Ground-Motion Parameters and Time Histories

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Executive Summary

Earthquake ground motions, including peak values and time histories, are key parameters for seismic design and analysis of tailing dams. It is not an easy task to derive the ground motions because there is a lack of records and earthquakes are infrequent in the central and eastern United States. Two approaches, probabilistic seismic hazard analysis (PSHA) and deterministic seismic hazard analysis (DSHA) are widely used in deriving the ground motion parameters. The two approaches use the same data sets, earthquake sources (where and how big), earthquake occurrence frequencies (how often), and ground-motion attenuation relationship (how strong), but the final products are fundamentally different. PSHA uses a series of probabilistic computations to combine the uncertainties in earthquake source, occurrence frequency, and ground-motion attenuation relationship. PSHA predicts a relationship between a ground-motion value, such as PGA, and a chance that a value will be exceeded, *a hazard curve*. Selection of the design ground-motion parameters is ambiguous from PSHA because there are infinite points (choices) on the hazard curve. DSHA develops a particular seismic scenario upon which a ground-motion hazard evaluation is based. The scenario consists of the postulated occurrence of an earthquake of a specified size at a specified location. The advantage of DSHA is that it provides ground-motion parameters from those earthquakes that have the most significant impacts. This is particularly advantageous for seismic design and analysis of tailing dams.

The ground-motion time histories can also be derived from PSHA or DSHA. However, the time histories derived from PSHA do not associate with any individual, but many earthquakes. This is one of the disadvantages of PSHA. On the other hand, it is straightforward for DSHA to provide time histories because DSHA determines earthquakes that have the most significant impacts. For engineering design and analysis, especially for tailing dams, a "design earthquake" is desired. The engineering seismic designs and standards in the United States, as well as in the world, are based on the experience in coastal California. The ground motion specified for engineering designs, such as highway bridges and buildings in California, is the deterministic ground motion derived from the maximum credible (considered) earthquake. In engineering analysis and design, DSHA is more appropriate for developing the ground-motion time histories.

There are two ways to get time histories: actual ground motion records or synthetic ground motions. In the central United States, the synthetic ground motions are widely used because there is no ground motion record available from strong and large

earthquakes (>M5.0). The most widely used method to generate synthetic ground motion is the stochastic point- and finite-source models. The stochastic models utilize the characteristics that observed ground motions can be characterized as finite-duration bandlimited Gaussian noise with an amplitude spectrum specified by a simple source model and path effects. Although its success and simplicity, the stochastic models have some drawbacks. The stochastic models do not simulate the near-source effects, such as rupture propagation, directivity, and asperity. The stochastic models do not consider the wave propagation (path effects) in two- and three-dimensional crust. The source and path effects could have significant influences on the simulated ground motions. The other drawback of the stochastic models is that the simulated three components of ground motions are not physically consistent. The stochastic models simulate an individual component of ground motion independently and randomly at a given site.

The composite source model, which can take into account the near-source effects and wave propagation (path effects) in detail, have recently been introduced and used in ground motion simulation. The composite source model utilizes Green's functions for the generation of synthetic ground motion for a layered medium. The composite source model has been used to simulate ground motions from two recent earthquakes, the June 18, 2002, Darmstadt, Ind., earthquake (M4.6), and The June 6, 2003, Bardwell, Ky., earthquake (M4.0). The composite source model has also been used to simulate a scenario earthquake of M7.7 in the New Madrid Seismic Zone. In comparison with the observations and other methods, the composite source model provides better and physically consistent ground motions. The composite source model has been recommended to be used to generate synthetic ground motions for seismic design and analysis of highway bridges in Kentucky.

Introduction

How earthquakes affect humans, buildings, and dams depends on how strong the seismic wave (ground motion). Most damage during an earthquake is caused by ground motion. The level of ground motion depends on earthquake magnitude, the distance from the earthquake center —epicenter—, type of the fault. The larger an earthquake's magnitude, the stronger ground motion it will generates. The closer a site is to the epicenter, the stronger the ground motion, and vice versa. The ground motion generated directly by an earthquake is the primary hazard – ground motion.

The strong ground motion can cause the secondary hazards, such as ground motion amplification, liquefaction, and landslide, under certain local geologic conditions. Soft soils overlying hard bedrock tend to amplify the ground motions—this is known as **ground-motion amplification**. Soft sandy soils can be liquefied by strong ground motion—a process called **liquefaction**. The strong ground motion can also trigger landslides—known as **earthquake-induced landslide—**in areas with steep slope, such as eastern Kentucky. These secondary hazards are of great concern for tailing dam seismic safety. These hazards are site-specific and required detail site investigation.

In this paper, we only discuss the primary seismic hazard, ground motion, directly related to the local and regional geology and seismology.

