Uniform Hazard Ground Motions for Mid-America Cities

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For performance evaluation of buildings and structures, synthetic uniform hazard (10% and 2% in 50 years) ground motions are generated for Memphis, Tennessee, St. Louis, Missouri, and Carbondale, Illinois. The method of simulation is based on the latest regional seismic information and stochastic ground motion models. Both point-source model and finite-fault model are used and the effects of soil profile are considered. The emphasis is on treatment of uncertainty and efficiency in application to evaluation of structural performance in both the linear and nonlinear range. The results show that the uniform hazard response spectra calculated from the simulated motions are comparable to those corresponding to USGS hazard maps. The suites of ten ground motions selected to match the uniform hazard response spectra represent events of different magnitudes, distances, and attenuation. The median value of the structural response to the selected ground motions matches closely the uniform hazard linear and nonlinear response spectra based on nine thousand ground motions and has a coefficient of variation of less than 10%. The suites of uniform hazard ground motions therefore can be used in probabilistic performance evaluation with good accuracy and efficiency.

INTRODUCTION

Mid-America is a region of moderate seismicity. Infrequent moderate to large events occurred in the past and can occur again and cause large losses. The performance of the building stock and other structures under future earthquakes is a serious concern. The major threats of future seismic events come from the New Madrid Seismic Zone (NMSZ) and several other areas of moderate seismicity. As ground motion records of engineering interest in this area have been scarce, to evaluate the performance of buildings and structures and estimate loss/cost, simulation of future events based on current data and knowledge is necessary. A method of simulation is developed for this purpose. The method is based on the latest information of seismicity in this region, the most recent ground motion models and simulation methods appropriate for engineering applications in this region. A strong emphasis is placed on uncertainty modeling and efficiency in application to probabilistic performance evaluation. The procedure may be improved as more knowledge on earthquakes in this region and more accurate and efficient methods of ground motion modeling become available. A brief description of the method of simulation and results obtained for three mid-America cities follow.

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SELECTION OF LOCATIONS AND SOIL PROFILES

Site locations of special interest in this study are Memphis, Tennessee (35.117°N, 90.083°W), Carbondale, Illinois (37.729°N, 89.246°W), and St. Louis, Missouri (38.667°N, 90.190°W). These cities are selected for study because they present a cross-section of the mid-America cities at risk. Since ground motions are strongly dependent on local soil condition and yet the soil profile variation within a city has not been mapped in detail, in this study it is assumed that the soil condition of a city can be approximately modeled by a generic profile. Ground motions at the bedrock are also generated for these cities so that if detailed information about local soil variation is available, one can use appropriate soil amplification computer software to obtain the surface ground motions.

METHOD OF SIMULATION

The ground motion simulation method basically follows the procedure proposed by Herrmann and Akinci (1999) based on Boore's point-source simulation method SMSIM (1996). To catch some of the important near-source effects due to large events, the finite fault model by Beresnev and Atkinson (1997, 1998) is selected for M 8 events. This model was selected over others (e.g., Saikia and Somerville 1997, Wald and Heaton 1994) for its computational efficiency. The soil amplification is modeled by the quarter-wavelength method by Boore and Joyner (1991, 1997). The tectonic and seismological data are mainly taken from *USGS Open-File Report 96-532* (Frankel et al. 1996). A large number of future events and ground motions are generated from which uniform hazard response spectra (UHRS) are obtained for each city for exceedance probabilities of 10%, 5%, and 2% in 50 years. Finally, to facilitate probabilistic performance evaluation of buildings and structures, suites of 10 ground motions are selected from the large pool of simulated ground motions such that the medians of the response spectra of the suites match those of UHRS in a least square sense at two probability levels, 10% and 2% in 50 years. UHRS can be used directly for probabilistic performance evaluation of linear structures and suites of ground motions can be used for the same purpose for nonlinear structures. Details of the simulation method are given in the following.

REFERENCE AREA AND OCCURRENCE MODEL

All probable earthquake sources in the central and eastern United States (CEUS) are considered. For a given city, however, only those that fall within the reference area (effective zone) of the city, and therefore have significant contributions to the seismic risk, are used in the simulation. Different cities may share some of the seismic sources and hence the same simulated seismic events. In view of the relatively low attenuation in the CEUS, the effective zone is defined as a circular area with a radius of 500 km centered at a specific site location, a value used by most researchers (e.g., *USGS Open-File Report 96-532*). Only earthquakes with body wave magnitude greater than 5 are considered. The statistics of occurrence and magnitude from the report by Frankel et al. are used in the simulations. Figure 1 shows the annual occurrence rate per 0.1× 0.1 degree square for earthquakes of M 5 or larger for the region. The occurrence in time is generated according to a Poisson process. The magnitude, given the occurrence of an earthquake, is then generated according to the magnitude distribution for events of magnitude less than 8 following the 1996 *USGS Open-File Report*. The M 8 events are generated separately using a Poisson process with a mean recurrence time of 1000 years (Frankel et al. 1996). The epicenter is uniformly distributed within the New Madrid fault zone shown as the dashed-line area in Figure 2, which covers only the central portion of Figure 1 of relatively high seismicity. The positions of the three cities relative to the fault zone are also shown.

Events of various magnitudes and epicenters are simulated in a ten-year period in the region. The process is repeated 9,000 times. As a result, 9260 events are within the effective zone of Memphis, Tennessee, 9,269 in the zone of Carbondale, Illinois, and 8,290 in the zone of St. Louis, Missouri. Figure 2 shows the epicenters and magnitudes of earthquakes corresponding to 300 simulations of 10 year records in the region of interest in CEUS. It corresponds, therefore, to about 3,000 years of records. The locations of the three cities are also indicated to show the proximity of the events to each city. Most of the events are in the NMSZ and the East Tennessee Seismic Zone. According to the simulation results, the occurrence rates of earthquakes of M 5 and above in the reference areas for Memphis, Carbondale, and St. Louis are 0.0989, 0.0980, and 0.0882 per year, respectively. These values are very close to the actual occurrence statistics.

Seismicity surrounding Memphis TN, Carbondale IL, and St. Louis MO

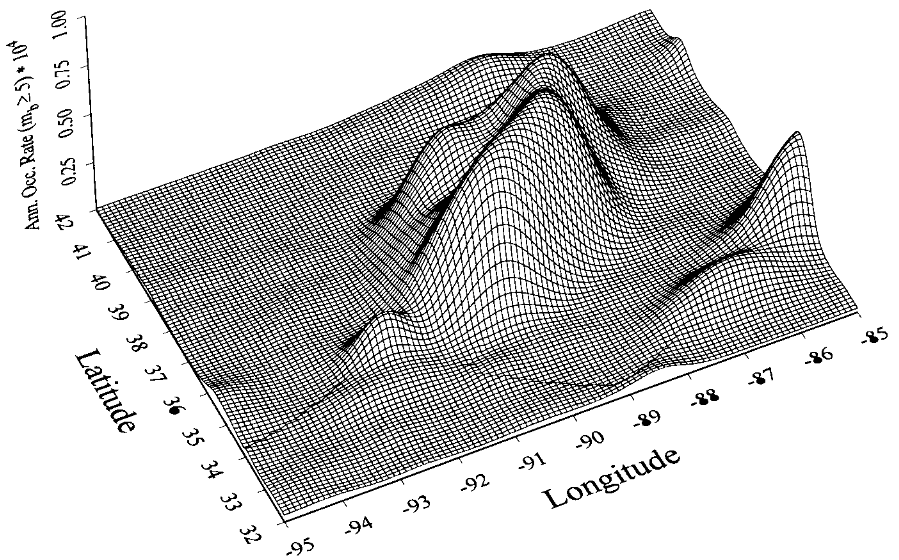

Figure 1. Annual occurrence rate per 0.1×0.1 degree square of earthquakes of m_b 5 or larger.

SOURCE AND PATH MODELS

The majority of the seismic sources are modeled as point sources due to lack of knowledge about the fault structure in the CEUS. However, the finite fault model is used for earthquakes of moment magnitude 8 in the New Madrid Seismic Zone since the seismotectonic information of such events is better known. For point sources, the two-corner-frequency model (Atkinson and Boore 1995) for generic S-wave type ground motions on hard rock is used since this model has been shown to give better ground motion prediction in the CEUS (Atkinson and Boore 1998).

