UK/KRCEE Doc #: P11.4 2007

Seismic Hazard and Risk Assessment in the Intraplate Environment

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Prepared for
United States Department of Energy Portsmouth/Paducah Project Office
Acknowledgment: This material is based upon work supported by the Department of Energy under
Award Number DE-FG05-03OR23032.

2007

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In

Stein, S. and Mazzotti, S., ed.
Continental Intraplate Earthquakes: Science, Hazard, and Policy Issues
Geological Society of America Special Paper 425, p. 363-373

2007

Seismic Hazard and Risk Assessment in the Intraplate Environment: The New Madrid Seismic Zone of the Central United States

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Abstract

Although the causes of large intraplate earthquakes are still not fully understood, they pose certain hazard and risk to societies. Many such earthquakes have occurred in intraplate regions throughout the world. Estimating hazard and risk in these regions is difficult because of lack of earthquake records. The New Madrid Seismic Zone is one such region where large and rare intraplate earthquakes (M7.0 or greater) pose significant hazard and risk. Many different definitions of hazard and risk have been used, and the resulting estimates differ dramatically. In this paper, seismic risk is defined as the probability of at least one earthquake equal to or greater than a specific magnitude, or ground motion generated by the earthquake in a certain period of time; whereas seismic hazard as at least one earthquake equal to or greater than a specific magnitude, or ground motion generated by the earthquake, recurring in a time interval. Probabilistic seismic hazard analysis (PSHA) derives a relationship between a ground motion parameter and its return period (hazard curve). The return period is not an independent temporal parameter but a mathematical extrapolation of the recurrence intervals of earthquakes and the probabilities of ground motions. Therefore, it is not appropriate to equate the return period to the recurrence interval of earthquake. A new method is proposed and applied for estimating seismic hazard in the New Madrid Seismic Zone. This method provides hazard estimates that are consistent with the state of our knowledge and can be easily applied to other intraplate regions.

Introduction

Although most damaging earthquakes occur along plate boundaries, such as the subduction zones around the Pacific Ocean and the San Andreas Fault in California, some large earthquakes have occurred in intraplate regions. For example, the 1811–1812 New Madrid earthquakes (M7.0–8.0) and the 1886 Charleston, S. C., earthquake (~M7.3) both occurred in intraplate regions. Geologic records (paleoliquefaction data) also show that large earthquakes occurred in other intraplate regions in eastern North America, such as the Wabash Valley (Obermeier and others, 1991; Obermeier, 1998). The causes of these large intraplate earthquakes are not well understood (Braile and others, 1986; Zoback, 1992; Newman and others, 1999; Kenner and Segall, 2000), and they pose hazards and risk because of their proximity to population centers.

The New Madrid Seismic Zone, located in northeastern Arkansas, western Kentucky, southeastern Missouri, and northwestern Tennessee, is a seismically active intraplate region in the central United States. It is so named because the town of New Madrid, Mo., was the closest settlement to the epicenters of the 1811–1812 quakes. Between 1811 and 1812, at least three large earthquakes, with magnitudes estimated between M7.0 and M8.0, occurred during a 3-month period (Nuttli, 1973). Instruments were installed in and around the seismic zone in 1974 to closely monitor seismic activity. Figure 1 shows locations of earthquakes with magnitude equal to or greater than 2.0 that occurred in the New Madrid Seismic Zone and the surrounding areas between 1974 and 2004 (CERI, 2004). The low seismicity and lack of strong-motion recordings from large earthquakes (M>6.0) make estimating seismic hazard and risk difficult.

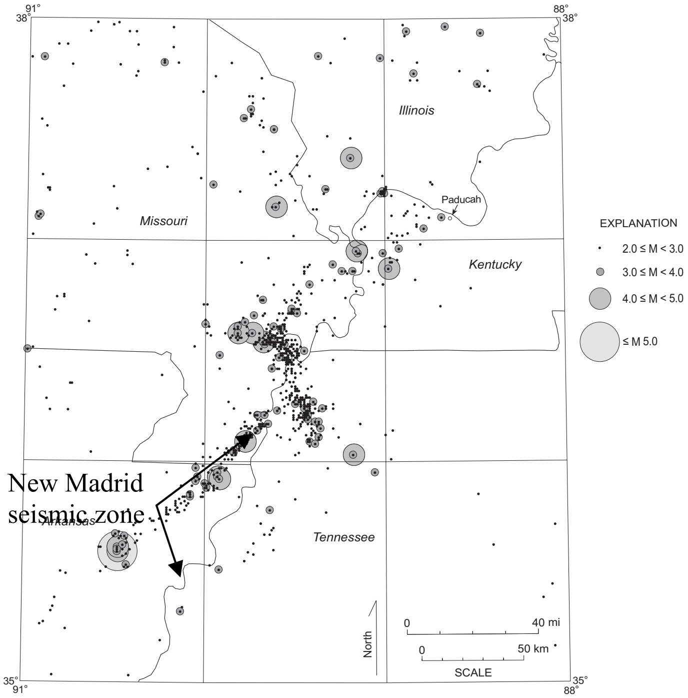

Figure 1. Seismicity in the New Madrid Seismic Zone of the central United States between 1974 and 2004 (CERI, 2004).

In this paper, I first review probabilistic seismic hazard analysis (PSHA), and then develop a new method, called seismic hazard assessment (SHA), and apply it to the New Madrid Seismic Zone.

PSHA

PSHA was originally developed by Cornell in 1968 for estimating engineering risk in comparison with the analogous flood or wind problem. A similar method was also developed by Milne and Davenport (1969) for estimating seismic risk in Canada. In 1971, Cornell extended his method to incorporate the possibility that ground motion at a site could be different (i.e., ground motion uncertainty) for different earthquakes of the same magnitude at the same distance, because of differences in site conditions or source parameters. This method (Cornell, 1971) was coded into a FORTRAN algorithm by McGuire (1976) and became a standard PSHA (Frankel and others, 1996, 2002). It should be noted that there is a fundamental difference between the formulations in Cornell (1968) and those in Cornell (1971); i.e., the former does not include ground-motion uncertainty, whereas the latter does.