Seismic Hazard Analysis

Earthquake ground motions, including peak values and time histories, are derived through a process called seismic hazard analysis. Seismic hazard analysis is an effort to estimate what level of ground motion could be expected at a site. Three data sets, earthquake sources (where and how big), earthquake occurrence frequencies (how often), and ground motion attenuation relationship (how strong), are required. In the central and eastern United States, answers to the questions: "where, how big, how often, and how strong?" are very difficult ones. In comparison to typical plate boundary seismic zones such as coastal California, the central and eastern United States is located in the middle of the continent and has a totally different tectonic setting. For example, the exact boundary of the New Madrid Seismic Zone is still difficult to define, even though it is the most active and well studied in the country. The biggest historical earthquake to have occurred in the central United States was the 1811–1812 New Madrid events. The estimated magnitude ranges from about M7 to M8—a large range, though it has been well studied (Johnston, 1996; Hough et al., 2000). Earthquakes are also infrequent, especially large earthquakes that have significant impacts on the built environment. Recurrence intervals for the large earthquakes are quite long, ranging from about 500 years in the New Madrid Seismic Zone to about 4,000 years in the Wabash Valley Seismic Zone; they are even longer in other zones. These recurrence intervals were primarily determined from paleo-liquefaction studies (Tuttle and Schweig, 1996). Several ground motion attenuation relationships are available for the central United States (Campbell, 2003; Frankel et al., 1996; Toro et al., 1997; Atkinson and Boore, 1995; Sumerville et al., 2001). However, all the attenuation relationships were developed based on numerical modeling and sparse strong-motion records from small earthquakes. These attenuation relationships have large uncertainty and predict much higher ground motions in comparison with similar magnitude earthquakes in California.

Two approaches, probabilistic seismic hazard analysis (PSHA) and deterministic seismic hazard analysis (DSHA), are widely used. The two approaches use same data sets, earthquake sources (where and how big), earthquake occurrence frequencies (how often), and ground-motion attenuation relationship (how strong), but are fundamentally difference in calculations and final results.

Probabilistic Seismic Hazard Analysis (PSHA)

PSHA involves a series of probabilistic computations to combine the uncertainties in earthquake source, occurrence frequency, and ground-motion attenuation relationship. PSHA consists of four basic elements (Reiter, 1990):

(1) Determination of earthquake sources;

(2) Determination of earthquake occurrence frequencies – selecting controlling earthquake(s): the maximum magnitude, maximum credible, or maximum considered earthquake;
(3) Determination of ground motion attenuation relationships;
(4) Determination of seismic hazard curves.

Mathematically, PSHA involves a triple integration over earthquake sources, occurrence frequencies, and ground-motion attenuation relationships (Figure 1) as the equation

$$\gamma(y) = \sum_{N} v_i \iiint_{M,R,\mathrm{E}} f_M(m)\, f_R(r)\, f_{\mathrm{E}}(\varepsilon) P[Y > y \,|\, m, r, \varepsilon]\, dm\,dr\,d\varepsilon\,, \qquad (1)$$

The results from a PSHA are commonly expressed in a series of curves, *seismic hazard curves*, which provide ground motion value (peak acceleration, peak velocity, response acceleration, and etc.) versus annual probability of exceedance (or return period) at a specific site or sites (Fig. 1 step 4). Fig. 2 shows 0.2 s response spectral acceleration hazard curves at seven selected cities in the United States (Leyendecker, and others, 2000). The hazard curves provide a range of ground-motion values, from 0.01 to 8.0 g, with corresponding annual frequencies of exceeding (or return period) from 0.1 to 0.00001 (10 to 100,000 years return periods). What level of ground motion or return period should be selected for engineering analysis and design from the curves? Currently, three levels of ground-motion associated with 10, 5, and 2 percent PE in 50 years (500, 1,000, and 2,500 years return periods) are commonly used. These three sets of ground motions represent only three specific points on the hazard curves. If the three points on the curves were the choice, all other points on the curves would also be "equally" valid choice. Therefore, in terms of PSHA, selections of ground motion for bridge design are not one, not two, not three, but infinite.

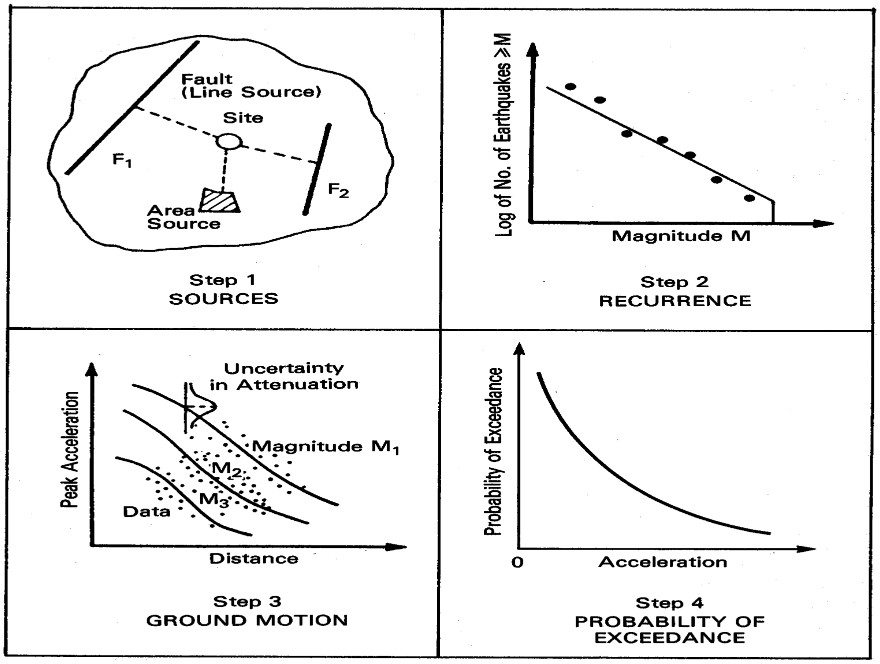

Figure 1. Steps involved in PSHA (Reiter, 1990).