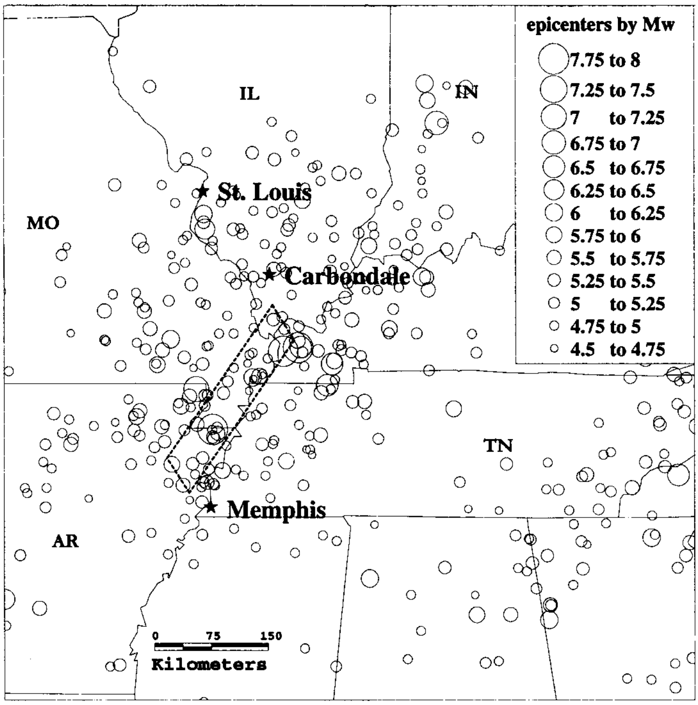

Figure 2. Epicenters and magnitudes of earthquakes of simulated 3,000-year record. (Source zone of synthetic M_w-8 earthquakes in the New Madrid area is marked with dashed lines).

To account for near-source effects of large earthquakes, the fault plane of a M 8 event in New Madrid Seismic Zone is divided into a number of sub-faults, each treated as a point source. The resulting ground motion is a combination of waveforms from different sub-faults accounting for difference in arrival times and path attenuation. This so-called finite fault model by Beresnev and Atkinson (1997, 1998) incorporates the effects of fault dimension, rupture propagation, directivity, and source-receiver geometry. The one-corner-frequency point-source model (Brune 1970, Frankel et al. 1996) was used for each sub-fault. The examples of application in Beresnev and Atkinson (1997, 1998) showed that the model produces ground motions that match earthquake records on rock sites well in the 1985 Michoacan, Mexico, the 1985 Valparaíso, Chile, the 1988 Saguenay, Québec, and the 1994 Northridge earthquakes. For soil sites, however, the ground motions are overestimated because the soil nonlinearity is not considered in their model. More detailed descriptions of the models are given in the following.

POINT-SOURCE MODEL

The Fourier amplitude spectrum of the point-source model is given by:

$$A(M_0, R, f) = E(M_0, f) \cdot D(R, f) \cdot P(f) \cdot I(f) \tag{1}$$

in which, f is frequency (Hz), R is focal distance, and M_0 is the moment magnitude. The various functions are:

$$E(M_0, f) = C \cdot (2\pi f)^2 \cdot M_0 \cdot \left\{ \frac{1-\zeta}{1+\left(\frac{f}{f_A}\right)^2} + \frac{\zeta}{1+\left(\frac{f}{f_B}\right)^2} \right\}, \text{ source spectrum} \quad (2)$$

in which, $C = \dfrac{R_p \cdot F \cdot V}{4\pi \cdot \rho \cdot \beta^3}$

$R_p = 0.55$, average radiation pattern

$F = 2$, free-surface amplification

$V = 0.7071$, partition factor

$\rho = 2.8$ gm/cm^3, crustal density

$\beta = 3.6$ km/sec, shear wave velocity

ζ = weighting parameter

f_A, f_B (Hz) = corner frequencies

$\log \varepsilon = 2.52 - 0.637 \cdot M_W$

$\log f_A = 2.41 - 0.533 \cdot M_W$

$\log f_B = 1.43 - 0.188 \cdot M_W$

$M_0 = 10^{1.5 \cdot M_W + 16.05}$ (dyne-cm)

$$D(R, f) = D_g(R) \cdot D_m(R, f), \text{ diminution factor} \quad (3)$$

in which

$$D_g(R) = \begin{cases} 1/R & if \quad R \le 70\, km \\ 1/70 & if \quad 70 \le R \le 130\, km \\ (1/70)(130/R)^{0.5} & if \quad 130\, km \le R \end{cases}, \text{ geometric attenuation}$$

$$D_m(R, f) = e^{-\frac{\pi \cdot f \cdot R}{\beta \cdot Q(f)}} \text{ and } Q(f) = 680 \cdot f^{0.36}, \text{ anelastic material attenuation}$$

$$P(f) = \frac{1}{\sqrt{1 + (f / f_{\max})^8}}, \text{ high-cut filter} \quad (4)$$

in which, R is hypocentral distance (km) and $f_{max} = 50$ Hz is used.

$$I(f) = \frac{1}{(2\pi f)^p} \text{ ; } p = 0 \text{ for acceleration, 1 for velocity, and 2 for displacement} \quad (5)$$

The total duration T consists of source and path durations, which takes a trilinear form of source-site distance (Atkinson and Boore 1995):

$$T = T_0 + T_p \tag{6}$$

in which,

$$T_0 = \frac{1}{2 \cdot f_A} \text{ (sec), Source duration}$$

$$T_p = \begin{cases} 0 & \text{if} \quad R \le 10\,km \\ 0.16 \cdot (R-10) & \text{if} \quad 10 \le R \le 70\,km \\ 9.6 - 0.03 \cdot (R-70) & \text{if} \quad 70 \le R \le 130\,km \\ 7.8 + 0.04 \cdot (R-130) & \text{if} \quad 130 \le R \le 1000\,km \end{cases}, \text{ Path duration}$$

The focal depth is modeled as a random variable following a distribution based on historical data (EPRI 1993, Wheeler and Johnston 1992,1993).

FINITE FAULT MODEL

For the finite fault model, a rupture plane of 140 km (along strike) by 33 km (along dip) (Johnston 1996) with a vertical strike-slip faulting and 34.69° azimuth is assumed, which is an approximate estimate based on USGS OFR-96-532. A total of 64 (16x4) sub-faults are used. The anelastic attenuation $Q(f) = 670*f^{0.33}$ is used following Beresnev and Atkinson (1998). The epicenter is assumed to occur at any location within the NMSZ zone (Figure 2) with equal likelihood. The orientation of the fault is assumed to be along that of the NMSZ. Once rupture occurs, it propagates toward both ends of the rupture surface. The slip distribution within the rupture surface is modeled by a correlated random field according to Saikia and Somerville (1997), and Somerville et al. (1999) with the following wave number spectrum,

$$A(k_x, k_y) = \frac{1}{\sqrt{1 + [(k_x / C_x)^2 + (k_y / C_y)^2]^n}} \tag{7}$$

in which $n = 2.0$; k_x and k_y are the wave numbers and C_x and C_y are correlation length constants depending on magnitude. This random field model is then modified to ensure larger slip in the middle than at the edge of the rupture surface, a feature observed in recent earthquakes. A Kanamori-Anderson (1975) stress parameter of 200 bars is used for the sub-fault in the finite fault model. A value of 150 bars is also tested for the finite fault model. As expected, it causes lower spectral values in the low frequency range at the 2% in 50 years hazard level. Local soil profiles are also used in conjunction with this model.

LOCAL SITE EFFECT/SOIL AMPLIFICATION

Soil amplification due to local site soil profile is considered. The quarter wavelength method (QWM) (Joyner et al. 1981; Boore and Joyner 1991, 1997; Boore and Brown 1998) is used to model the soil amplification. Soil profiles are based on boring log data in Memphis, Carbondale and St. Louis (Hashash 1999, Herrmann 1999). The amplification is approximated by

$$A = \sqrt{\rho_0 \beta_0 / \rho_s \beta_s} \quad (8)$$

in which ρ and β are the density and shear wave velocity at the source (subscript 0) and site (subscript s). At the site, the frequency-dependent effective velocity β_s is defined as the average velocity from the surface to a depth of a quarter wavelength for a given frequency. At high frequencies, the soil attenuation is accounted for by

$$P(f) = \exp(-\pi \kappa f) \quad (9)$$

in which κ is a term that accounts for shear wave velocity and damping over the soil column.