Following McGuire's (1995) formula for multiple sources, an annual probability of exceedance (γ) of a ground-motion amplitude y is

$$\gamma(y) = \sum_i v_i \iiint f_M(m) f_R(r) f_\varepsilon(\varepsilon) P[Y > y \mid m, r, \varepsilon] dm dr d\varepsilon , \quad (1)$$

where v_i is the activity rate for seismic source i; $f_M(m)$, $f_R(r)$, and $f_\varepsilon(\varepsilon)$ are earthquake magnitude, source-to-site distance, and ground motion density functions, respectively; ε is ground motion uncertainty and quantified by a standard deviation (logarithmic); and $P[Y>y|m,r, \varepsilon]$ is the probability that Y exceeds y for a given m and r. The triple integration in equation (1) is very complicated, and a numerical solution is required. For characteristic seismic sources, equation (1) can be simplified as

$$\gamma(y) = \sum_i \frac{1}{T_i} P_i(Y > y) , \quad (2)$$

where T_i is the average recurrence interval of the characteristic earthquake for source i, and $P_i(Y \geq y)$ is the probability that the ground motion (Y) from source i will exceed y. Generally, PSHA involves many seismic sources, ground-motion attenuation relationships, recurrence intervals, and associated uncertainties. No matter how complicated the parameters are, however, the end results from PSHA are simple, total hazard curves, which give a range of annual probability of exceedance versus a range of ground-motion values (Frankel and others, 1996, 2002).

As shown in equations (1) and (2), the annual probability of exceedance, γ, is a function of average recurrence interval of earthquake and ground-motion uncertainty. This can be illustrated through an example for a single characteristic source. Figure 2 shows a peak ground acceleration (PGA) hazard curve (a) and probability density of PGA for a hypothetical characteristic earthquake of M7.5 with an average recurrence interval of 500 years at a point 20 km from the epicenter. According to equation (2), annual probability of exceedance (hazard) is the product of the annual occurrence rate, 0.002 (1/500), and the probability that PGA exceeds a given value. For example, for a PGA of 0.3g, the probability of exceedance is 0.5, which results in an annual probability of exceedance of 0.001 (0.002 x 0.5). For an annual probability of exceedance of 0.0004 (or return period of 2,500 years), a PGA of 0.5g can be obtained using the curves in Figure 2. The annual probability of exceedance of 0.0004 is equal to 0.002 (annual occurrence rate) times 0.2 (probability of PGA exceeding 0.5g). This example demonstrates the basic function of

PSHA: i.e., a mathematical extrapolation from the time-domain characteristics of earthquakes and the spatial characteristics of ground motion.

The inverse of annual probabilities of exceedance ($1/\gamma$), called return periods, are often used (Frankel and others, 1996, 2002). For example, a 2,500-year return period is the inverse of annual probabilities of exceedance of 0.0004. As shown in Figure 2, return periods range between 500 and 1 million years, and could reach infinity because there is no upper boundary on the log-normal distribution (Fig. 2B). Moreover, ground motion with a return period derived from PSHA has been communicated and used as the ground motion that will occur in that return period: for example, the ground motion with a 2,500-year return period (Frankel and others, 1996, 2002; Frankel, 2005). As shown in Figure 2), it is assumed that there is only one characteristic earthquake with an average recurrence interval of 500 years (input). The ground motion will not occur in 2,500 years because it is a consequence of the earthquake; rather, it will have a 20 percent probability of being exceeded when the earthquake occurs in 500 years. Similarly, for multiple sources, Wang and Ormsbee (2005) showed that ground motion with a particular return period does not mean that that ground motion will occur in that return period; rather, there are certain probabilities that the ground motion will be exceeded when all the considered earthquakes occur. The return period is a number extrapolated from the recurrence intervals of earthquakes and the probability of ground motions. Hence, using the return period to communicate seismic hazard is not only inappropriate, but also results in a fundamental change of PSHA; i.e., from a probable occurrence to a certain occurrence of a ground motion.

It is difficult to explain the physical meaning of ground motion derived from PSHA. The first thorough review of PSHA was conducted by a committee chaired by K. Aki, at the National Research Council (NRC, 1988). One of conclusions reached by the Aki Committee was that “the aggregated results of PSHA are not always easily related to the inputs” (NRC, 1988). In other words, “the concept of a ‘design earthquake’ is lost; i.e., there is no single event (specified, in simplest terms, by a magnitude and distance) that represents the earthquake threat at, for example, the 10,000-yr ground-motion level” (McGuire, 1995). Wang and others (2003) and Wang and Ormsbee (2005) also demonstrated that it is difficult to explain the physical meaning of ground motion derived from PSHA for a single or three characteristic sources.