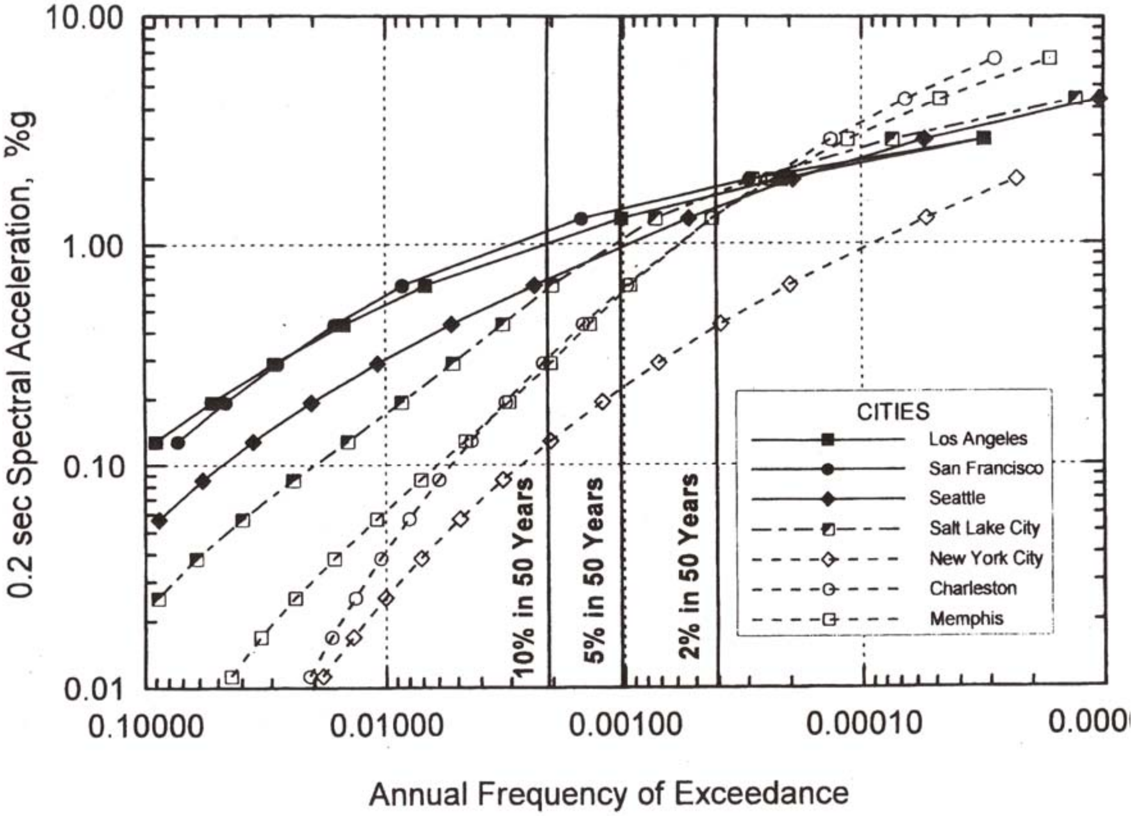

Figure 2. Hazard curves for selected cities (Leyendecker and others, 2000).

Deterministic Seismic Hazard Analysis (DSHA)

DSHA involves the development of a particular seismic scenario upon which a ground motion hazard evaluation is based. The scenario consists of the postulated occurrence of an earthquake of a specified size at a specified location. DSHA involves four basic elements (Reiter, 1990):

(1) Determination of earthquake sources;
(2) Determination of earthquake occurrence frequencies – selecting controlling earthquake(s): the maximum magnitude, maximum credible, or maximum considered earthquake;
(3) Determination of ground motion attenuation relationships;
(4) Determination of seismic hazard from a particular scenario.

DSHA determines the ground motion from a single or several earthquakes that have maximum impact. DSHA addresses the ground motion from individual (i.e., maximum magnitude, maximum considered, or maximum credible) earthquakes. Ground motion derived from DSHA represents real ground motion from an individual earthquake.

PSHA vs. DSHA

PSHA and DSHA use the same data sets on the earthquake sources, occurrence frequencies, and ground-motion attenuation relationships. However, the results from PSHA and DSHA are fundamentally different. PSHA addresses the chance of being exceeded at a level of ground motion from all possible earthquakes. The ground motion derived from PSHA does not have a clear physical meaning (Wang et al., 2003). This is illustrated in the following simple example (Fig. 3, 4, and 5). Figure 3 shows a hypothetical region in which there are three seismic sources (*A*, *B*, and *C* faults) and a site of interest. It is assumed that only characteristic earthquakes will repeat along the faults in certain time periods (recurrence times). The magnitude (M7.5) and recurrence times (*Ta*, *Tb*, and *Tc*) for the characteristic faults are shown in Figure 3, and the ground-motion attenuation relationship of Frankel et al. (1996) was used. For each characteristic fault, the annual frequency of exceedance at the site is equal to the annual recurrence rate (1/T) times the probability that the ground motion will be exceeded. For example, for the characteristic fault *A*, the annual frequency of exceedance of 0.0004 (return period of 2,500 years) (Fig. 4a) is equal to the annual recurrence rate (1/200) times the probability of 0.08 (shaded area under ground- motion density function shown in Fig. 4b) that the peak ground acceleration of 1.11g will be exceeded. The total hazard (total annual frequency of exceedance) at the site is the sum of the individual hazards (annual frequency of exceedance) (Fig. 5). In Figure 5, the total annual frequency of exceedance of 0.0004 (return period of 2,500 years) is the sum of the individual annual frequencies of exceedance of 0.00025, 0.0001, and 0.00005 from faults *A*, *B*, and *C*, respectively. The ground motion with the total annual frequency of exceedance of 0.0004 (return period of 2,500 years) in Fig. 5 does not associate with any individual earthquake, but three earthquakes. In this example, DSHA is straightforward and simple. The medium ground motion is 0.5g PGA and medium plus a standard deviation is 1.06g PGA. This ground motion represents a scenario earthquake with magnitude of M7.5 occurring at 30km distance.