According to Herrmann and Akinci (1999), κ = 0.063 sec, 0.043 sec and 0.0076 sec for Memphis, Carbondale, and St. Louis, respectively. The "representative" profiles for the three cities used in this study are shown in Tables 1 to 3. The resultant soil amplification as a function of frequency for Memphis and St. Louis are shown in thick lines labeled as "quarter wavelength method" in Figures 3 and 4. It is seen that while amplification at St. Louis is restricted to the high frequency range (> 3 Hz) due to the very shallow soil layer on hard rock, the much deeper soil layers in Memphis produce much larger amplification in the longer period range. For comparison, the soil amplification based on the well-known computer software SHAKE is also shown for bedrock ground motions of 10% and 2% probability of exceedance in 50 years. The soil amplification factor used in the *1997 NEHRP*

Table 1. Representative soil profile of Memphis, TN

LAYER	SOIL COLUMN	Thickness (m)	Vs (m/sec)	Density (g/cm^3)
1	Alluvium	7.2	360	1.92
2	Alluvium	4.8	360	2.00
3	Alluvium	14.9	360	2.08
4	Loess	9.0	360	2.16
5	Fluvial Deposits	7.9	360	1.98
6	Jackson Formation	47.3	520	2.08
7	Memphis Sand	245.6	667	2.30
8	Wilex Group	83.3	733	2.40
9	Midway Group	580	820	2.50
10	Bed Rock	Half-Space	3600	2.80

Table 2. Representative soil profile of Carbondale, IL

LAYER	SOIL COLUMN	Thickness (m)	Vs (m/sec)	Density (g/cm^3)
1	Cahokia Alluvium	10.4	140	2.0
2	Henry Formation	10.0	250	2.1
3	Henry Formation	25.6	270	2.1
4	Mississippi Embayment	119.0	280	2.3
5	Pennsylvanian Limestone	835.0	2900	2.6
6	Bed Rock	Half-Space	3600	2.8

Table 3. Representative soil profile of St. Louis, MO

LAYER	SOIL COLUMN	Thickness (m)	Vs (m/sec)	Density (g/cm^3)
1	Modified Loess	5.7	185	1.9
2	Glacio-Fluvial	10.0	310	2.1
3	Mississippian Limestone	984.3	2900	2.6
4	Bed Rock	Half-Space	3600	2.8

Guidelines (ATC 1997) for soil classification of B/C boundary is also shown since this is the soil condition used for USGS national earthquake hazard maps. Note that the quarter-wavelength model gives a good estimate of the averaged amplification and misses the peaks and valleys. Also, it has a tendency of overestimating the amplification in the high frequency range for ground motion of very high intensity when effects of soil nonlinearity may be significant. In spite of these limitations, the agreements are generally good.

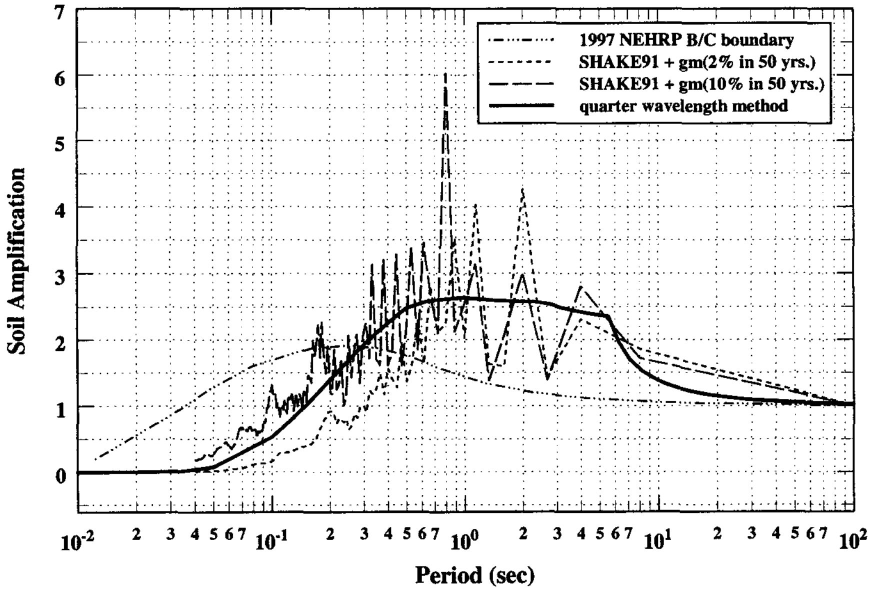

Figure 3. Soil amplification factor for representative soil profile, Memphis, TN.

In passing, it is pointed out that soil amplification considering nonlinear effects is an extremely complex problem. Although the dependence of soil shear modulus and damping on strain is considered in SHAKE, it is based on an equivalent linear wave propagation method. It is expected to yield good results when the excitation intensity is not very high and the soil layer is not very deep. It is therefore expected to work better for the St. Louis soil profile than those of Memphis and Carbondale. There are other truly nonlinear programs available for this purpose. However, they have not been commonly accepted by engineers, therefore are not used for comparison in this study.

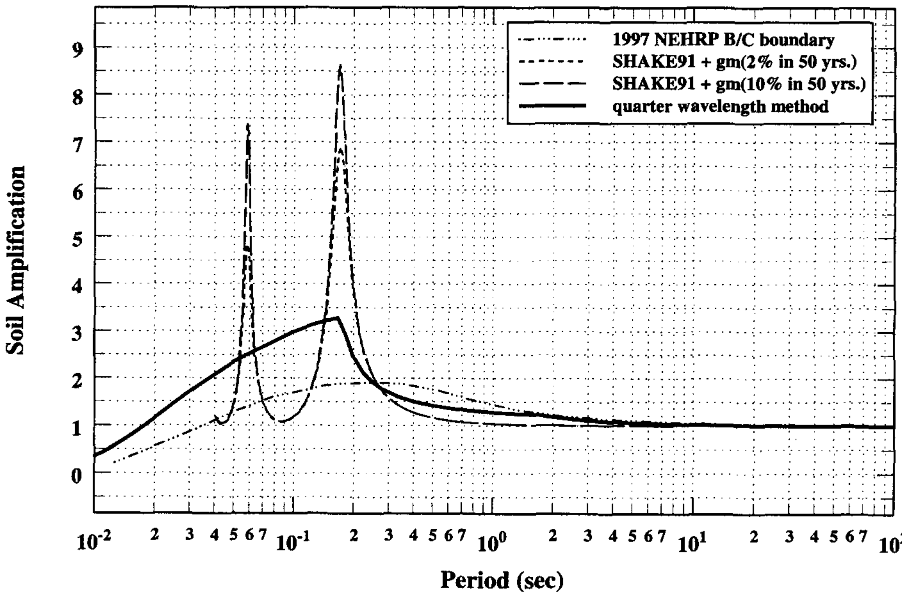

Figure 4. Soil amplification factor for representative soil profile, St. Louis, MO.

UNCERTAINTY MODELING

Uncertainty in the source, path and site effects need to be included in the simulation. In Frankel et al. (1996), a logarithmic standard deviation of 0.75 to 0.80 was used for PGA and spectral acceleration. In this study, a logarithmic standard deviation of 0.75 is used. To prevent physically unrealistic large ground motions for a given event the lognormal distribution is modified such that the value will be bounded. Frankel et al. (1996) imposed a limit on the median PGA (1.5g) and spectral acceleration (3.75g). Based on Taiwan data, Loh et al. (1994) recommended limits defined by the mean plus and minus 2.5 standard deviations. Since no such data are available in mid-America, limits of the mean plus and minus three standard deviations are used in this study. In both the point-source and finite fault models, there is also uncertainty in the peak amplitude for a given spectral density, which is not too large and may be neglected. In the finite fault model, the additional uncertainty in slip distribution and hypocenter location was considered by randomization of these parameters as previously indicated.

GENERATION OF GROUND MOTIONS AND UNIFORM HAZARD RESPONSE SPECTRA

In each simulation, the magnitude, the epicenter location, the focal depth, and fault size (for M 8 events) are first generated according to the distribution for each parameter (see also Figure 2). For each event, a ground motion is generated at the three cities using the procedure outlined above. For a point-source event, the Fourier amplitude spectrum and duration as a functions of the magnitude and the distance from the source to the city (Equation 1) are used to generate the ground motion time history. For this purpose, the computer software SMSIM (Boore 1996) is modified to include path attenuation uncertainty and soil amplification. The path attenuation factor is generated from a lognormal distribution. For the M 8 events, the finite fault model is used in which the slip distribution is simulated according to the spatially correlated random field model. Ground motions are then generated from the sub-faults and correlated random field model. Ground motions are then generated from the sub-faults and superimposed. The intensity and duration of the generated ground motions are therefore random and dependent on the parameters of source and path models and the hypocenters. Ground acceleration time histories are generated for the ground surface sites considering the soil profiles and for rock sites (bedrock or rock outcrop) for the three cities for each event. The process is then repeated for a large number of events equivalent to 90,000 years of records.

This large number of ground motion time histories allows one to construct the uniform hazard response spectra (UHRS). At a given city, the acceleration response spectrum for each time history is first calculated. The probability distribution of spectral acceleration for a given period is then obtained, from which one can construct the UHRS for a given exceedance probability. The UHRS can be used directly to evaluate the performance of linear systems using the method of modal superposition, i.e., the maximum structural response corresponding to a probability level. For nonlinear systems, time history response analyses are generally required. For this purpose, suites of ground motions for each probability level are selected. The selection criterion is that the deviation from the target UHRS of the median response spectra of the suite is minimized. The median value is used because it is less sensitive to sample fluctuation and it allows an easy estimation of the parameters of the underlying lognormal distribution commonly used in seismic risk analysis. To accomplish this, response spectral acceleration, S_a, at 10 key structural periods from 0.1 to 2.0 sec to the simulated ground motions are compared with those of the target UHRS for a given probability level. The ten ground motions with the smallest mean square logarithmic ($\log S_a$) differences are selected. The resultant suite will have a median spectral acceleration that best matches the target UHRS.