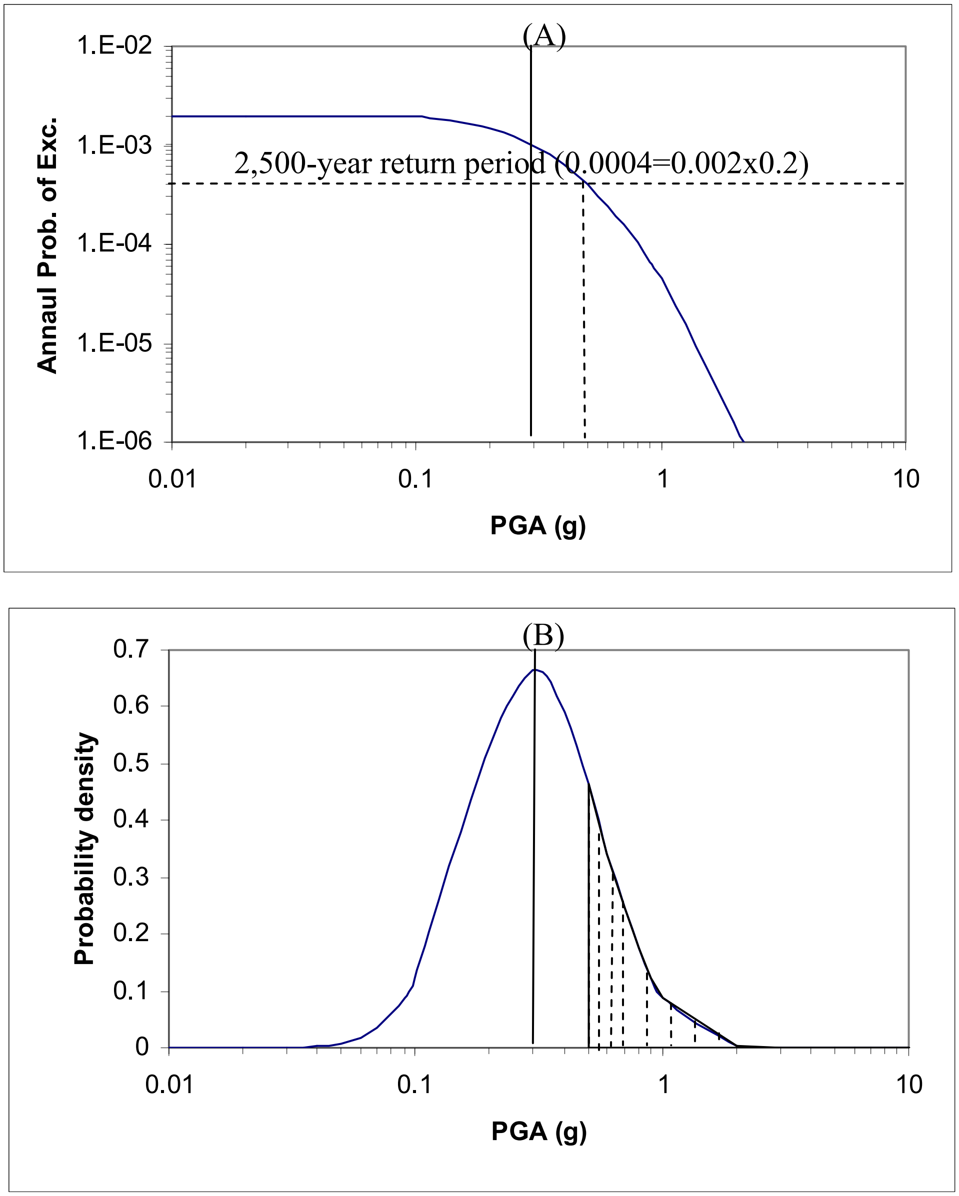

Figure 2. (A) hazard (annual probability of exceedance) curve for a hypothetical characteristic earthquake of M7.5 with average recurrence interval of 500 years at a point 20 km from the epicenter. (B) median PGA of 0.3g and a standard deviation (log) of 0.6 are assumed.

Frankel (2005) offered a physical explanation for ground motion with a 2,500-year return period from a characteristic earthquake with a 500-year recurrence interval. He stated "one of the five earthquakes expected to occur over the 2,500 years will produce ground motions at that site greater than the 2% PE in 50 years (2,500-year return period) value." This explanation contradicts the basics of PSHA; i.e., probability of ground-motion occurrence. As shown in Figure 2, the probability that PGA exceeds 0.5g is 0.2 if the characteristic earthquake occurs. The probability of PGA exceeding 0.5g after five characteristic earthquakes (in 2,500 years) is about 0.67 ($p \approx 1-(1-0.2)^5$), not 1.0. This means that the PGA with a 2,500-year return period may not occur. An explanation similar to Frankel's was offered by Holzer (2005) for ground motion with a 2,500-year return period from three characteristic earthquakes. Holzer's explanation also contradicts the basics of PSHA (Wang, 2005).

As pointed out by Hanks (1997), "PSHA is a creature of the engineering sciences, not the Earth sciences, and most of its top practitioners come from engineering backgrounds." The main problem with PSHA is how it is being used in engineering risk analysis, particularly in regard to return period. Three risk levels, ground motions with 10, 5, and 2 percent probability of exceedance (PE) in 50 years, are commonly considered in engineering design. In engineering risk analysis, the ground motion with 10, 5, or 2 percent PE in 50 years means that a particular ground motion (an event) will occur at least once in 500, 1,000, or 2,500 years (recurrence intervals) (Cornell, 1968; Milne and Davenport, 1969; Wang and Ormsbee, 2005; Wang and others, 2005). As shown by Frankel and others (1996, 2002) and Frankel (2004), the ground motion with 2 percent PE in 50 years is equivalent to the ground motion with a return period of 2,500 years (or annual probability of exceedance of 0.0004) derived from PSHA. As discussed earlier, the ground motion with a 2,500-year return period does not mean it will occur in 2,500 years; rather, it has certain probabilities of being exceeded when all the considered earthquakes occur. In other words, the return period defined in PSHA is not equivalent to the recurrence interval defined in engineering risk analysis. Hence, using PSHA for engineering risk analysis is not appropriate (Wang and Ormsbee, 2005).

Seismic Hazard Analysis

Seismic Risk Estimation

It is necessary to briefly review the definition of seismic risk because the purpose of seismic hazard analysis is to provide parameters for estimating risk (Cornell, 1968; Milne and Davenport, 1969). Although risk has different meanings among different professions, it can generally be quantified by three terms: probability, hazard (loss or other measurements), and time exposure. For example, in health sciences risk may be defined as the probability of getting cancer if an average daily dose of a hazardous substance (hazard) is taken over a lifetime (70 years on average). In the financial market, risk may be defined as the probability of losing a certain amount of money (loss) over a period of time. In seismology, risk may be defined as the probability of earthquakes with a certain magnitude or greater striking at least once in a region during a specific period of time. Therefore, a clear definition of risk is necessary in any discussion and communication of the risk.

In earthquake engineering, risk is defined as the probability that ground motion at a site of interest exceeds a specific level (hazard) at least once in a period of time (Cornell, 1968; Milne and Davenport, 1969). This definition is similar to those defined in hydraulic engineering (Gupta, 1989) and wind engineering (Sacks, 1978). In fact, seismic risk was originally defined from analogous flood and wind risks (Cornell, 1968; Milne and Davenport, 1969). Seismic risk estimation is based on a Poisson model, which assumes that earthquake occurrence is independent of time and independent of the past history of occurrences or nonoccurrences. Although the Poisson model fails to incorporate the most basic physics of the earthquake process, whereby the tectonic stress released when a fault fails must rebuild before the next earthquake can occur at that location (Stein and Wysession, 2003; Working Group on California Earthquake Probabilities, 2003), it is the standard model for seismic risk analysis, as well as for other risk analyses such as for flood and wind. In the Poisson model (Cornell, 1968; Stein and Wysession, 2003), the probability of n earthquakes of interest in an area or along a fault occurring during an interval of t years is

$$p(n,t,\tau) = \frac{e^{-t/\tau}(t/\tau)^n}{n!}, \tag{3}$$

where τ is the average recurrence interval (or average recurrence rate, $1/\tau$) of earthquakes with magnitudes equal to or greater than a specific size. The probability that no earthquake will occur in an area or along a fault during an interval of t years is

$$p(0,t,\tau) = e^{-t/\tau}. \tag{4}$$

The probability of one or more (at least one) earthquakes with magnitudes equal to or greater than a specific size occurring in t years is

$$p(n \geq 1,t,\tau) = 1 - p(0,t,\tau) = 1 - e^{-t/\tau} \approx 1 - (1 - 1/\tau)^t. \tag{5}$$