In a typical PSHA, the ground motion (total hazard) at an annual frequency of exceedance is contributed by many earthquakes. For example, on the 1996 USGS national seismic hazard maps, the total hazard in Chicago, Ill., was contributed by a series of earthquakes with magnitude ranging from M5.0 to M8.0 at distance from 0 to 500 km (Harmsen et al., 1999). It is hard to imagine the actual physical model (i.e., real earthquake) with ground motion that is composed of so many earthquakes.

It is well understood that there is an uncertainty in seismic hazard assessments because of the uncertainties inherent in parameters that are used in the hazard analysis. No matter which method, PSHA or DSHA, is applied, the results always contain uncertainty. The advantage of PSHA is that it could incorporate a range of uncertainties inherent in earthquake source, occurrence frequency, and ground-motion attenuation relationships. However, PSHA also has some limitations, especially ambiguity in selection of design ground motion. On the other hand, DSHA could not incorporate the range of uncertainties inherent in earthquake source, occurrence frequency, and ground-motion attenuation relationships. The advantage of DSHA is that it provides seismic hazard estimates from those earthquakes that have most significant impacts. This advantage is of significance in engineering practices.

The engineering seismic designs and standards in the United States, as well as in the world, are based on the experience learned in the coastal California. The ground motion specified for bridge design in California is the deterministic ground motion from the maximum credible earthquakes (MCE) (Caltrans, 1999). Also, the ground motion from the maximum considered earthquakes (MCE ground motion) was recommended for building seismic design in California (BSSC, 1998; ICC, 2000). In engineering practices in California, it is DSHA, not PSHA, being used in developing the design ground motion. It is the actual earthquake experience in coastal California that is providing increased confidence in the seismic margins contained in the NEHRP Provisions (BSSC, 1998).

The purpose of this paper is to develop ground motions, including peak values and time histories, for seismic analysis and design of tailing dams. It would be more appropriate to use DSHA for this purpose.

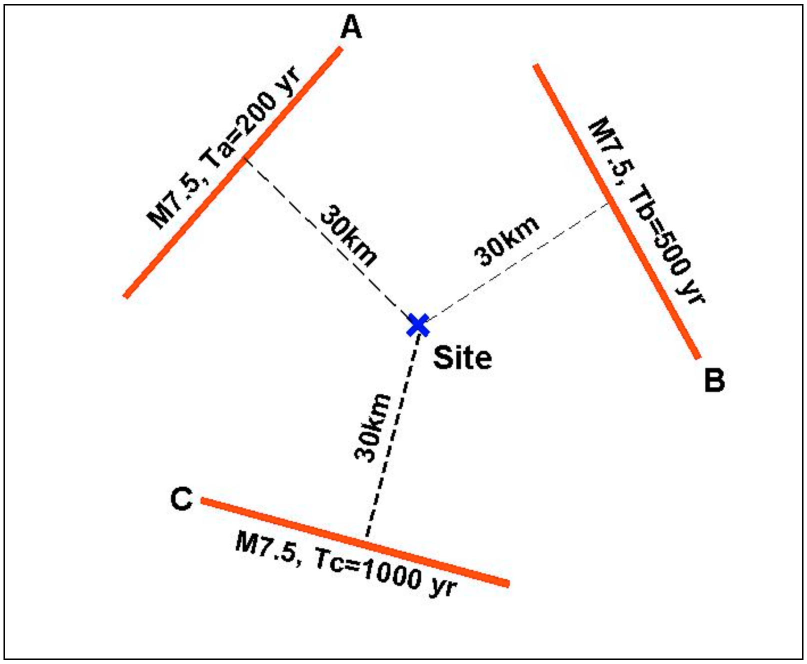

Figure 3. Hypothetical region with three seismic sources (A, B, and C faults) and a site of interest within 30 km of the faults.

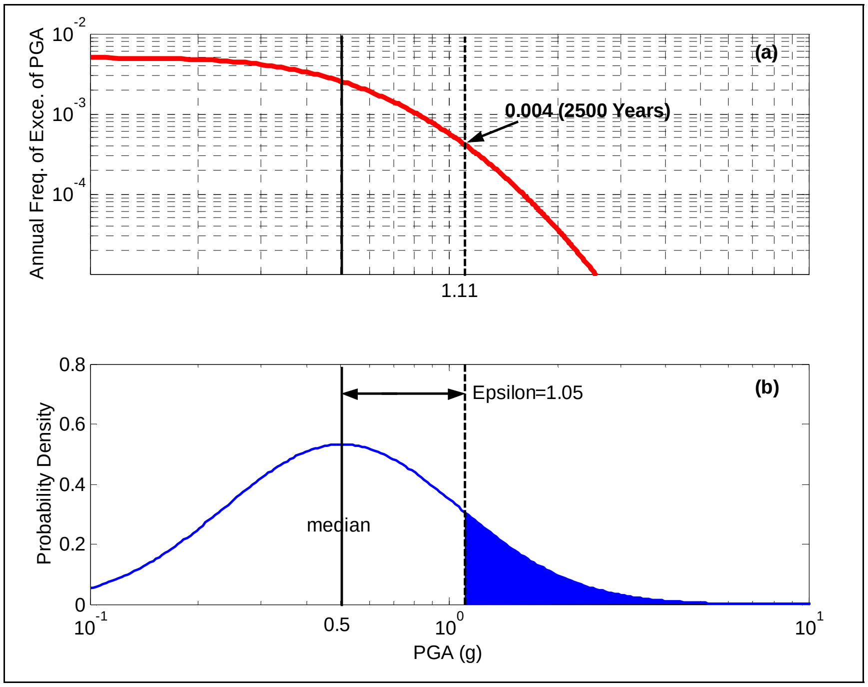

Figure 4. (a) Hazard curve from the fault A and (b) ground-motion density function (log-normal) for the M7.5 characteristic earthquake with recurrence interval of 200 years. The median ground motion is 0.5g, and the standard deviation is 0.75.

