavenumber domain implementing the finite-element technique. The technical approach for solving the wave equations is fully described in Olson et al. (1984) and Spudich and Xu (2003). A brief description of general equations is provided in the Appendix.

High-Frequency Simulation

High-frequency seismograms are computed using the summed point-source stochastic synthetics first formulated by Boore (1983) using the program SMSIM (Boore, 2005, 2012) over the fault plane. 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

\[
Y(M_0, R, f) = E(M_0, f) \times P(R, f) \times G(f) \times I(f)
\]

(Boore, 2003), in which \( E(M_0, f) \) 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 (dyn·cm), \( R \) is the distance (km), and \( f \) is the frequency (Hz).

In this study, the fault is divided into the number of subfaults, and the response of synthetic seismogram for each subfault is calculated and multiplied by a stress-drop factor. The use of stress drop (rather than slip) in HF simulation is due to the correlation between spectral amplitudes of radiated energy and the stress drop at higher frequencies (Frankel, 2009). Assatourians and Atkinson (2007) suggested the use of variable stress parameters in the finite-fault method. Frankel (2009) implemented fractional distribution of the stress drop on the fault and used stress-drop factors in HF synthetics of his simulations.

Here, we employed the static stress-drop distribution for a given slip distribution proposed by Andrews (1980) and Ripperger and Mai (2004). Hence, the local stress drop that is used in HF synthetic simulations is correlated with the local slip on the fault that was implemented in the simulation of LF synthetics. An identical subfaults’ size and the rupture timing along the fault have been used in HF and LF synthetic simulations. The total root mean square value of stress drop over the fault is considered to be 250 bars for CEUS following Pezeshk et al. (2011).

A simple \( \omega^2 \)-square source spectrum model is implemented for HF synthetic simulations. The path effect includes both geometrical spreading and anelastic attenuation. The frequency-dependent \( Q \) function is given by \( Q = 893 \phi^{0.32} \) to represent the anelastic attenuation of the spectral amplitude for CEUS (Pezeshk et al., 2011). The geometrical spreading (as a function of the distance) is assumed following Pezeshk et al. (2011). The value of site \( k_0 = 0.005 \) is used to account for the diminution of path-independent loss of HF motions following Atkinson and Boore (2006, 2011) and Pezeshk et al. (2011). The combined source and path duration is given by \( 1/f_a + \chi \times R \), in which \( R \) is the distance, \( f_a \) is the corner frequency associated with the subevent, and \( \chi \) is a distance-dependent constant. The subevent \( f_a \) is calculated from \( f_a = 4.9 \times 10^6 \times \beta \times (\Delta \sigma/M_0)^{1/3} \) given by Brune (1970) in which \( \beta \) is the shear-wave velocity, \( \Delta \sigma \) and \( M_0 \) are the sub-event stress drop and subevent seismic moment, respectively. Table 2 shows the summary of values that are used for different parameters for the HF stochastic simulations.

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<table>
<thead>
<tr>
<th>Parameter</th>
<th>CEUS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source spectrum model</td>
<td>Single-corner-frequency ( \omega^2 )</td>
</tr>
<tr>
<td>Stress parameter, ( \Delta \sigma ) (bars)</td>
<td>250</td>
</tr>
<tr>
<td>Shear-wave velocity at source depth, ( \beta ) (km/s)</td>
<td>3.7</td>
</tr>
<tr>
<td>Density at source depth, ( \rho ) (gm/cc)</td>
<td>2.8</td>
</tr>
</tbody>
</table>
| Geometric spreading, \( Z(R) \) | \[
R^{-1.3}; \quad R < 70 \text{ km} \\
R^{1.02}; \quad 70 \leq R < 140 \text{ km} \\
R^{-0.5}; \quad R \geq 140 \text{ km}
\] |
| Quality factor, \( Q \) | max(1000, 893\( \phi^{0.32} \)) |
| Source duration, \( T_s \) (s) | \( 1/f_a \) |
| Path duration, \( T_p \) (s) | \[
0; \quad R \leq 10 \text{ km} \\
+0.16R; \quad 10 < R < 70 \text{ km} \\
-0.03R; \quad 70 < R \leq 130 \text{ km} \\
+0.04R; \quad R > 130 \text{ km}
\] |
| Site amplification, \( A(f) \) | Atkinson and Boore (2006) |
| Kappa, \( k_0 \) (s) | 0.005 |