Equation (5) can be used to calculate the risk, expressed as X percent PE in Y years, for a given recurrence interval (τ) of earthquakes with a certain magnitude or greater. For example, the U.S. Geological Survey (2002) estimated a 7 to 10 percent probability of a repeat of the 1811–1812 New Madrid earthquakes (M7.5 to 8.0) in 50 years in the New Madrid region. This estimate was determined from equation (5) and an average recurrence interval of about 500 years which was inferred from interpretation of paleoliquefaction records (Tuttle and others, 2002). Equation (5) can also be used to calculate the average recurrence interval (τ) of earthquakes with a certain magnitude or greater for a given risk level. For example, 10, 5, and 2 percent PE in 50 years are commonly used in earthquake engineering (BSSC, 1998; ICC, 2000). According to equation (5), these risk levels are equivalent to 500-, 1,000-, and 2,500-year recurrence intervals for earthquakes. For comparison, 1 percent PE in 1 year and 2 percent PE in 1 year are being considered for building designs for flood and wind, respectively (ICC, 2000). These risk levels are equivalent to 100- and 50-year recurrence intervals for floods (100-year-flood) and wind storms, respectively.

In practice, knowing the consequences of earthquakes (i.e., ground motions or Modified Mercalli Intensity [MMI]) at a point or in a region of interest is desirable. For example, PGA and response acceleration (S.A.) at a given period are common measurements needed for a site. This is similar to the situation in flood and wind analyses whereby knowing the consequences of floods and winds, such as peak discharge and 3-s gust wind speed is desired for specific sites. The ground motions (consequences of earthquake) and their recurrence intervals (τ), hazard curves, are determined through seismic hazard analyses.

Seismic Hazard Assessment

The hazard curves used in seismic risk analysis describe relationships between a ground motion parameter and its recurrence interval. As discussed earlier, the hazard curves derived from PSHA describe relationships between a ground motion parameter and its return period, and the return period is not equal to the recurrence interval. Therefore, the hazard curves derived from PSHA are not appropriate for seismic risk analysis. A new method, seismic hazard assessment (SHA), is proposed for developing a relationship between ground motion parameter and its recurrence interval (i.e., seismic hazard curve) here.

In seismology, the number of earthquakes that occur yearly can be represented by a magnitude-frequency relationship or Gutenberg-Richter relationship:

$$Log(N) = a - bM \;\; or \;\; N = 10^{a-bM} \tag{6}$$

where N is the cumulative number of earthquakes with magnitude equal to or greater than M occurring yearly, and a and b are constants. As discussed earlier, the average recurrence rate ($1/\tau$) of earthquakes with magnitudes equal to or greater than a specific size (M) in equation (5) has the same meaning as N. Therefore,

$$\frac{1}{\tau} = N = e^{2.303a-2.303bM} \;\; or \;\; \tau = \frac{1}{N} = e^{-2.303a+2.303bM} . \tag{7}$$

Estimating the expected ground motion at a site is done by assuming a ground-motion attenuation relationship, which describes a relationship between a ground-motion parameter (Y) and magnitude of an earthquake (M) and epicentral distance (R) (Campbell, 1981, 2003). Generally, the attenuation relationship follows the functional form of

$$\ln Y = a_0 + f(M, R) + \varepsilon , \tag{8}$$

where ε is uncertainty. The uncertainty (ε) can be modeled using a log-normal distribution with a standard deviation (σ). From equation (8), M can be expressed as a function of R, $\ln Y$, and ε:

$$M = f(R, \ln Y, \varepsilon) . \tag{9}$$

Combining equations (7) and (9) results in:

$$\frac{1}{\tau} = e^{2.303a - 2.303bf(R, \ln Y, \varepsilon)} \quad or \ \tau = e^{-2.303a + 2.303bf(R, \ln Y, \varepsilon)} . \tag{10}$$

Equation (10) describes a relationship between the ground motion (ln*Y*) with an uncertainty (ε) and its annual recurrence rate ($1/\tau$) or recurrence interval (τ) at a distance (*R*); i.e., a hazard curve. Equation (10) can be used to estimate ground motion at a site or in a region.

Seismic Hazard and Risk in the New Madrid Seismic Zone

Seismicity in the New Madrid Seismic Zone is quite low. Table 1 lists instrumental and historical earthquakes with magnitude equal to or greater than M4.0 known to have occurred in the New Madrid Seismic Zone (Bakun and Hopper, 2004). Two M4.0 earthquakes that occurred in 2003 were also included in Table 1. As shown in the table, there is only one event with M6.0 since the last 1811–1812 events, the 1843 Marked Tree, Ark., earthquake. This earthquake catalog is too short to be sufficient for constructing a reliable Gutenberg-Richter curve, as illustrated in Figure 3 which shows the Gutenberg-Richter curve for earthquakes with magnitudes between M4.0 and M5.0 in the New Madrid Seismic Zone (Stein and Newman, 2004). The *a* and *b* values are estimated to be about 3.15 and 1.0, respectively. The *b* value of 1.0 is consistent with that used in the national seismic hazard maps (Frankel and others, 1996, 2002). Figure 3 also shows that recurrence intervals for large earthquakes (M≥6.0) would be quite long, about 700 years for M6.0, 7,000 years for M7.0, and 70,000 years for M8.0, if *a* and *b* are assumed to be applicable for large earthquakes in the New Madrid Seismic Zone. This is not consistent with paleoseismic interpretations by Tuttle and others (2002): an average recurrence interval of about 500 years was inferred from the interpretation of the paleoliquefaction records for large earthquakes, similar to the 1811–1812 New Madrid events. These large earthquakes were treated as characteristic events (Frankel and others, 1996, 2002) even though it is difficult to determine that they are characteristic because of the lack of data (Stein and Newman, 2004).