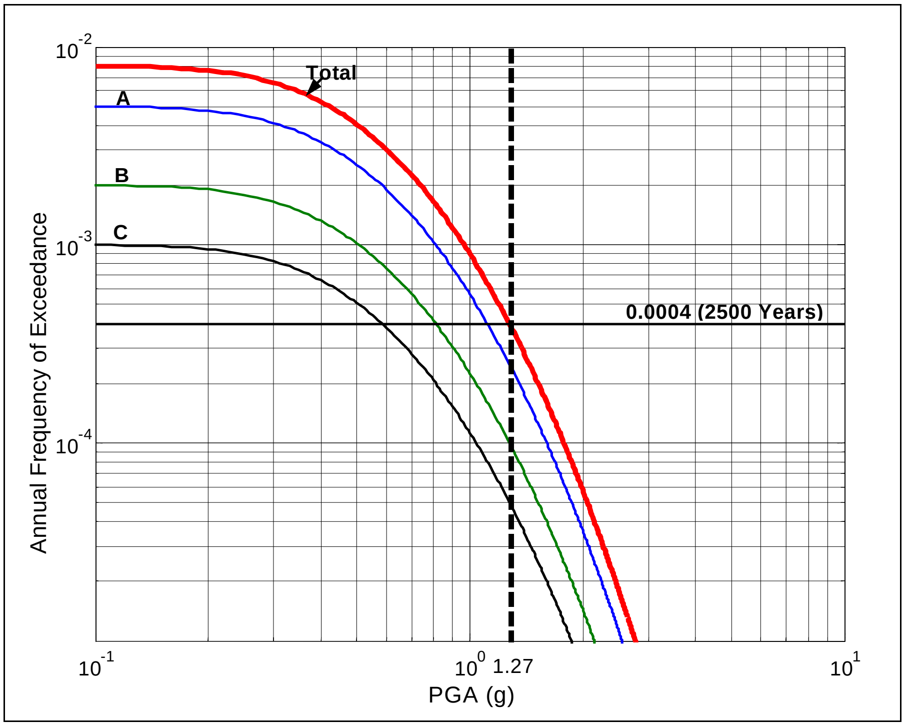

Figure 5. Total and individual hazards (annual probabilities of exceedance) at the site.

Time Histories

There are two ways to get time histories for engineering design and analysis: actual ground motion records or synthetic ground motions. The actual ground motion records can be obtained from the USGS at http://nsmp.wr.usgs.gov or COSMOS at db.cosmos-eq.org. There are very few records from the central and eastern United States, especially for strong and large earthquakes (>M5.0). It is very common to use synthetic ground motions in the central and eastern United States.

The most widely used method to generate synthetic ground motion are the stochastic point- and finite-source models (Hanks and McGuire, 1981; Boore, 1983; Boore and Atkinson, 1987; Toro and McGuire, 1987) and the stochastic finite-fault model, which can simulate some of the near-source effects (Atkinson and Silva, 1997; Beresnev and Atkinson, 1997). The stochastic models utilize the characteristics that observed ground motions can be characterized as finite-duration bandlimited Gaussian noise with an amplitude spectrum specified by a simple source model and path effects. Although its success and simplicity, the stochastic models have some drawbacks. The stochastic models do not simulate the near-source effects, such as rupture propagation, directivity, and asperity. The stochastic models do not consider two- and three-dimensional wave propagation. Source effects and wave propagation have a significant influence on simulated ground motion.

With the improvement of computers it has become possible to use more sophisticated numerical methods for simulating strong ground motion based on empirical or theoretical source functions and two-and three-dimensional wave propagation theory (Somerville et al., 1991; Anderson, 2003). Somerville et al. (1991) had developed a semi-empirical model that will take into account the near-source effects and three-dimensional wave propagation in detail. The semi-empirical model (Somerville et al., 1991) has been successfully used in ground-motion simulations for many earthquakes (Somerville et al., 1991, 2001; Saikia and Somerville, 1997). Zeng et al. (1994) also developed a composite source model that will take into account the near-source effects and three-dimensional wave propagation in detail. The composite source model (Zeng et al., 1994) has also been successfully used in ground-motion simulations (Yu, 1994; Zeng et al., 1994; Zeng and Anderson, 1995; Anderson, 1997; Anderson et al., 2003). The recent success in predicting ground motions for the M_W 7.9 Alaska earthquake by both the semi-empirical and composite source models (Anderson et al., 2003) demonstrates that the methods provide better simulation of ground motions.