By implementing the empirical relation between seismic moment \( M_0 \) and moment magnitude \( M \) as \( \log M_0 = 1.5M + 9.05 \) \( (M_0 \text{ in N·m unit}) \) in equation (8), the relation between moment magnitude of the main event \( (M_{\text{main}}) \), sub-event moment magnitude \( (M_{\text{sub}}) \), and the number of subfaults would be

\[
M_{\text{sub}} = M_{\text{main}} - \log_{10}(n_1 \times n_2),
\]

in which \( n_1 \) and \( n_2 \) are numbers of the grid spacing along the fault length and width, respectively. The stochastic HF Green’s functions in any subfault are generated using a
different initial random seed number. HF stochastic synthetics in subfaults are summed over the fault plane and then convolved with an STF proposed by Frankel (1995). The purpose of the convolution is to ensure the acceleration spectrum (Fourier) amplitude is somehow constant for frequencies less than the corner frequency of the subevents and greater than the transition frequency (Frankel, 1995, 2009).

Finally, the LF and HF synthetics are passed through the matched Butterworth filters and combined to make the broadband synthetics. The variability of the slip rate and stress-drop distributions over the fault plane have significant effects on the simulated ground motions, particularly on the near-source ground motions. The importance of the implemented standard deviation of the static and dynamic stress drop has been investigated in studies by Cotton et al. (2013) and Song and Dalguer (2013). In this study, the standard deviation (sigma) for slip (and stress) is allowed to be at most twice the computed mean slip (and stress) in different simulations.

**Setting Up Shaking Scenarios**

**Fault Model**

In this study, synthetic seismograms are generated from different shaking scenarios associated with $M_{5.5}$, $M_{6.5}$, and $M_{7.5}$ magnitudes. The first and most important part of setting up a problem is to properly define the fault geometry of the main event as well as subevents. A number of relations have been proposed to estimate the rupture area derived from different data types. Wells and Coppersmith (1994), Hanks and Bakun (2002), and Working Group on California Earthquake Probabilities (2003) relations are derived from the indirect earthquake measurements (e.g., aftershock zones and surface-rupture length). Some other relations are based on the direct measurements from the rupture models and are derived from the seismic radiation (see Somerville et al., 1999; Mai and Beroza, 2000; Somerville, 2006). Following Wells and Coppersmith (1994), rupture dimensions of 18 km length ($L$) by 15 km width ($W$) are determined for $M_{6.5}$. Olsen (2012) calculated three sets of fault parameters for 1811–1812 New Madrid shaking scenarios based on Somerville et al. (2009) relation for stable continental regions ($M = 4.35 + \log_{10}[\text{area}]$). He applied the following fault geometry: $70 \times 22$ km for $M_{7.4}$ (dip 90°), 60 by 40 km for $M_{7.6}$ (dip 38°), and 140 by 22 km for $M_{7.7}$ (dip 90°). Frankel (2009) averaged the results from the previously discussed relations (both direct and indirect data type relations) and used $150 \times 15$ km for $M_{7.5}$ in his simulations. A rupture geometry of 5 by 5 km and 150 by 15 km is used for $M_{5.5}$ and $M_{7.5}$, respectively.

The earthquakes’ depths (so-called seismogenic zone) are generally distributed in the 3–15 km range. The lower seismogenic depth is usually estimated based on the maximum depth of microseismicity in a given region. The upper limit of the seismogenic zone is a controversial topic and marks the depth above which the rupture does not occur (Stanislavsky and Garven, 2002). This minimum depth is generally considered in the earthquake scenario models to diminish the near-surface seismic moment at each region to match observations. Frankel (2009) assumes a minimum depth of rupture of 3 km in all magnitude simulations. Atkinson and Boore (2011) applied a magnitude-dependent relation of $Z_{\text{TOR}} = 21 - 2.5M$ to estimate the depth to the top of the rupture surface ($Z_{\text{TOR}}$). Compatible with the geological observations, Olsen (2012) used 1 km as the minimum depth of rupture $M_{7.4}$–7.4 events in NMSZ. In our simulations, we assumed 1.0–3.0 km for $M_{7.5}$, 2.0–4.0 km for $M_{6.5}$, and 3.0–5.0 km for $M_{5.5}$ simulations as the minimum depth of seismogenic zone for CEUS.