I assume that (1) the *a* and *b* values could be applied to earthquakes with magnitudes up to M5.5 (Fig. 2), and (2) the large earthquake (M7.6) is characteristic. For *a*=3.15 and *b*=1.0:

$$\frac{1}{\tau} = e^{7.254 - 2.303M} \quad for\, 4.0 \le M \le 5.5 . \tag{11}$$

Equation (11) describes a hazard curve in terms of earthquake magnitude and its annual recurrence rate. For *M*=4.85, equation (11) results in an annual recurrence rate ($1/\tau$) of about 0.02 or a recurrence interval (τ) of 50 years, which means that at least one earthquake with magnitude equal to or greater than 4.85 would be expected to occur in 50 years. Similarly, equation (11) results in an annual recurrence rate of about 0.01 or a recurrence interval of 100 years if *M*=5.15. Hence, according to equation (5), we can calculate risks for the New Madrid area; i.e., about a 63 percent PE in 50 years that the area will be hit by at least one earthquake with M4.85 or greater, and about a 39 percent PE in 50 years that the area will be hit by at least one earthquake with M5.15 or greater.

Table 1. Earthquakes with magnitude equal to or greater than M4.0 in the New Madrid Seismic Zone (Bakun and Hopper, 2004).

Date	Latitude	Longitude	M
1811-12-16	36.00	-89.96	7.6
1811-12-16 "dawn"	36.25	-89.50	7.0
1812-01-23	36.80	-89.50	7.5
1843-01-05	35.90	-89.90	6.2
1843-02-17	35.90	-89.90	4.2
1865-08-17	35.54	-90.40	4.7
1878-11-19	35.65	-90.25	5.0
1883-01-11	36.80	-89.50	4.2
1903-11-04	36.59	-89.58	4.7
1923-10-28	35.54	-90.40	4.1
1927-05-07	35.65	-90.25	4.5
1938-09-17	35.55	-90.37	4.4
1962-02-02	36.37	-89.51	4.2
1963-03-03	36.64	-90.05	4.7
1970-11-17	35.86	-89.95	4.1
1976-03-25a	35.59	-90.48	4.6
1976-03-25b	35.60	-90.50	4.2
1991-05-04	36.56	-89.80	4.1
2003-04-30	35.920	-89.920	4.0
2003-06-06	36.87	-88.98	4.0

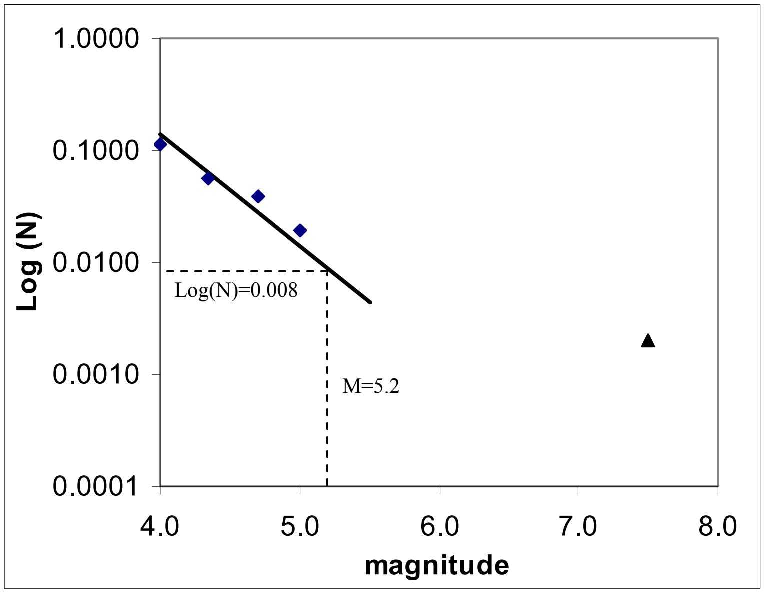

Figure 3. Magnitude-frequency (Gutenberg-Richter) curve for the New Madrid Seismic Zone. Diamond–historical rate, triangle–geological (paleoliquefaction) rate.

The estimated risk of a large earthquake (~M7.6) hitting the New Madrid area is about 10 percent PE in 50 years. This estimate is consistent with the USGS results for the New Madrid area. Figure 4 is the earthquake probability map for the New Madrid area generated from the USGS earthquake hazard website (eqint.cr.usgs.gov/eq/html/eqprob.html).

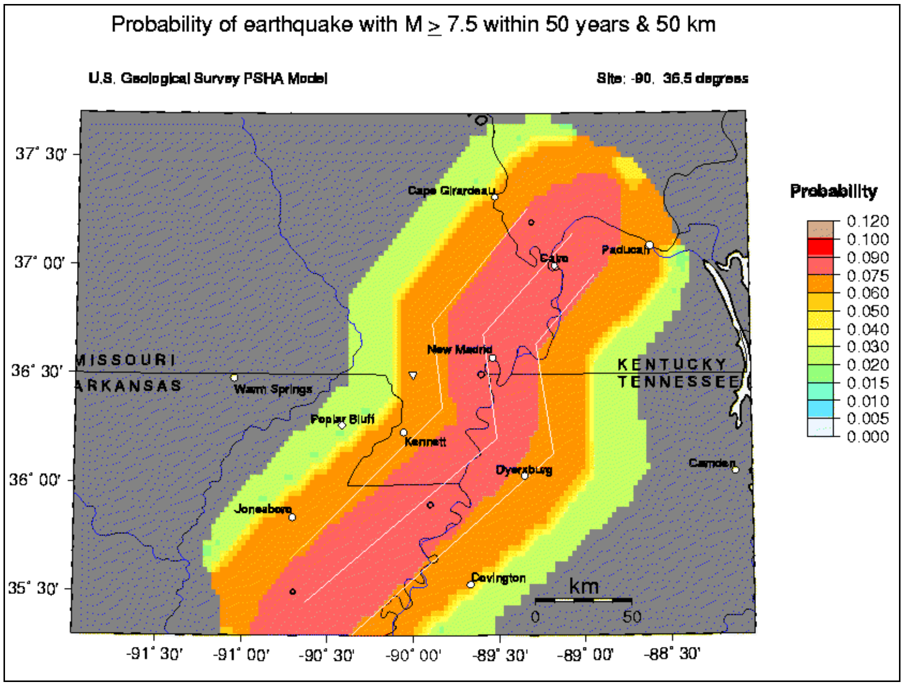

Figure 4. Earthquake probability map of the New Madrid Seismic Zone (USGS, 2005)