It is mentioned that the scatter (or deviation from the target) of the spectra of the selected motions depends on the number of simulated motions and the probability level. In general, lower probability (e.g., 2% compared to 10% in 50 years) requires a larger number of simulations to maintain the same level of scatter. The number of simulations may be adjusted to meet a scatter requirement or achieve uniform scatter. The effect of scatter on structural response estimates will be discussed further in the context of the numerical results.

The matching of the spectral acceleration has been shown by Shome and Cornell (1999) to be the most effective means of selecting ground motions for probabilistic nonlinear structural demand analysis. For performance evaluation, one can calculate the structural response by time history analysis of the structure subjected to the suites of ground motions. The median response will have the probability of exceedance approximately equal to the hazard level (i.e., 10% or 2% in 50 years in this study). In this context, the selection of uniform hazard ground motions is similar in concept to determination of the most likely failure point or "design point" corresponding to a given limit state in the time-invariant first order reliability method (FORM). A numerical example follows.

It is mentioned that the popular method of "de-aggregation" is not used is this study in selecting the events for ground motion generation for the following reasons:

1. De-aggregation works best when there is a dominant event of certain magnitude (M) and distance (R) and not so well when the M-R "landscape" is smooth. The favorable condition for de-aggregation does not necessarily prevail at all sites.

2. De-aggregation is dependent on structural limit state and probability level, i.e., different spectral accelerations and probabilities of exceedance lead to different M-R "landscapes" and hence different de-aggregations and suites of ground motions. It is suitable for performance evaluation of a particular structure such as a nuclear power plant but not for a performance check of the general building stock which exhibits a wide range of natural frequencies and different probability levels.
3. Magnitude and distance are much less important, compared to spectral acceleration, in terms of impact on the structural linear and nonlinear responses (Shome and Cornell 1999).

LIMITATIONS

The source and path models and the quarter-wavelength method do not explicitly consider effects of surface waves, which is important for very low frequency (e.g., Dorman and Smalley 1994), and soil nonlinearity. Therefore, the change in frequency content with time and the nonlinear soil amplification of the ground motions are not modeled in this simulation. However, it is pointed out that comparisons of results by Boore and Joyner (1991, 1996, 1997) with observations and analytical results generally show the robustness of their methods. Also there have not been any efficient methods of modeling nonlinear soil effects that can be used in a large-scale simulation as required in this study. Finally, as will be shown later, the uniform hazard response spectra based on the simulated ground motions compare favorably with those of 1997 USGS national earthquake hazard maps and the *FEMA 273 (NEHRP Guidelines for the Seismic Rehabilitation of Buildings)* recommendations. Since the response spectra are the most effective measure of ground motion damage potential, the UHRS and suites of simulated ground motions generated by the proposed method represent reasonably well the seismic hazards to buildings and other structures in these three cities. As efficient methods for modeling soil nonlinearity and surface waves become available, they can be incorporated into the simulation method.

RESULTS

COMPARISON OF POINT-SOURCE MODEL WITH BROADBAND MODEL

The accuracy and the validity of the point-source model can be found in the literature (Boore 1996). There have been no records of moderate to large events near any of the three cities that can be used for comparison with the simulated ground motions. As a substitute for actual records we used the simulation results based on the broadband approach for St. Louis due to events of M 6.5 to 7.5 in the NMSZ by Saikia and Somerville (1997). The broadband approach uses wave propagation for low frequency motion considering the geometry of the fault and the rupture surface, and uses records for high frequency motion. It requires detailed information about each fault which is generally unknown and it is also computationally too expensive for large-scale simulations. The results of these two methods for a rock site at St. Louis are compared. An event based on the point-source model is chosen whose source and path parameters are comparable to those of the M 7 event studied by Saikia and Somerville. The response spectra of hard rock motions based on these two models are compared in Figure 5. It is seen that agreements are good in the period range from 0.2 sec to 3 sec.

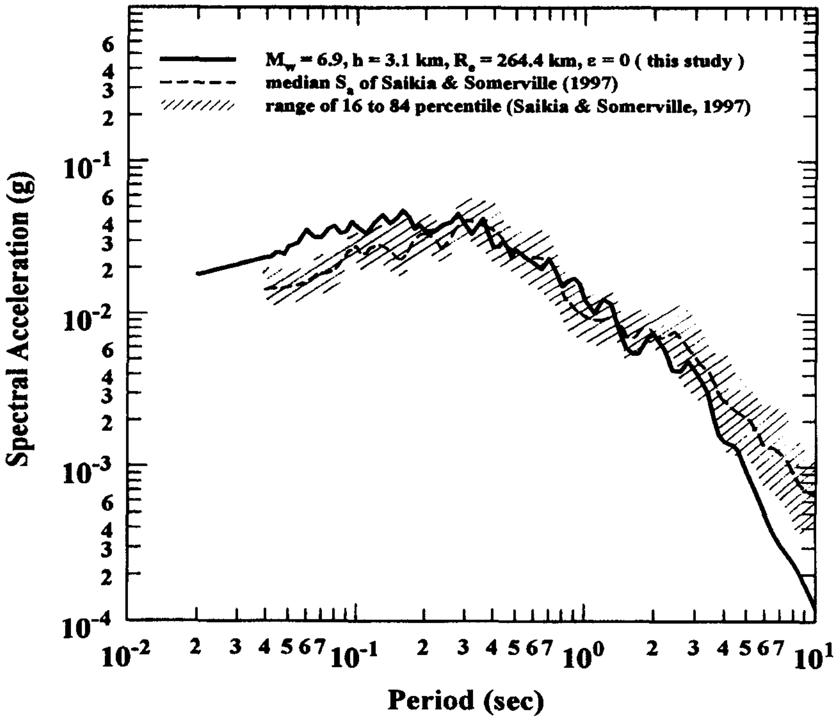

Figure 5. Comparison of response spectra based on point source model with Saikia and Somerville's broadband model (1997).

NEAR-SOURCE EFFECTS OF M 8 EVENTS

The near-source effects using the finite fault model are demonstrated by a comparison of the ground motions at Memphis due to two simulated events, both of M 8. The location, size, and orientation of the faults are the same with a closest distance of 61.8 km from the fault surface to the site. The epicenters, however, are located such that one is far (186 km) from the site with the rupture propagating toward the site and the other closer (79 km) to the site with the rupture propagating generally away from the site. Sample rupture surface (33 km×140 km) slip distributions based on the correlated random field model and the corresponding discretizations for the finite fault model for the latter are shown in the Figure 6. The time histories of the ground motions for a soil site at Memphis are shown in Figure 7 for both events. The near-source effects can be seen that the former produces a shorter but more intense ground motion even though the epicenter is much farther away.

UNIFORM HAZARD RESPONSE SPECTRA (UHRS) AND COMPARISON WITH USGS HAZARD MAPS AND *FEMA 273* GUIDELINES

The uniform hazard response spectra (UHRS) is an efficient means of representing seismic hazards for probabilistic performance evaluation of linear structures and nonlinear structures (e.g., Collins et al. 1996). The UHRS for Memphis, Carbondale, and St. Louis are obtained from the simulated ground motions. For a validation of the results, the UHRS at Memphis obtained in this study are first compared with those of USGS national earthquake hazard maps(1997) for B/C boundary soil classification (i.e., firm rock with an average shear

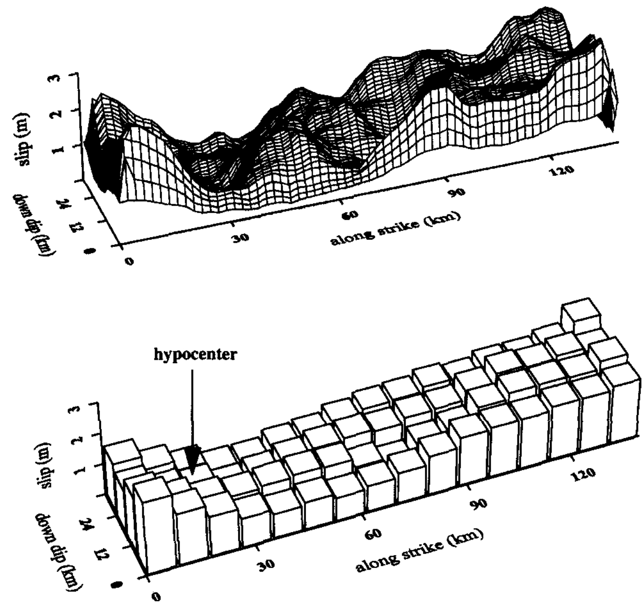

Figure 6. Sample of random slip distribution based on correlated random field model and discretization for finite fault model.