Applying smaller subfault sizes in finite-fault modeling is appealing because they allow more precise modeling of rupture directivity effects and spatial slip variation (Hartzell et al., 1999); however, increase in the number of cells is computationally expensive. Frankel (2009) found that the area of subfault (and the corresponding magnitude of subevent) has an insignificant effect on the calculated mainshock’s spectral accelerations (SAs), and he used a subfault size of 0.31 km $\times$ 0.31 km for simulations of all magnitude events. Graves and Pitarka (2010) limit the subfault size for the HF simulations to about 1.0 km to inhibit destructive interference effects of random phasing in certain frequencies (Joyner and Boore, 1986). Considering the previous discussion, we choose the subfault size of 1.0 km $\times$ 1.0 km for $M_{7.5}$, 0.5 km $\times$ 0.5 km for $M_{6.5}$, and 0.25 km $\times$ 0.25 km for $M_{5.5}$ simulations.

The relations between the areas and moments of subevents and the mainshock are given in equations (8) and (9).

**Hypocenter Locations**

Atkinson and Silva (2000) suggested use of the magnitude-dependent equivalent point-source depth, $h$, to account for the hypocenter depth and to modify the distance in synthetic simulations as a function of the moment magnitude, $M$. The relation is given by

$$ \log_{10} h = -0.05 + 0.15M. \quad (10) $$

Scherbaum et al. (2004) suggested a linear magnitude-dependent relation for the hypocenter depth $Z_{\text{HYP}}$ for different strike-slip and non-strike-slip events as

$$ Z_{\text{HYP}} = \begin{cases} 5.63 + 0.68M & \text{strike-slip} \\ 11.24 - 0.2M & \text{non-strike-slip} \end{cases}. \quad (11) $$

Mai et al. (2005) performed a comprehensive statistical analysis on hypocenter locations in finite-source rupture models to find their location with respect to the overall fault dimension and asperity regions. They concluded that ruptures initiate close to the large slip asperities and encounter the larger slip asperity within the first half of the rupture distance. Moreover, the hypocenter for the crustal dip-slip
earthquakes is preferentially in the deeper portions of the fault plane (about 60% down the fault width). Considering both equations (10) and (11) and the previous discussion, we used hypothetical hypocenters at depths of $Z_{\text{HYP}}/0.0136$ km for $M_{7.5}$, $Z_{\text{HYP}}/0.0006$ km for $M_{6.5}$, and $Z_{\text{HYP}}/0.002$ km for $M_{5.5}$ strike-slip simulations.

A summary of the fault parameters used in the simulations is provided in Table 3.

Station Distribution

We generated synthetic seismograms at different azimuthal ranges and with the closest distance, the Joyner–Boore distance, $R_{JB}$ (Joyner and Boore, 1981), of 2–200 km. Stations were azimuthally distributed in such a way to have an approximately equal distance from each other at any given $R_{JB}$ distance. Figure 2 shows the map of stations used for $M_{7.5}$ simulations. At very close distances to the fault, stations were densely distributed, but at far distances a minimum number of stations was set to sample the ground motions at different azimuths. A similar station distribution pattern at the surface was used for $M_{6.5}$ and $M_{5.5}$ simulations.

The average slip and rise-time values were calculated based on equations (1) and (5), respectively. The Hurst exponent values in different shaking scenarios were allowed to fluctuate; however, they were restrained to be in the 0.65–0.9 range. Other parameters used in simulations are listed in Table 4.