Campbell (2003) found that in the central and eastern United States, ground motion on very hard rock (Vs of 2.8 km/sec) follows the relationship

$$\ln Y = c_1 + f_1(M) + f_2(M, r_{rup}) + f_3(r_{rup}) + \varepsilon_a + \varepsilon_e \,, \tag{12}$$

where r_{rup} is the closest distance to fault rupture, ε_a is aleatory (randomness) uncertainty, and ε_e is epistemic uncertainty. For $r_{\text{rup}} \le 70$ km, PGA and S.A. of 0.2 and 1.0s:

$$\begin{aligned}\ln(PGA) &= 0.0305 + 0.633M - 0.0427(8.5 - M)^2 - 1.591\ln R \\ &\quad + (-0.00428 + 0.000483M)r_{rup} + \varepsilon_a + \varepsilon_e\end{aligned} \,, \tag{13}$$

$$\begin{aligned}\ln(S.A._{0.2s}) &= -0.4328 + 0.617M - 0.0586(8.5 - M)^2 - 1.320\ln R \\ &\quad + (-0.00460 + 0.000337M)r_{rup} + \varepsilon_a + \varepsilon_e\end{aligned} \,, \tag{14}$$

and

$$\begin{aligned}\ln(S.A._{1.0s}) &= -0.6104 + 0.451M - 0.2090(8.5 - M)^2 - 1.158\ln R \\ &\quad + (-0.00255 + 0.000141M)r_{rup} + \varepsilon_a + \varepsilon_e\end{aligned} \,, \tag{15}$$

and

$$R = \sqrt{r_{rup}^2 + [c_7 \exp(c_8 M)]^2} \;. \tag{16}$$

The standard deviation ($\sigma_{\ln Y}$) of ε_a is magnitude dependent and equal to

$$\sigma_{\ln Y} = \begin{cases} c_{11} + c_{12} M & \text{for } M < 7.16 \\ c_{13} & \text{for } M \geq 7.16 \end{cases} \cdot \tag{17}$$

The coefficients c_7, c_8, c_{11}, c_{12}, and c_{13} are listed in Table 2. The standard deviation of ε_e depends on earthquake magnitude and the rupture distance as listed in Campbell (2003).

Table 2. Coefficients c_7, c_8, c_{11}, c_{12}, and c_{13} of Campbell's attenuation (2003).

Coefficients	PGA	0.2s S.A.	1.0 S.A.
c_7	0.683	0.399	0.299
c_8	0.416	0.493	0.503
C_{11}	1.030	1.077	1.110
C_{12}	-0.0860	-0.0838	-0.0793
C_{13}	0.414	0.478	0.543

Combining the ground-motion attenuation relationships (equations 13, 14, and 15) and the Gutenberg-Richter relationship (equation 11), we can derive seismic hazard curves in terms of ground motions and their annual recurrence rates for a site at a certain distance from the source. Figures 5, 6, and 7 show the median (ε=0.0) hazard curves for PGA, 0.2s S.A., and 1.0s S.A. at a site 30 km from the source. As shown above, there is significant uncertainty ($\sigma \approx 0.66$─0.90) in the predicted ground motions, and the uncertainty depends on magnitude and distance. The uncertainty can be estimated in the hazard analysis by adding a total uncertainty ($\varepsilon \neq 0.0$) to the attenuation relationship. Also shown in Figures 4, 5, and 6 are the hazard curves with 16 percent and 84 percent confidence levels (i.e., $\pm 1.0\sigma$). These hazard curves (Fig. 4, 5, and 6) are similar to those derived by flood-frequency analysis (Gupta, 1989; Wang and Ormsbee, 2005) and wind-frequency analysis (Sacks, 1978). Points on the hazard curves have a similar meaning. For example, the median PGA of about 0.07g has an annual recurrence rate of 0.008, or recurrence interval of 125 years. This PGA (0.07g) could occur at least once in a 125-year period because it is a consequence of an earthquake with magnitude equal to 5.2 or greater (Fig. 3).

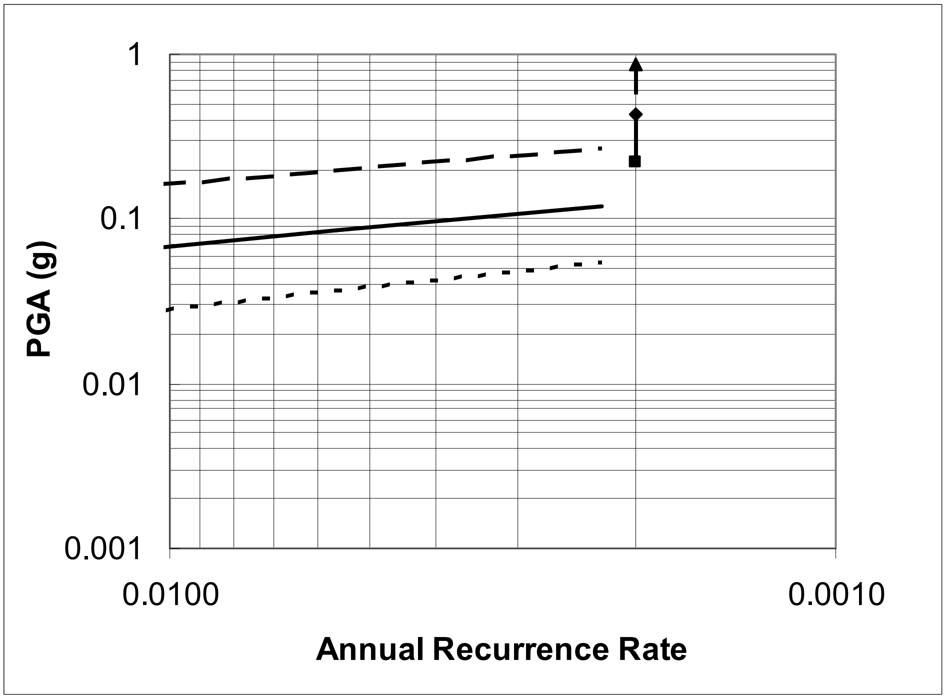

Figure 5. PGA hazard curves at a site 30 km from the New Madrid faults. Diamond – median (mean) PGA, square – PGA with 16 percent confidence, and triangle – PGA with 84 percent confidence from the characteristic earthquake of M7.6.