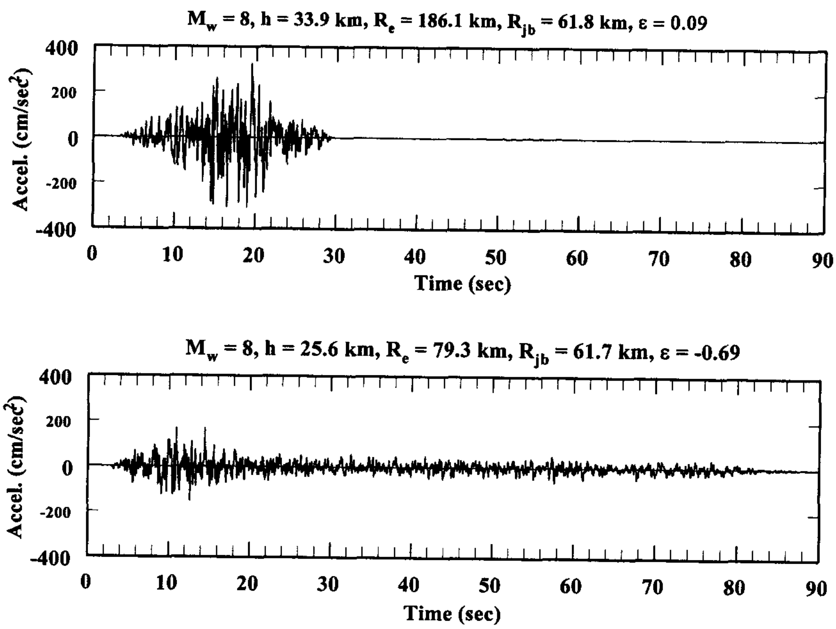

Figure 7. Near-source effects of simulated acceleration time histories at Memphis, TN, by the finite fault model.

wave velocity of 760 m/sec in the top 30 m). This generic site condition facilitates the comparison with previous studies by USGS and other researchers. Figure 8 shows the UHRS for three probability levels for Memphis calculated from the simulated ground motions. The spectral accelerations at three periods (0.2 sec, 0.3 sec, and 1.0 sec) according to 1997 USGS national earthquake hazard maps for Memphis are also shown in the figure. The agreements are generally very good. Since the input seismicity data to these two models are essentially the same, the differences can be attributed to:

1. The USGS study used a point-source model and rupture length of 230 km for M 8 events and the closest distance from the fault to the site. A logic tree uncertainty analysis was also used for magnitude and attenuation. This study uses a finite fault model with random location of the epicenter within the fault and a rupture length of 140 km and no logic trees for magnitude and attenuation.
2. For point sources, the one-corner-frequency source model was used in the USGS study whereas the two-corner-frequency source model is used in this study (Equation 2) which has been shown to give better fit to records in CEUS (Atkinson and Boore 1998).

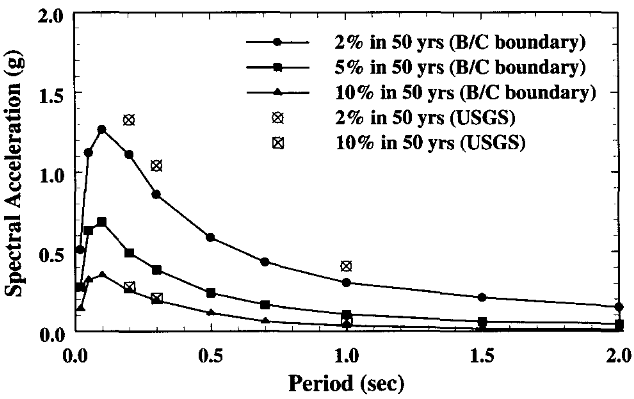

Figure 8. Uniform hazard response spectra calculated from simulated ground motions for B/C boundary at Memphis, TN. A comparison is made with USGS national hazard maps spectral acceleration.

The UHRS for the three cities with the "representative" soil profiles are obtained and compared with *FEMA 273* recommendations for design. *FEMA 273* spectra are for design check and are based on the 1997 USGS national earthquake hazard maps. There are five generic soil profile classifications according to the soil of the upper 30 m and the amplification factor is largely based on empirical results of the Loma Prieta and Northridge earthquakes (e.g., Borcherdt, 1994). The UHRS for the Memphis representative soil profile are shown in Figure 9, in which the FEMA Class C Spectra are also shown. Compared with those for the B/C boundary, the UHRS are amplified almost by a factor of two for periods greater than 1.0 sec and reduced for $T<0.3$ sec due to the differences in the source models as mentioned previously and partly due to the differences in soil amplification factors. The UHRS for the Carbondale representative soil profile are shown in Figure 10. The agreements are generally good.

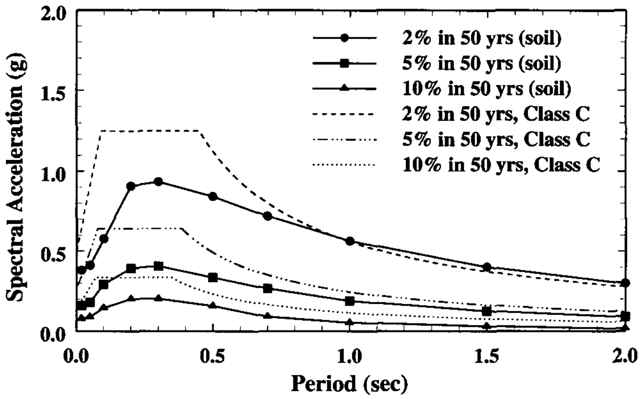

Figure 9. Comparison of uniform hazard response spectra for representative soil profile at Memphis, TN, with *FEMA 273* response spectra (solid lines are the UHRS and broken lines for *FEMA 273*).

The UHRS for the St. Louis representative soil profile are shown in Figure 11. There are some major differences in the spectral content from the spectra for Memphis. Compared with the FEMA Class C spectra, the UHRS are much lower for T > 0.2 sec and higher for T < 0.2 sec because of the comparatively thin (16 m) layer of soil on rock. The current results are more in agreement with the findings of Saikia and Somerville (1997), indicating a much lower seismic hazard for St. Louis. It is pointed out that the actual soil profile in the St. Louis area may have a wide variation and could differ significantly from the "representative profile" used in this study, especially at locations close to the Mississippi River. A deeper soil layer causing larger soil amplification at longer periods is certainly possible at these locations. Ground motions at the surface can be generated from the bedrock ground motions using a proper soil amplification model when detailed information about soil profile is available.

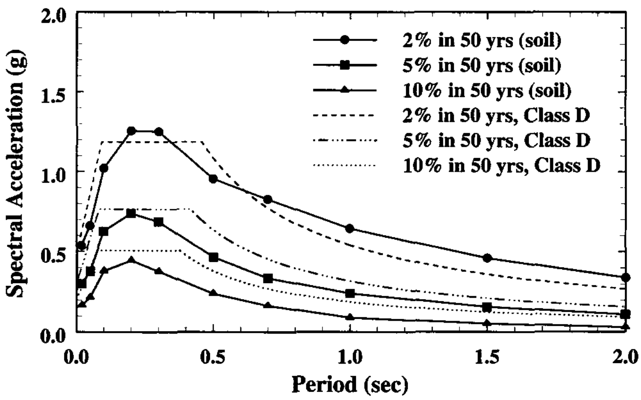

Figure 10. Comparison of uniform hazard response spectra for representative soil profile at Carbondale, IL, with *FEMA 273* response spectra (solid lines are the UHRS and broken lines for *FEMA 273*).

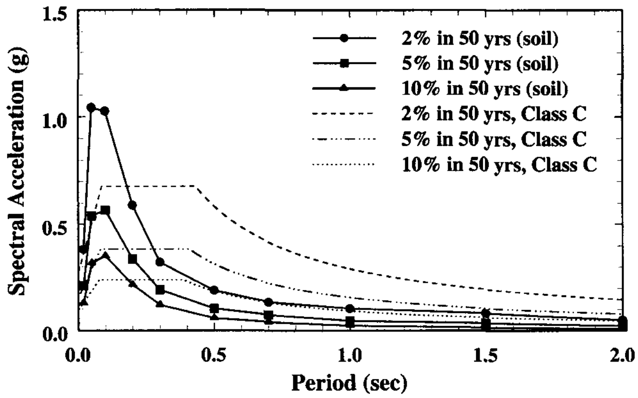

Figure 11. Comparison of uniform hazard response spectra for representative soil profile at St. Louis, MO, with *FEMA 273* response spectra (solid lines are the UHRS and broken lines for *FEMA 273*).