Figures 3 and 4 show realizations of the slip, stress drop, rise time, and slip rate distributions as well as rupture propagations over the fault planes for one of the $M_{7.5}$, $M_{6.5}$, and $M_{5.5}$ simulations. Here, we specified three hypocenter locations at 1/4, 1/2, and 3/4 along the fault length. The hypocenter locations are marked with stars in the slip distribution realization panels. We employed the magnitude-

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Fault Parameters Used in Simulations</th>
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<tbody>
<tr>
<td>Moment</td>
<td>Fault Length (km)</td>
</tr>
<tr>
<td>5.5</td>
<td>5</td>
</tr>
<tr>
<td>6.5</td>
<td>18</td>
</tr>
<tr>
<td>7.5</td>
<td>150</td>
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</table>

<table>
<thead>
<tr>
<th>Table 4</th>
<th>Summary of the Key Parameters Used in the Broadband Simulations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moment</td>
<td>$M_{0}$ ($10^{17}$ N·m)</td>
</tr>
<tr>
<td>5.5</td>
<td>2.0</td>
</tr>
<tr>
<td>6.5</td>
<td>63.1</td>
</tr>
<tr>
<td>7.5</td>
<td>1995.0</td>
</tr>
</tbody>
</table>

Figure 2. The fault trace and the map of stations used for $M_{7.5}$ simulations. Circles represent stations. The vertical fault trace (90° dip) on the surface is shown as a solid line with east–west strikes. At any given closest distance to the fault, stations are azimuthally distributed so as to have almost equal distance to each other. The color version of this figure is available only in the electronic edition.
dependent depth for the nucleation point of hypocenter. The range of hypocenter depths are given in Table 3. A minimum slip value equal to zero was set, and the slip distribution scaled to match the desired moment for the entire faulting area. Contours on slip distribution panels represent the rupture front (equations 2–3). The stress-drop distribution was scaled to have the root mean square of 250 bars and was used in HF stochastic finite-fault synthetic simulations. Kinematic rise-time values were calculated and distributed over the fault using equations (9)–(11).

Results and Validation

Hybrid broadband synthetics were generated using the methodology described above. The crustal model used is shown in Table 1. The generated broadband accelerograms in this study were recorded at 459 stations for M 7.5, 438 stations for M 6.5, and 384 stations for M 5.5 simulations. By specifying three hypothetical hypocenter locations along the length of the fault and assigning three slip distributions per each hypocenter location, a total of nine shaking scenarios were defined for each magnitude.

Shaking scenarios for engineering applications are observed in terms of different intensity measures of peak ground acceleration (PGA), peak ground velocity (PGV), peak ground displacement (PGD), and spectral amplitudes. Each individual intensity measure signifies different characteristics of seismograms and has been influenced by the frequency content of a different frequency band (Cultrera et al., 2010). A complete response of the earth structure was calculated in three components (one vertical and two horizontal) of LF synthetics. For any shaking scenario and at any station location, two sets of HF time histories were generated, applying different initial random seed numbers to combine with the LF synthetics and to construct the broadband seismograms. The computational effort for simulations of multiple shaking scenarios was performed on the University of Memphis Penguin Computing Cluster Servers.

Figure 5 depicts an example of construction of a broadband seismogram from the summation of filtered-deterministic LF and filtered-stochastic HF synthetics. Synthetic time histories presented in Figure 5 were generated from a strike-slip shaking scenario with M 7.5 (the hypocenter was at a quarter-length of the fault) and were recorded at a station with $R_{JB} = 20$ km along the strike of the fault.

The deterministic LF amplitudes should be comparable overall with the stochastic HF ground-motion amplitudes around the crossover (transition) frequency (Frankel, 2009). At any particular station, the geometric mean of Fourier spectral amplitudes (FSAs) before they were filtered and combined was computed around the transition frequency (i.e., $f_{\text{transition}} \pm 0.2$ Hz) for HF and LF synthetics, separately. Considering the magnitude-dependent crossover frequencies listed in Table 4, the geometric mean of FSAs were calculated in frequency bands of 2.8–3.2 Hz for M 5.5, 2.2–2.6 Hz for M 6.5, and 0.6–1.0 Hz for M 7.5 simulations. Two samples of FSA comparisons around transition frequencies (one for M 6.5 and one for M 7.5) are presented in Figure 6. In this figure, the geometric means of FSAs are plotted based on...
seismograms from all stations for one of the shaking scenarios (for each magnitude). We can observe a general similarity in FSAsof HF and LF synthetics around the crossover frequencies.