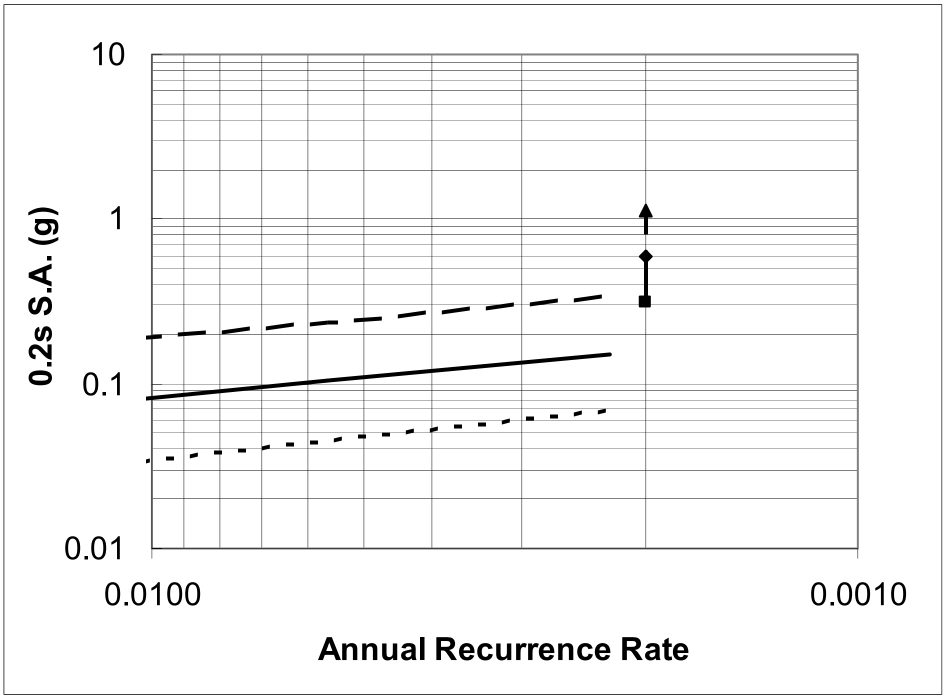

Figure 6. Hazard curves for 0.2s S.A. at a site 30 km from the New Madrid faults. Diamond – median (mean) 0.2s S.A., square – 0.2s S.A. with 16 percent confidence, and triangle – 0.2s S.A. with 84 percent confidence from the characteristic earthquake of M7.6.

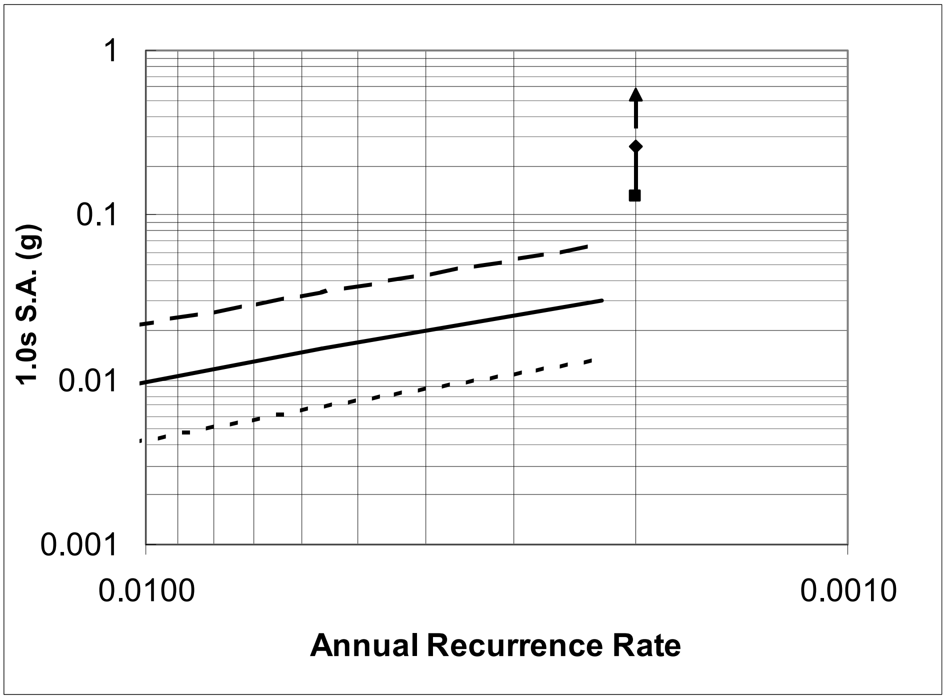

Figure 7. Hazard curves for 1.0s S.A. at a site 30 km from the New Madrid faults. Diamond – median (mean) 1.0s S.A., square – 1.0s S.A. with 16 percent confidence, and triangle – 1.0s S.A. with 84 percent confidence from the characteristic earthquake of M7.6.

As shown in Figures 5 through 7, the median ground motions with the annual recurrence rate of 0.002 are significant: 0.44g PGA, 0.59g 0.2s S.A., and 0.26g 1.0s S.A., respectively. According to these results, the characteristic earthquake (M7.5─8.0) is of safety concern in the New Madrid area. The risk posed by the characteristic earthquake is about 10 percent PE in 50 years. There is no knowledge on large earthquakes or ground motions generated by the earthquakes that have recurrence intervals much longer than 500 years in the New Madrid area. In another words, there is no information on the earthquakes or ground motions with PE much less than 10 percent in 50 years, such as 2 percent PE or less in 50 years, in the New Madrid area. However, PSHA could derive the ground motions with 2 percent PE or less in 50 years (Frankel and others, 2002; Frankel, 2005).

The ground-motion maps corresponding to a specific annual recurrence rate or a PE in Y years can also be generated from the hazard curves at grid points according to equation (10). For example, for the annual recurrence rate of 0.002 or 10 percent PE in 50 years, PGA and S.A. can be generated according to equation (10) using a ground-motion attenuation relationship, such as Campbell's (2003) attenuation relationship. Figure 8 shows median PGA, 0.2s S.A., and 1.0s S.A. maps for the New Madrid area.