Composite Source Model

The composite source model (Zeng and others, 1994) uses Green's functions for the generation of synthetic strong ground-motion seismograms for a layered medium. For the Green's function synthetic computation, a generalized reflection and transmission coefficient matrix method, developed by Luco and Apsel (1983) and coded by Zeng and Anderson (1995), has been used to compute elastic wave propagation in a layered elastic half-space in frequency/wave number domain. The generalized reflection and transmission coefficient matrix method is advantageous in synthetic seismogram computation because it is based on solving the elastodynamic equation complying with the boundary conditions of the free surface, bonded motion at infinity, and continuity of the wave field across each interface. The composite source is described with superposition of a circular subevent. The number of subevents of a given radius (R) follows a power-law distribution ($\sim R^{-D}$). All the subevents have the same stress drop ($\Delta\sigma$). The largest subevent has a radius (R_{max}) that fits within the fault, and the smallest is chosen so that it does not have any effect on the numerical outcome of the computations. The total number of subevents is constrained to match the desired seismic moment of the earthquake. Thus, as $\Delta\sigma$ is increased, the overall number of subevents decreases. The subevents are placed randomly within the fault plane, and the boundaries of subevents are allowed to overlap (intersect). Each event is given a source time function defined by Brune pulse (1970, 1971). The duration of each subevent's time function is proportional to its radius, and the amplitude is proportional to $\Delta\sigma$. Rupture on the fault starts at the hypocenter, and the radiation from each subevent begins when the rupture front, propagating at a constant rupture velocity, reaches the center of the subevent. An important feature of the composite source model is that all of its input parameters have the potential to be constrained by independent physical data. The input parameters that will be used in this study are listed in Table 1.

Table 1: Parameters for ground-motion simulation.

Parameter	*Range of Values*
Magnitude (M_w)	4.5~8.0
Fault mechanism	Strike-slip and thrust
Crust structure	USGS model[1] and Midcontinent model[2] (α, β, ρ, Q, h)
Site condition	Surface geologic and geophysical data
Centroid depth	0~30 km
Distance	0–500 km
Fault length and width	Derived from source scaling law[2]
Fault area	Derived from source scaling law[2]
Stress drop	$\Delta\sigma$=50~500 bars
R_{max} (largest radius of circular subevent)	Derived from source scaling law[2]
Slip time function	Brune's pulse (Brune, 1970, 1971)
Rupture velocity	Constant and less than shear-wave velocity
Fractal dimension	D=2
Seismic moment	Derived from moment-magnitude scale (Hanks and Kanamori, 1979)

1. Frankel and others (1996)
2. Somerville and others (2001)

The composite source model has been applied to the June 18, 2003, Darmstedt, Ind. earthquake. The Kentucky Strong Motion Network and the U.S. Army Corps of Engineers' strong motion stations recorded the Darmstadt earthquake (Wang et al., 2003). These records provide valuable ground motion data set. The parameters used in the modeling is listed in Table 2. Figure 6 and 7 show the synthetic seismograms and real data recorded in the stations of J. T. Myers and Newburgh with epicenter distances of 30km and 35km, respectively. In each figure, the right column shows recorded three components of acceleration and velocity time histories, and the left column gives synthetic results correspondingly. The appearance of the waveform, time duration and frequency contents have a good match with the observations. Several key parameters of the source model used for these calculations were obtained by repeated trial and by examining the resultant seismogram at the J. T. Myers and Newburgh stations.

Table 2: Parameters of the composite model for the June 18, 2003 Darmstadt, Indiana Earthquake

Parameter	Value
L (fault length along the strike)	2.5 km
W (rupture width)	2.0 km
M_o (seismic moment)	$3.52*10^{23}$ dyne cm
Rmax (largest subevent radius)	0.5 ~0.75 km
$\Delta\sigma$ (subevent stress drop)	150 bars
V_r (rupture velocity)	2.8 km/sec
D (fractal dimension)	2.0

The composite source model has also been used to simulate a scenario earthquake of M7.7 in the New Madrid Seismic Zone. In comparison with the observations and other methods, the composite source model provides better and physically consistent ground motions. The composite source model has been used to generate the synthetic ground motions for seismic design and analysis of highway bridges in Kentucky. Fig. 8, 9, and 10 show the acceleration time histories from the composite source model simulations for a M7.7 earthquake in the New Madrid Seismic Zone, M6.6 earthquake in the Wabash Valley Seismic Zone, and the Eastern Tennessee Seismic Zone.

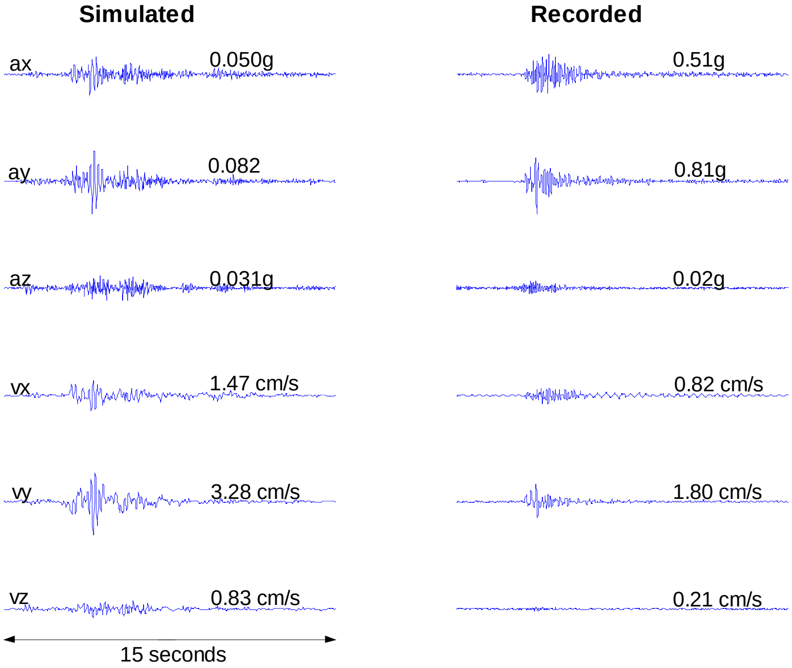

Figure 6. Comparison of observed and synthetic ground motion at J. T. Myers. Observed acceleration and velocity are in the right column. The horizontal components a_x and a_y refer to instrument orientations and vertical component is denoted by a_z.