Figure 7 shows the ratios of the FSAsof LF to HF synthetics around the transition frequencies for $M_{7.5}$ and $M_{6.5}$. In this figure, these ratios of LF to HF at each site are calculated and then averaged among all stations with the same distance but different azimuths. We considered results from three shaking scenarios with the hypocenter locations at $L/4$, $L/2$, and $3L/4$ at each magnitude in this figure.

Figures 8, 9, and 10 depict an ensemble of generated broadband acceleration time histories for stations with closest distances, $R_{JB}$, of 10, 50, 80, 120, and 200 km from one of the shaking scenarios with $M_{7.5}$, $M_{6.5}$, and $M_{5.5}$, respectively. In these figures, fault-normal components of accelerograms are plotted for two sets of stations: one set along the strike of the fault and the other set perpendicular to the fault’s strike at the fault center. The time represents the origin of the time after the initiation of rupture at the hypocenters. As was expected, PGAs were reduced with the distance. The effect of the magnitude on the shaking duration was apparent in these seismograms. An overall increase of shaking duration from $M_{5.5}$ to $M_{6.5}$ and to $M_{7.5}$ could be perceived. This concept could be clearly observed by comparing the duration of synthetics from different magnitude simulations, recorded at stations with similar distances to the fault (and particularly at closer distances).

In Figure 11, examples of LF fault-normal and fault-parallel components of velocity time histories for a set of stations in the distance range of 10–200 km from one of $M_{6.5}$ simulations are shown. The stations are located perpendicular to the strike of the fault at the fault center. The positions of the nucleation points and patches were assumed almost at the center of the fault area.

We compared pseudospectral accelerations (PSAs) of synthetic seismograms with GMPEs suggested for the CEUS region. The PSAs are computed for a single-degree-of-freedom system with a 5% critical damping ratio. Boore et al. (2006) proposed two orientation-independent measures of ground motions: geometric mean using period-dependent rotation angles (GMRotDpp) and geometric mean using period-independent rotation angles (GMRotIpp). In this study, the orientation-independent and period-dependent geometric mean (i.e., GMRotD50) of two orthogonal horizontal motions at any station were calculated using the procedure described.
in Boore et al. (2006) and implemented using the package provided in Boore’s website.

Figures 12, 13, and 14 show the PSAs of the generated seismograms at periods of 0.2, 1.0, and 3.0 s from six simulations of $M_{7.5}$, $M_{6.5}$, and $M_{5.5}$, in the closest distance range of 2–200 km. The GMPEs by Pezeshk et al. (2011, referred to as P11) and by Atkinson and Boore (2006, 2011, referred to as AB06), were used for comparison. In these

Figure 7. Ratios FSAs of the LF to HF synthetics around the transition frequency. The ratios represent the average from three different shaking scenarios with the hypocenters located at $L/4$, $L/2$, and $3L/4$ along the strike for magnitudes of (left) $M_{7.5}$ and (right) $M_{6.5}$. Error bars are ±1 standard deviation. The color version of this figure is available only in the electronic edition.