UNIFORM HAZARD GROUND MOTIONS

For each of the two hazard levels, 10% and 2% in 50 years, a suite of ten ground motions are selected from the large number of simulated motions such that the median spectral accelerations best fit the target UHRS. The selection is done for both ground surface and bedrock (or rock outcrop). The complete sets of ground motions for these three cities are available at *http://mae.ce.uiuc.edu/Research/RR-1/GMotions/Index.html.* Sample ground motion time histories for a 10% in 50 years hazard at a Memphis soil site are shown in Figure 12. The source (magnitude M_w, focal depth h, epicentral distance R_e, and closest distance R_{jb}) and path (attenuation uncertainty ε) parameters associated with each ground motion are also shown in the figure. At this probability level, seven ground motions come from M 6 events, two from close and shallow M 5 events and one from a distant M 8 event. The response spectra of the ten ground motions are shown in Figure 13 with the target UHRS. The median spectrum constructed from the 10 sample ground motions and the record-to-record fluctuation in terms of the 16-to-84 percentile band are also shown.

The median response spectra are seen to fit the target response spectra closely. The fluctuation of the median is about one third ($1/\sqrt{10}$) of that of the samples. The median value of structural responses due to this suite of ground motions corresponding to a probability of exceedance of 10% in 50 years, therefore, will have very small uncertainty due to record-to-record variation. It can be used in structural performance evaluation with some confidence.

Sample ground motion time histories for a 2% in 50 years hazard and the response spectra comparison are shown in Figures 14 and 15. At such high intensity and low probability level, all ground motions come from M 8 events. The scatter in the response spectra is slightly larger in the long period range but the coefficient of variation of the median value is still less than 10%. Without the soil amplification, the frequency content of the response spectra at rock outcrop (or bedrock) shifts toward shorter periods and the spectral accelerations are generally much lower. These ground motions may be used as inputs to soil amplification software to obtain surface ground motions when detailed information about the site soil profile is available.

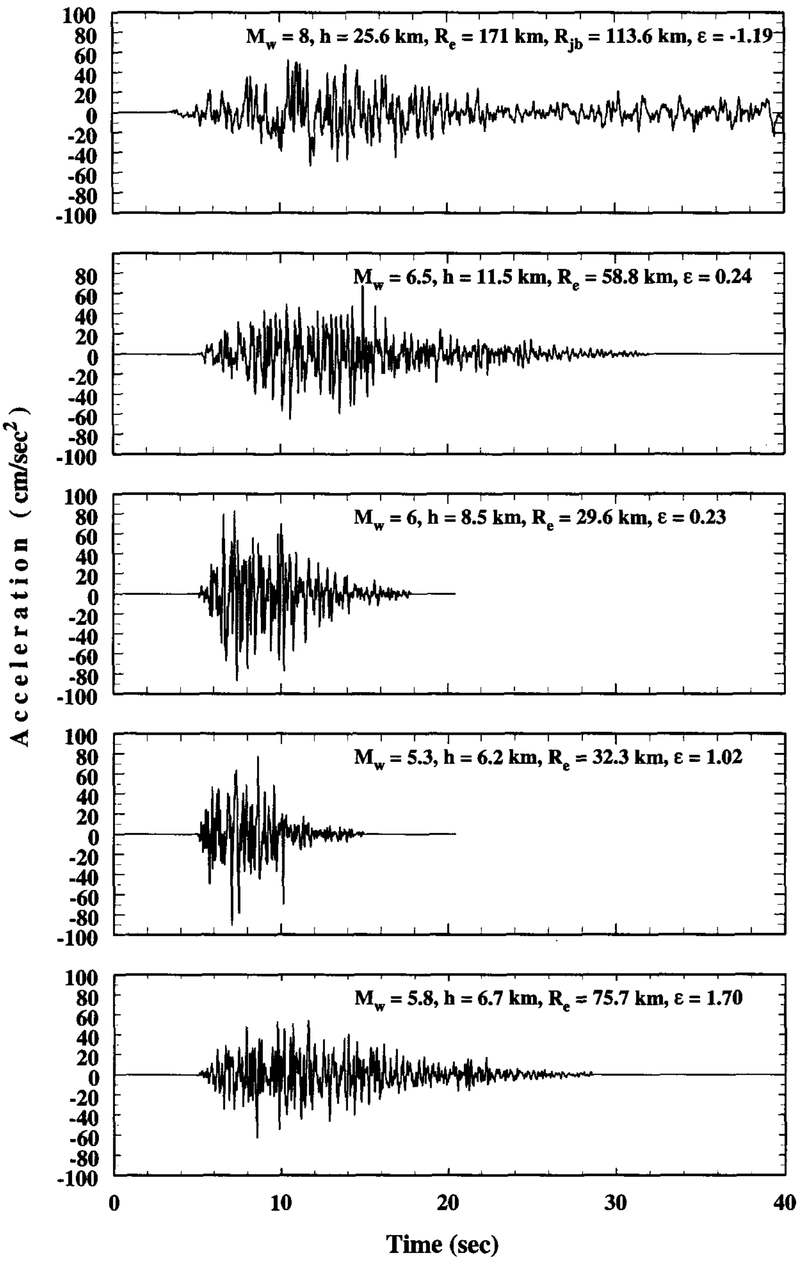

Figure 12. Sample of simulated 10% in 50 years ground motions for representative soil profile, Memphis, TN.

At St. Louis, a salient feature of the surface ground motions is the lack of amplification for periods greater than 0.5 seconds because of the thin soil layer. At the 10% in 50 years

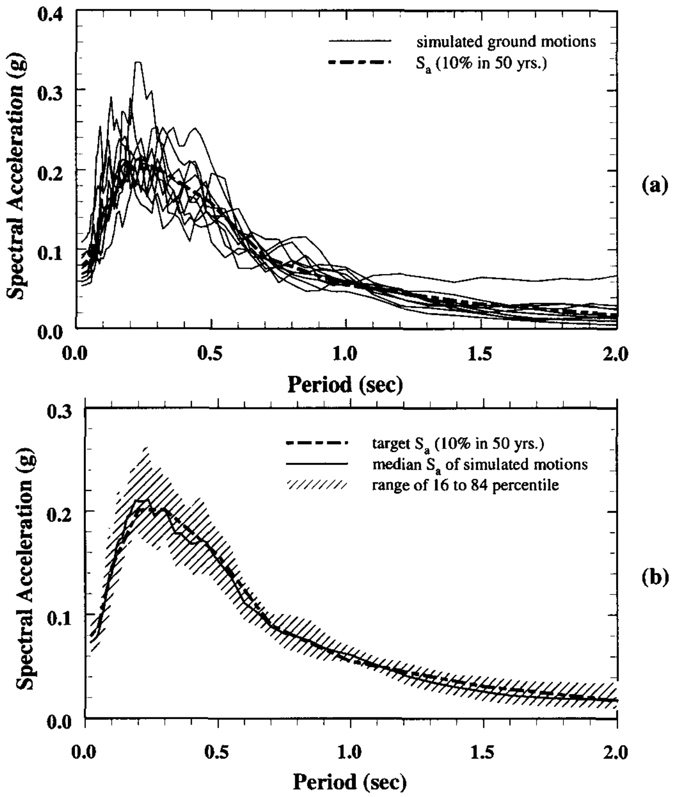

Figure 13. 10% in 50 years response spectra for representative soil profile, Memphis, TN: (a) Comparison of spectra of uniform hazard ground motion (thin solid lines) with target spectrum (thick dashed line), and (b) Median spectral accelerations and the 16-to-84 percentile band compared with the target spectrum.

level, one ground motion comes from an M 5.5 event and nine from events of M 6 to 7.2. At 2% in 50 years level, six come from M 8 events with long duration. Smaller (M 5 to 7) and much closer events with shorter durations make up the rest. There is comparatively a much larger scatter at peak of the response spectra (period from 0.1 to 0.2 sec). The maximum 16-to-84-percentile band for the median, however, is still around 10%.

At Carbondale, Illinois, there is a significant amplification of motion in the long period range because of the deep and soft soil profile. At the 10% in 50 years level, contributions come from events of M 5.8 to 7.1. At the 2% in 50 years level, all come from M 8 events. The 16-to-84 percentile bands are also narrow.

The epicenters and magnitudes of the contributing events to the uniform hazard ground motions at three cities are shown in Figure 16. For a given city, they generally consist of distant large events from NMSZ and closer smaller events. As a result, the ground motions have a wide range of frequency contents and durations. The results are in general agreement with the USGS de-aggregation maps (Harmsen et al. 1999) considering that the maps are for a given spectral acceleration whereas the contributing events in the uniform hazard ground motions were selected over a wide range of structural periods.