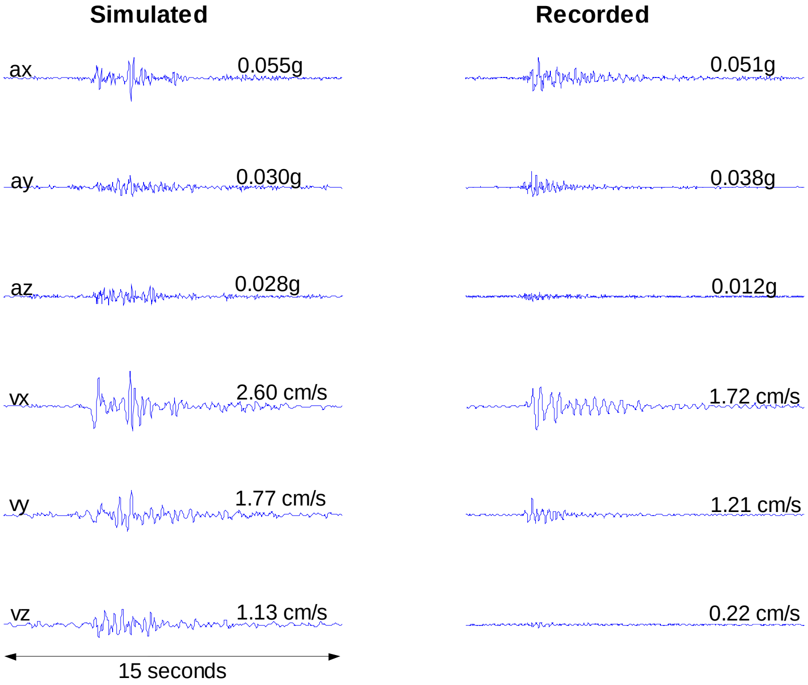

Figure 7. Comparison of observed and synthetic ground motion at Newburgh. Observed acceleration and velocity are in the right column. The horizontal components a_x and a_y refer to instrument orientations and vertical component is denoted by a_z.

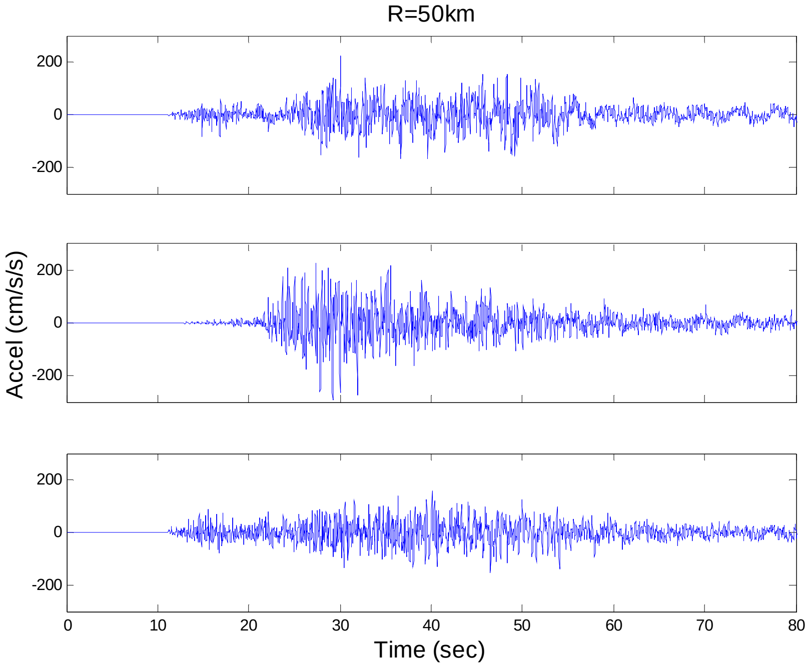

Figure 8. Synthetic ground motion for M7.7 earthquake in the New Madrid Seismic Zone.