Figure 8. Generated broadband acceleration time histories (cm/s²) from one of the shaking scenarios with $M_{7.5}$ for two sets of the stations with the closest distances of 10, 50, 80, 120, and 200 km. The fault-normal component of seismograms are shown in all panels. (Left) Stations along the strike of the fault and (right) stations located perpendicular to the fault’s strike at the middle of the fault. The color version of this figure is available only in the electronic edition.
figures, the median (and median ± 1 standard deviation for Pezeshk et al., 2011) SA values were plotted as well as the synthetics’ PSAs. The overall agreement between the attenuations and the synthetics’ PSAs was observed at different periods. Considering a range of transition frequencies (i.e., 0.8–3.0 Hz) used for different earthquake magnitudes, the PSA values at periods of 0.2 and 3.0 s were mainly controlled by HF and LF synthetics, respectively. Both HF and LF synthetics contribute to the SAs at the period of 1.0 s; however, PSAs at 1.0 s for M 7.5 and M 5.5 have mostly been influenced by HF and LF synthetics, respectively. Thus, owing to the assumed magnitude-dependent transition frequencies, the effect of LF synthetics on PSAs at the 1.0 s period lessened with increase of magnitude. The larger scatter at longer periods (i.e., 3.0 s and higher) PSAs was perceived. It could be interpreted as the effects of kinematic source modeling and the deterministic wave propagation (such as the variability of slip distribution, rupture propagation, radiation pattern, directivity effects, etc.) and PSA sensitivity to these parameters (Frankel, 2009; Cultrera et al., 2010).

A more precise investigation of the spectrum compatibility of synthetics indicated that for M 7.5 events, Atkinson and Boore (2006, 2011) and Pezeshk et al. (2011) GMPEs give higher PSA values at 0.2 s than the synthetics at distances of 20–70 km. At 1.0 and 3.0 s periods, synthetics generally agree well with both GMPEs from 2 to 200 km. In addition, spectral saturation at both 1.0 and 3.0 s periods was observed at very close distances of \( R_{JB} < 10 \) km to the fault. The 3.0 s PSAs showed larger scatter than the 1.0 s. As discussed earlier, the larger variability of PSAs at longer periods was the consequence of the sensitivity of seismograms to the slip distribution, the focal mechanism, and the radiation pattern used in the kinematic source modeling, as well as the rupture directivity effects.

The 0.2 s PSAs for M 6.5 events and for the close-in distances were lower than the median values of attenuations (however, within one standard deviation band for Pezeshk et al., 2011, GMPE). In both the 1.0 and 3.0 s periods, the synthetics’ PSAs matched with both attenuation relations. At the 3.0 s period and for close-in distances, the tendency toward super saturation of SA was observed.

Similar to the other magnitudes, for M 5.5 earthquake scenarios, an overall agreement between attenuations and synthetics SAs at 0.2, 1.0, and 3.0 s periods was apparent.

Figure 9. Same as Figure 8 but from M 6.5 simulations. (Left) Stations along the strike of the fault and (right) stations located perpendicular to the fault’s strike and in the middle of the fault. The color version of this figure is available only in the electronic edition.
in all distances. At the 1.0 and 3.0 s periods and close distances to the fault, the synthetics’ PSAs fell mainly between the median of two attenuation relations. At far distances, the 3.0 s PSAs showed higher spectral amplitudes than the GMPEs. Similar to M 7.5 and M 6.5 events, the 3.0 s PSAs had larger variability than the 1.0 s period for M 5.5 shaking scenarios.

As discussed earlier, the SAs at the 0.2 s period were mainly controlled by the stochastic portion of broadband synthetics. To test the proposed finite-fault simulation approach, we compared 0.2 s PSAs resulting from M 5.5 and M 6.5 simulations in this study with those derived from point-source stochastic method using the program SMSIM (Boore, 2005, 2012). It was expected to observe comparable ground motions from small earthquakes at far distances produced from finite-fault and point-source simulation methods (Boore, 2009). The M 5.5 and M 6.5 events were chosen because they have smaller faulting areas and may be treated as the point sources at far distances (particularly M 5.5 events). For this purpose, 25 point-source simulations were run (for each magnitude and with different initial random seed number). Figure 15 illustrates the comparison of the mean and one standard deviation of 0.2 s PSAs associated with synthetics deriving from the point-source stochastic method and this study for M 5.5, M 6.5, and M 7.5 events. The results showed that the 0.2 s PSAs from the two methods were analogous at far distances compared with the associated faulting areas (i.e., for distances of $R_{JB} > 20$ km and $R_{JB} > 40$ km for M 5.5 and M 6.5 earthquakes, respectively). At short distances, the point-source method generates slightly higher 0.2 s PSAs than the finite-fault broadband method except for M 5.5 events at the very close distance of 2 km (on average the ratios are about 1.08–1.20). Figures 16 and 17 show the comparison of the finite-fault and point-source methods for all three magnitudes at different spectral periods of 1.0 and 3.0 s, respectively.