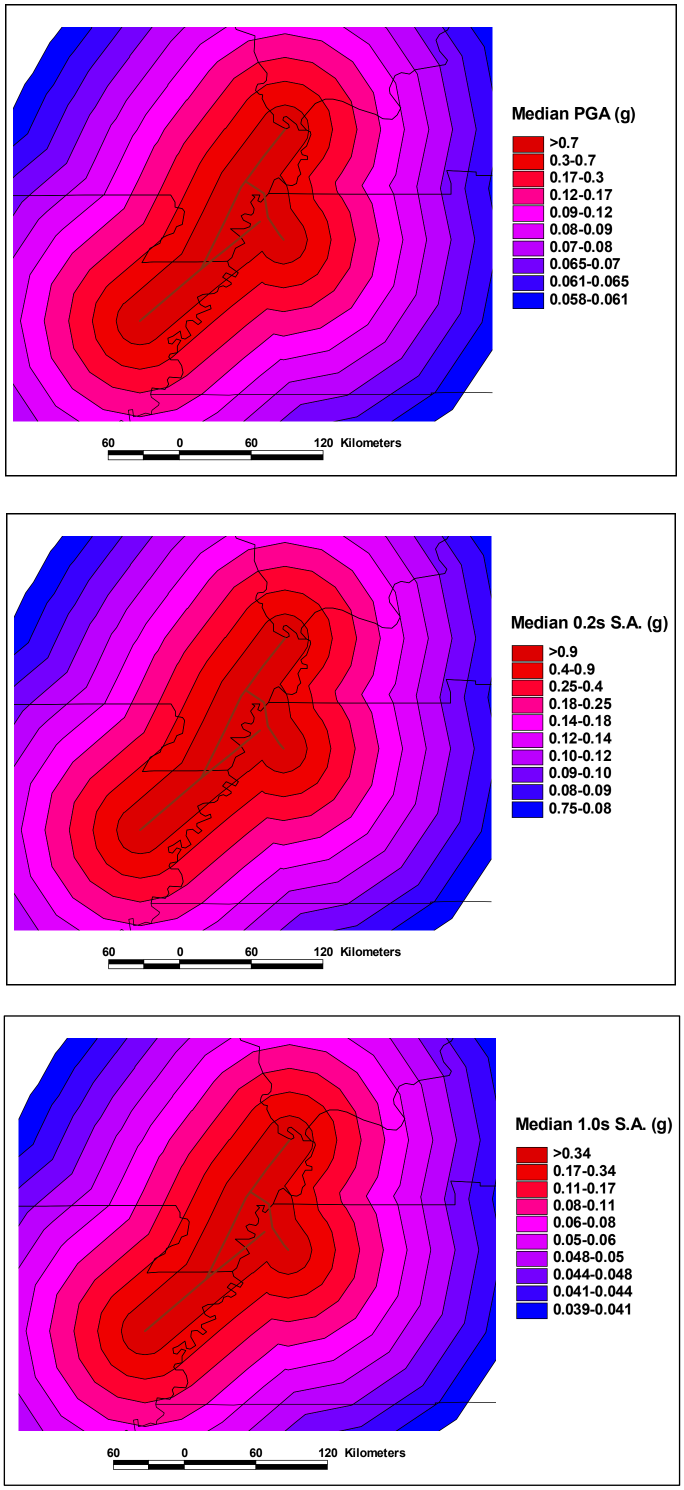

Figure 8. Median PGA (top), 0.2s S.A. (middle), and 1.0s S.A. (bottom) with 10 percent PE in 50 years for the New Madrid Seismic Zone. The New Madrid faults of Johnston and Schweig (1996) and attenuation relationship of Campbell (2003) were used.

Discussion

Estimating seismic hazard and risk depends both on the definition of hazard and the definition of risk. In general terms, the hazard is the intrinsic natural occurrence of earthquakes and the resulting ground motion and other effects, whereas the risk is the danger the hazard poses to life and property. Because many different definitions of hazard and risk can be used, the resulting estimates can differ dramatically. For example, seismic risk was originally defined in terms of the probability of a given level of strong shaking occurring in a year or a time interval (Cornell, 1968; Milne and Davenport, 1969). This definition of seismic risk has become definition of seismic hazard in PSHA (Frankel, 2004, 2005), however. Hence, a clear definition of hazard and risk is needed in any discussion of hazard and risk.

In this paper seismic risk is defined as the probability of one or more (at least one) earthquakes with magnitudes equal to or greater than a specific size, or ground motion generated by the earthquakes in a certain period of time; whereas seismic hazard as one or more (at least one) earthquakes with magnitudes equal to or greater than a specific size, or ground motion generated by the earthquakes, recurring in a time interval. These definitions are consistent with those of Cornell (1968) and Milne and Davenport (1969). These definitions are also consistent with those defined in hydraulic engineering (Gupta, 1989) and wind engineering (Sacks, 1978).

A new method (SHA) for estimating seismic hazards (ground motions) at a point of interest is porposed. SHA is similar to the procedure described by Cornell (1968), but there is one important difference: Cornell (1968) treated the uncertain focal distance (distance between the focus and site) as an independent term with a probability density function and incorporated the uncertainty directly into hazard analysis, but in our procedure this uncertainty (at least part of it) is implicitly included in the ground-motion attenuation relationships (Atkinson and Boore, 1995; Frankel and others, 1996; Toro and others, 1997; Somerville and others, 2001; Campbell, 2003). For example, the uncertainty in focal depth was treated as an aleatory uncertainty in the attenuation relationship of Toro and others (1997). The uncertainty (epistemic uncertainty) in the attenuation relationship of Campbell (2003) depends on the rupture distance. The uncertainty of the focal distance may be counted twice in the hazard calculation if the uncertainty is explicitly included (Klügel, 2005). Therefore, it would be more appropriate to directly use the ground-motion attenuation relationship to estimate the hazards (ground motions) at a point of interest.

For the New Madrid area, there are at least 13 ground-motion attenuation relationships available (EPRI, 2003), and all of them were developed from theoretical models with or without calibration from limited ground-motion records from small earthquakes (< M6.0). There is no unique way to use these attenuation relationships in seismic hazard analysis (SSHAC, 1997). SHA can be easily applied to any one or all of them. No matter how these ground motion attenuation relationships are used, as either a single one or multiple ones with assigned weights (logic-tree), SHA will explicitly provide hazard estimates with associated uncertainties.

The hazard curves derived through SHA are similar to those derived through flood-frequency and wind-frequency analyses and have the same meaning. Therefore, use of SHA in risk analysis is appropriate. SHA also provides hazard (ground motion) estimates that are consistent with the state of knowledge. The U.S. Geological Survey (2002) estimated the probability of a repeat of the 1811–1812 earthquakes with magnitude of M7.5–8.0 to be 7 to 10 percent PE in 50 years (risk). This estimate was based on an average recurrence interval of about 500 years, interpreted from paleoliquefaction records (Tuttle and others, 2002). Use of SHA results in risk estimates (Fig. 8) that are consistent with the estimates of the U.S. Geological Survey (2002).

Acknowledgment

This research is in part supported by a grant from the U.S. Department of Energy, contract no. DE-FG05-03OR23032. We thank Meg Smath of the Kentucky Geological Survey for editorial help. We appreciate comments and suggestions from Seth Stein, Stephane Mazzotti, and two anonymous reviewers, which helped to improve the manuscript greatly.

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