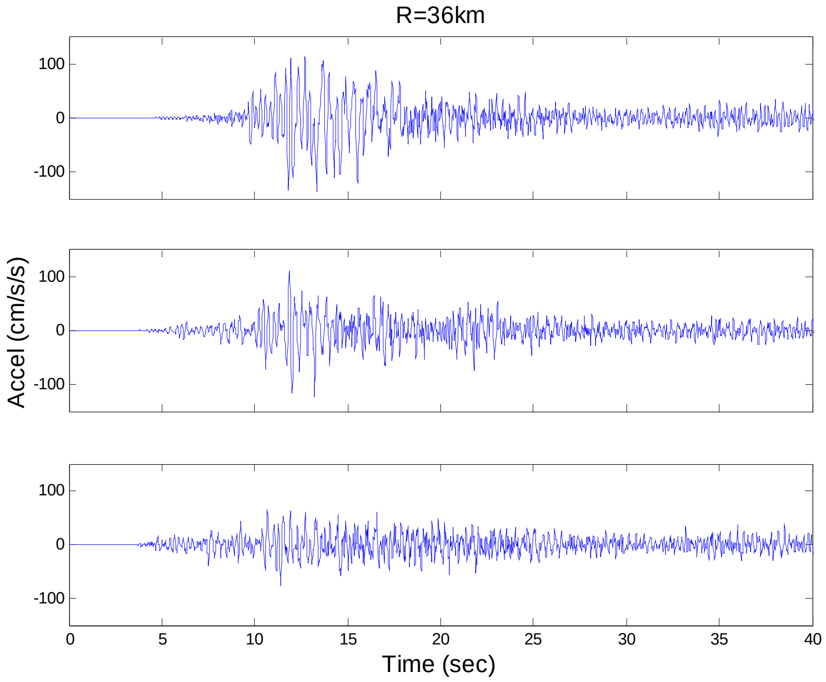

Figure 9. Synthetic ground motion for M6.6 earthquake in the Wabash Valley Seismic Zone.

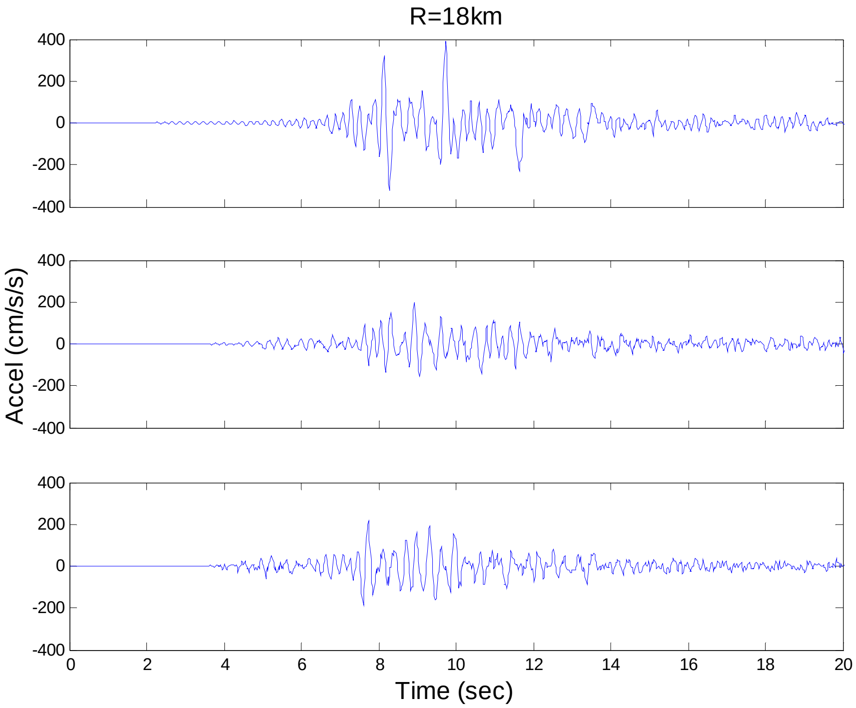

Figure 10. Synthetic ground motion for M6.3 earthquake in the Eastern Tennessee Seismic Zone.

Summary

In central and eastern United States, the questions is not “do we have earthquakes, seismic hazards, and risk?” but “where, how big, how often, and how strong?” Even though the New Madrid Seismic Zone is well known and studied in the central United States, we still do not fully understand many aspects of earthquakes, including source mechanics and location. The biggest historical earthquake to have occurred in the central United States was the 1811–1812 New Madrid events. The estimated magnitude ranges from about M7 to M8—a large range, though it has been well studied. Earthquakes are also infrequent, especially large earthquakes that have significant impacts on human and structures. Limited paleo-liquefaction data suggested the recurrence intervals for the large earthquakes are about 500 years in the New Madrid Seismic Zone and about 4,000 years in the Wabash Valley Seismic Zone; they are even longer in other zones. There is no ground motion record from large earthquakes in the central and eastern United States.

Seismic hazard analysis is an effort to predict or estimate what level of ground motion (seismic hazards) could be expected at a site or in an area. This effort depends on what we know about the earthquakes, such as location and magnitude, earthquake occurrence frequencies, and ground motion attenuation relationship. PSHA is the most used method to assess seismic hazards for input into various aspects of public and financial policy. For example, the U.S. Geological Survey used PSHA to develop the national seismic hazard maps. These maps are the basis for national seismic safety regulations and design standards, such as the NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures, the 2000 International Building and Residential Codes. One of the advantages of PSHA is that it can incorporate uncertainties. However, PSHA also has limitations. The limitations make PSHA difficult to be used, especially in the central and eastern United States. It was found that seismic design based on PSHA do not provide the intended uniform protection against seismic risk; risk assessment is either over-conservative in some areas or not conservative enough in other areas in the central and eastern United States (Wang, 2002).

DSHA is another method that has been widely used in seismic hazard assessments, especially for engineering purpose. DSHA involves the development of a particular seismic scenario upon which a ground motion hazard evaluation is based. The scenario consists of the postulated occurrence of an earthquake of a specified size at a specified location. DSHA addresses the ground motion from individual (i.e., maximum magnitude, maximum considered, or maximum credible) earthquakes. Ground motion derived from DSHA represents ground motion from an individual earthquake. In the central and eastern United States, the earthquakes that are of engineering significant are few and large ones. Therefore, DSHA is more appropriate to be used for seismic design and analysis of tailing dams in the central and eastern United States.

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