Conclusions

We have simulated broadband synthetics based on a proposed HBB technique for the CEUS region. Synthetic seismograms were produced for M 5.5, M 6.5, and M 7.5 events and were recorded at stations with the closest distances to the fault of 2–200 km. A DWFE technique was implemented to
calculate the long-period Green’s functions. The HF part of synthetics was derived from a finite-fault stochastic model. Finally, the HBB seismograms were obtained by implementing pair-matched low-pass and high-pass Butterworth filters applied to the LF and HF synthetics, respectively. To conserve the radiated energy over the entire fault, a stress-scaling factor was multiplied to the subfault’s stochastic Green’s functions before they were summed. Different shaking scenarios compatible with \( M_{\text{MMJ}} 5.5–7.5 \) were defined. Some of the scenarios were set to capture significant directivity effects, with larger peak ground motions in the direction of rupture propagation.

To validate the procedure, PSAs of the broadband synthetics (with 5% damping) were compared with the GMPEs proposed by Atkinson and Boore (2006, 2011) and Pezeshk et al. (2011). An overall agreement between the synthetics’ PSAs and attenuation relations has been observed (see Figs. 12–14). The results were discussed in more detail in the Results and Validation section.

A comparison between the stochastic point source and the proposed finite-fault method was performed as a test of the procedure to evaluate spectral amplitudes at far distances from low magnitude events. The results (see Fig. 15) indicated that PSAs at the 0.2 s period from broadband synthetics agreed well with point-source simulations at comparable far-in distances. In addition, we compared the results of the stochastic point source with the finite-fault method at longer periods of 1.0 and 3.0 s. At close distances and longer periods, the oversaturation effect is observed, and the finite-fault method generates lower SAs than the stochastic point-source method. In the intermediate distance range (40–120 km), the finite-fault method simulates the higher PSAs; however, this trend is reversed at far distances.

In this study, we implemented the recent proposed parameters and relations compatible with geological and seismological data of CEUS. This information provided overall characteristics of the expected ground motions in this region. The variability of some kinematic parameters such as position of hypocenter, slip distribution, STF, and rupture propagation was considered; however, the effects of different crustal models and different focal mechanisms (other than strike slip) have not yet been investigated. Additional
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Figure 12. Comparison of pseudospectral accelerations (PSAs) of generated broadband synthetics for a number of M 7.5 simulations with ground-motion prediction equations (GMPEs) of Pezeshk et al. (2011, referred to as P11) and Atkinson and Boore (2006, 2011, referred to as AB06). PSAs are plotted for periods of (top) 0.2 s, (middle) 1.0 s, and (bottom) 3.0 s. Error bars show ±1 standard deviation from mean values at any given distance. The color version of this figure is available only in the electronic edition.

Figure 13. Same as Figure 12 but for M 6.5 simulations. The color version of this figure is available only in the electronic edition.
Figure 14. Same as Figure 12 but for M 5.5 simulations. The color version of this figure is available only in the electronic edition.

Figure 15. Comparison of 0.2 s spectral acceleration for (top) M 5.5, (middle) M 6.5, and (bottom) M 7.5 from the point-source (SMSIM) and the finite-fault (this study) simulation methods. Error bars show ±1 standard deviation from mean values at any given distance. The color version of this figure is available only in the electronic edition.
Figure 16. Same as Figure 15 but for spectral period of 1.0 s. The color version of this figure is available only in the electronic edition.

Figure 17. Same as Figure 15 but for spectral period of 3.0 s. The color version of this figure is available only in the electronic edition.
earthquake scenarios should be run in the future to assess the effect of different crustal model and other focal mechanisms. Variability analysis of the parameters will be performed and addressed in future studies.