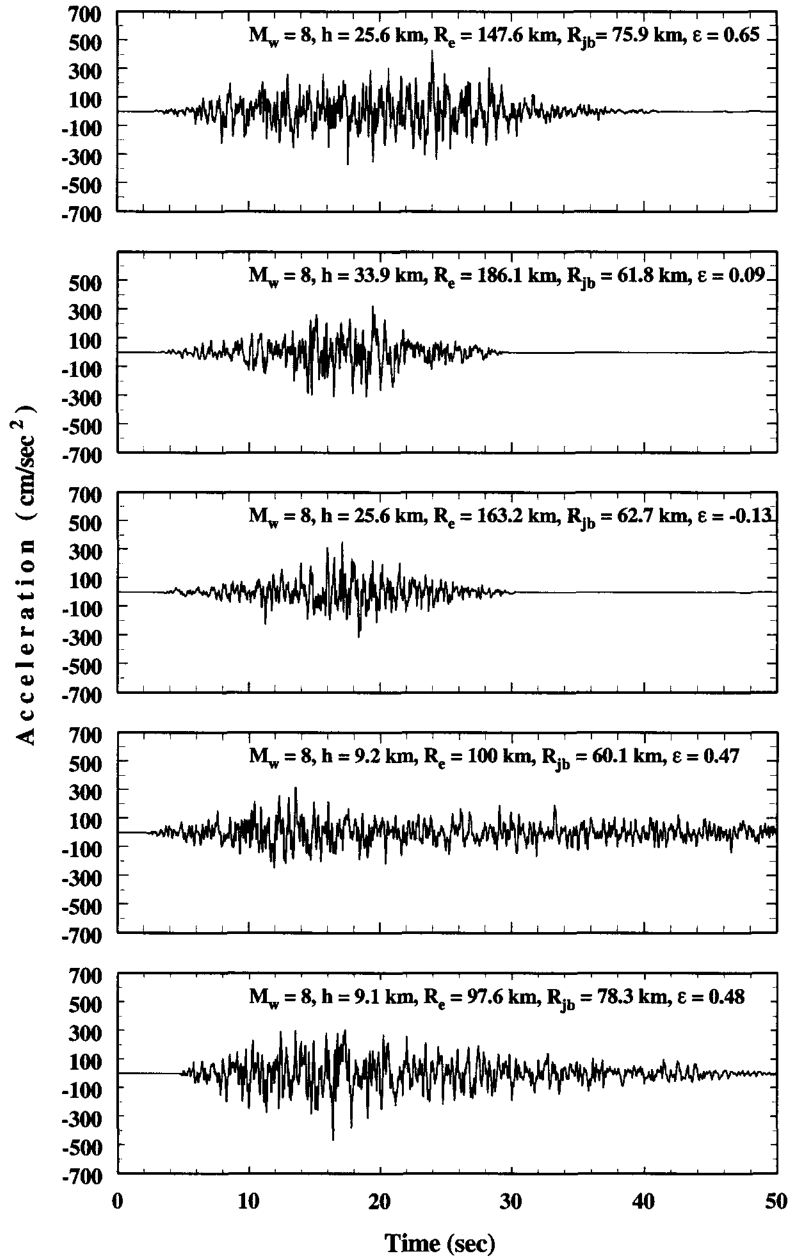

Figure 14. Sample of simulated 2% in 50 years ground motions for representative soil profile, Memphis, TN.

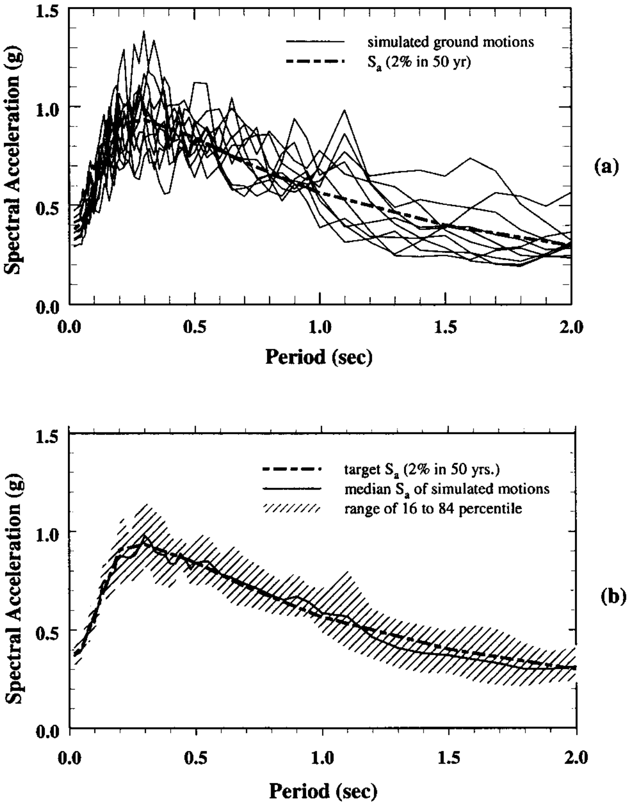

Figure 15. 2% in 50 years response spectra for representative soil profile, Memphis, TN: (a) Comparison of spectra of uniform hazard ground motions (thin solid lines) with target spectrum (thick dashed line), and (b) Median spectral accelerations and the 16-to-84 percentile band compared with the target spectrum.

INELASTIC RESPONSE SPECTRA

The response spectra for inelastic systems with and without degradation are also calculated based on the ten ground motions and found to compare well with the inelastic uniform hazard spectra based on nine thousand ground motions. Figure 17 shows such a comparison for SDOF degrading systems representing ductile steel frames (Wu and Wen 2000). The median response is seen to fit the target response spectra closely indicating that the scatter of the simulated ground motion spectra from the target is reasonable since over-matching the elastic response spectra reduces uncertainty but causes bias in the median response estimate for inelastic systems (Carballo and Cornell 2000). The implication is that the median response of a structure in the nonlinear range to the ten ground motions represents an accurate estimate of the structural response corresponding to a given probability of exceedance (10% or 2% in 50 years). The method is expected to work well also for MDOF systems, for which higher mode contribution may become important since the fit is good for a wide range of structural periods. It can be therefore used for performance check of buildings and structures.

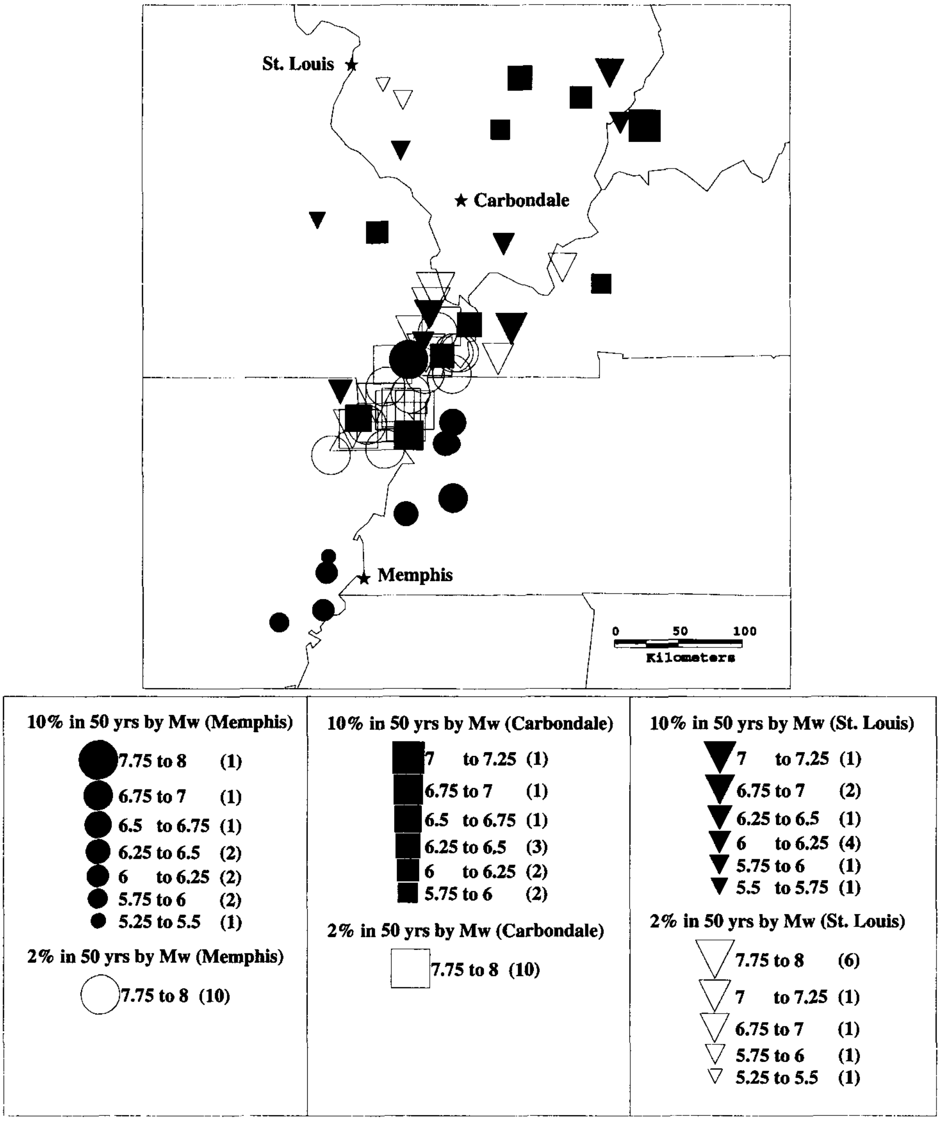

Figure 16. Epicenters and magnitudes of events contributing to uniform hazard ground motions for Memphis, Carbondale, and St. Louis (number of events in the magnitude range is shown in the parentheses).