The large number of generated seismograms provided variability in intensity measures of PGA, PGV, PGD, and PSAs that could be observed at different sites in CEUS. To obtain a broader variability at CEUS, the modeling of other earthquake source mechanisms is required. The seismograms could be used in different earthquake engineering and/or engineering seismology applications.

Data and Resources

We used the COMPSYN software package provided by Paul Spudich. Some of the kinematic modeling is performed using the rupture model generator package provided by Martin Mai available at http://ces.kaust.edu.sa/Pages/Home.aspx (last accessed August 2013). The authors implemented several FORTRAN subroutines available at www.daveboore.com in the simulations (last accessed January 2013).

Acknowledgments

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References


Appendix

Additional Descriptions of the Long Period Ground-Motion Model Description

ACF Source Model

In this study, the von Karman autocorrelation function (ACF) is employed to model the slip distributions over the fault plane. Following Mai and Beroza (2002), von Karman ACF is characterized in space by

\[ C(r) = \frac{G_H(r)}{G_H(0)}, \]  
(A1)

and

\[ P(k) = \frac{a_x a_z}{1 + k^2 H^2}, \]  
(A2)

in which \( K_H \) is the modified Bessel function of the first kind with the order of \( H \), \( r \) is the distance, \( H \) is the Hurst exponent, which represents the spectral decay at high wavenumbers, and \( k \) is the wavenumber. The characteristic scales are symbolized by the correlation length along the strike and downdip directions, \( a_x \) and \( a_z \), respectively. The wavenumber \( k \) and distance \( r \) are characterized using the directional correlation length according to equations (A4) and (A5). In these equations, \( x \) and \( kx \) are the distance and the wavenumber along the strike, respectively. Similarly, \( z \) and \( kz \) are the distance and the wavenumber downdip direction, respectively:

\[ r = \sqrt{\left(\frac{x^2}{a_x^2} + \frac{z^2}{a_z^2}\right)} \]  
(A4)

and

\[ k = \sqrt{(a_x^2 k_x^2 + a_z^2 k_z^2)}. \]  
(A5)

Source Time Function

The comparison between different source time functions in frequency and time domains are shown in Figure A1. The slip rate STFs are normalized to have a unit area (i.e., unit slip).

Figure A1. Different normalized source time functions (STFs): Boxcar, triangle, and regularized Yoffe (Tinti et al., 2005; Liu et al., 2006). All STFs are normalized to have a unit area (unit slip). (Top) Slip-rate functions in time domain, (middle) normalized slip functions in time domain, and (bottom) normalized Fourier amplitude spectra. Times and periods are also normalized to the slip rise time (Tr). The color version of this figure is available only in the electronic edition.

Wave Propagation

In the COMPSYN package, the Green’s function is calculated in the frequency/wavenumber domain and using the finite-element technique. The low-frequency displacement \( u \) and its vertical derivative \( u' \) is
\[ u(r, \phi, z, t) = \sum_m \int_0^\infty \frac{k}{2\pi} \left\{ (U^m_{zk}(z, t)R^m_k(r, \phi) + U^m_{rk}(z, t)S^m_k(r, \phi) + U^m_{\phi k}(z, t)T^m_k(r, \phi) \right\} dk \]

(A6)

and

\[ u'(r, \phi, z, t) = \sum_m \int_0^\infty \frac{k}{2\pi} \left\{ (U'^m_{zk}(z, t)R^m_k(r, \phi) + U'^m_{rk}(z, t)S^m_k(r, \phi) + U'^m_{\phi k}(z, t)T^m_k(r, \phi) \right\} dk \]

(A7)

(Spudich and Xu, 2003), in which \( u' \equiv du/\partial z \), \( k \) is the horizontal wavenumber, \( m \) is the angular order, \( (r, \phi, z) \) are cylindrical coordinates, \( t \) is the time, \( R^m_k, S^m_k, \) and \( T^m_k \) are the vector surface harmonics and \( U^m_{zk}, U^m_{rk}, U^m_{\phi k}, U'^m_{zk}, U'^m_{rk}, U'^m_{\phi k} \) are expansion coefficients (see Olson et al., 1984, for more details).

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