APPLICATION TO PERFORMANCE EVALUATION

As an illustrative example, the probabilistic performance curves of a two-story steel moment frame building at Carbondale, Illinois, are given in Figure 18 before and after retrofit by shear walls (Wen and Song 2000). The suites of ten ground motions for probability levels of 10% and 2% in 50 years are used as excitations. The nonlinear structural responses due to these ground motions are obtained and shown in the figure (indicated by × for before and + for after retrofit). It is seen that the median values of the column drift ratios (indicated by O)

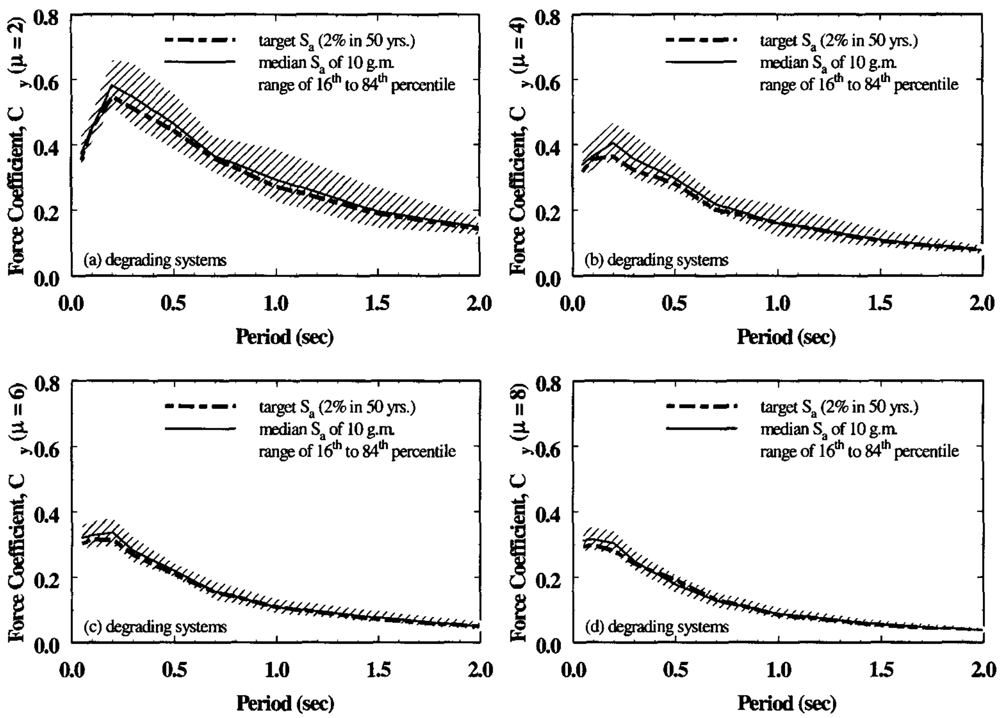

Figure 17. Comparison of 2% in 50 years median inelastic response spectra based on 10 ground motions (thin solid line) with target response spectra based on 9000 ground motions for DSOF degrading system (μ = ductility ratio) (Wu and Wen 2000).

before and after retrofit at 2% in 50 years probability level are approximately 0.04 and 0.02. These values increase to 0.05 and 0.024 (indicated by □) after resistance uncertainties are taken into consideration. In other words, the median responses for two probability levels based on twenty ground motions would give a reasonably accurate probabilistic performance curve as shown in Figure 18 which can be used for establishing acceptance criteria or in a lifecycle cost study.

It is emphasized that in general the suites of selected time series of the ground motions for various pairs of M and R will not be similar and nor will the resultant structural response be similar as indicated by the scatter of response in Figure 18. One should always use the median value as the unbiased estimate of the structural response corresponding to a given probability level.

COMPUTATIONAL ASPECT

An emphasis of the proposed method is efficiency in large-scale simulations. As a reference, the computation was done on a Pentium II 300 MHz machine. The computation time is 2 hours for 9000 simulations of ground motions in a 10-year period. A total of some 9000 accelerograms are generated which take 2.4 G bytes of storage on the hard drive. With larger and faster machines, which have become commonplace, simulations for events of much smaller occurrence probability such as 10,000 year or longer motions can be carried out without any problems. It needs to be done, however, with care since there is limit on how far one can extrapolate from physical evidence, which is collected over relatively short period of time. Also, as indicated previously, overmatching the target elastic response spectra from a large pool of simulated motions may lead to biased estimates of the response of inelastic systems. The saving in computation effort in this proposed approach is in the small number of response analyses required of nonlinear structural systems in performance evaluation as shown in the above example.

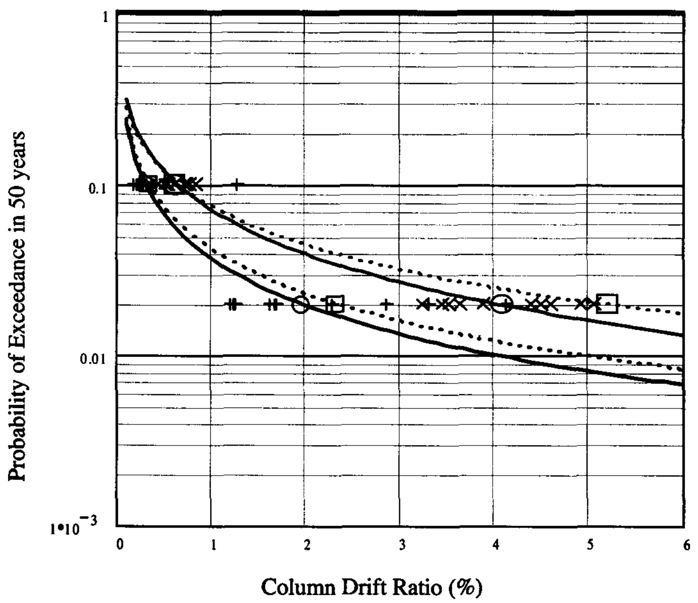

Figure 18. Fifty years probability of exceedance of column drift of a two-story steel moment frame building at Carbondale, IL, before and after retrofit with shear walls (before retrofit [×], after retrofit [+], median value (O), and median including structural capacity uncertainty [□]; dashed and solid lines indicate performance curve with and without consideration of capacity uncertainty).

SUMMARY AND CONCLUSIONS

To evaluate the performance of buildings and structures and estimate loss/cost in mid-America, simulation of future events based on current data and knowledge is necessary. A method of simulation has been developed for this purpose. It is based on the latest seismicity information in this region, the most recent ground motion models and simulation methods appropriate for engineering applications in this region. A strong emphasis is placed on uncertainty modeling and efficiency in application to probabilistic performance evaluation. The soil condition of a city is approximately modeled by a generic, "representative" profile and soil amplification is considered based on an approximate "quarter-wavelength" model. Limitations of the method have been pointed out. Uniform hazard response spectra and suites of ten ground motions are generated for Memphis, Tennessee, St. Louis, Missouri, and Carbondale, Illinois, for both soil and rock sites corresponding to a probability of exceedance of 10% in 50 years and 2% in 50 years. The rock site motions can be used as input for sites where detailed soil profile information is available. The results show that the point-source, finite fault and quarter-wavelength models are efficient in large-scale simulations of ground motions including some of the important near-source effects. The uniform hazard response spectra based on the simulated motion are in good agreement with spectra of *FEMA 273*. The suites of 10 selected ground motions yield median response spectra that closely match the uniform hazard spectra in both elastic and inelastic ranges with a coefficient of variation less than 10%. Numerical examples show that these ground motions can be used in probabilistic performance evaluation of structures with accuracy and efficiency.

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