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## ***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. 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 ( $M = 7.0$  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 hazard is defined as the natural phenomenon generated by earthquakes, such as ground motion, and is quantified by two parameters: a level of hazard and its occurrence frequency or mean recurrence interval; seismic risk is defined as the probability of occurrence of a specific level of seismic hazard over a certain time and is quantified by three parameters: probability, a level of hazard, and exposure time. Probabilistic seismic hazard analysis (PSHA), a commonly used method for estimating seismic hazard and risk, 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 interval of earthquakes and the uncertainty of ground motion. Therefore, it is difficult to understand and use PSHA. A new method is proposed and applied here 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.

**Keywords:** New Madrid seismic zone, seismic hazard, seismic risk, probabilistic seismic hazard analysis, seismic hazard assessment.

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## 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 ( $M$  7.0–8.0) and the 1886 Charleston, South Carolina, earthquake ( $\sim M$  7.3) both occurred in intraplate regions. Geologic records (paleoliquefaction data) also show that large earthquakes have occurred in other intraplate

regions in eastern North America, such as the Wabash Valley (Obermeier et al., 1991; Obermeier, 1998). The causes of these large intraplate earthquakes are not well understood (Braile et al., 1986; Zoback, 1992; Newman et al., 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



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

Madrid, Missouri, was the closest settlement to the epicenters of the 1811–1812 earthquakes. Between 1811 and 1812, at least three large earthquakes, with magnitudes estimated between  $M = 7.0$  and  $8.0$ , occurred during a 3 mo 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.

In this paper, I first review probabilistic seismic hazard analysis (PSHA), the most commonly used method for estimating seismic hazard and risk. I then develop a new method, called seismic hazard assessment (SHA), and apply it to the New Madrid seismic zone.

## PROBABILISTIC SEISMIC HAZARD ANALYSIS

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 et al., 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 Cornell's (1971) and McGuire's (1995, 2004) formula for multiple sources, an annual probability of exceedance ( $\gamma$ ) of a ground-motion amplitude  $y$  is

$$\gamma(y) = \sum_j v_j P_j[Y \geq y] = \sum_j v_j \iint P_j[Y \geq y | m, r] f_{M,j}(m) f_{R,j}(r) dm dr, \quad (1)$$

where  $v_j$  is the activity rate for seismic source  $j$ ;  $f_{M,j}(m)$  and  $f_{R,j}(r)$  are earthquake magnitude and source-to-site distance density functions, respectively; and  $P_j(Y > y | m, r)$  is the probability ground motion  $Y$  exceeds a specific level  $y$  conditioned at a given  $m$  and  $r$ . The conditional exceedance probability  $P_j(Y > y | m, r)$  is equal to the exceedance probability of the ground-motion uncertainty (a log-normal distribution) as

$$P_j[Y \geq y | m, r] = 1 - \int_0^y \frac{1}{\sqrt{2\pi}\sigma_{\ln,y}} \exp\left(-\frac{(\ln y - \ln y_{mr})^2}{2\sigma_{\ln,y}^2}\right) d(\ln(y)), \quad (2)$$

where  $y_{mr}$  and  $\sigma_{\ln,y}$  are the median and standard deviation (log) determined by the ground-motion attenuation relationships (Campbell, 1981, 2003). Earthquakes in the intraplate regions are rare and can be described as a characteristic: the large and damaging earthquakes repeat regularly with few or no moderate and small earthquakes. For characteristic seismic sources, we have

$$\gamma(y) = \sum_j \frac{1}{T_j} \left\{ 1 - \int_0^y \frac{1}{\sqrt{2\pi}\sigma_{\ln,y}} \exp\left(-\frac{(\ln y - \ln y_{mr})^2}{2\sigma_{\ln,y}^2}\right) d(\ln(y)) \right\}, \quad (3)$$

where  $T_j$  is the average recurrence interval of the characteristic earthquake for source  $j$ . As shown in Equations 1 and 3, PSHA generally 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 et al., 1996, 2002).

As shown in Equation 3, the annual probability of exceedance,  $\gamma$ , 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,

$$\gamma(y) = \frac{1}{T} \left\{ 1 - \int_0^y \frac{1}{\sqrt{2\pi}\sigma_{\ln,y}} \exp\left(-\frac{(\ln y - \ln y_{mr})^2}{2\sigma_{\ln,y}^2}\right) d(\ln(y)) \right\}. \quad (4)$$

Figure 2 shows a peak ground acceleration (PGA) hazard curve (A) and probability density of PGA for a hypothetical characteristic earthquake of  $M = 7.5$  with an average recurrence interval of 500 yr at a point 20 km from the epicenter. According to Equation 4, 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  $\times$  0.5). For an annual probability of exceedance of 0.0004 (or return period of 2500 yr), 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 (uncertainty).

The inverse of annual probabilities of exceedance ( $1/\gamma$ ), called return period ( $T_p$ ), is also often used (Frankel et al., 1996, 2002),

$$T_p(y) = \frac{T}{1 - \int_0^y \frac{1}{\sqrt{2\pi}\sigma_{\ln,y}} \exp\left(-\frac{(\ln y - \ln y_c)^2}{2\sigma_{\ln,y}^2}\right) d(\ln(y))}. \quad (5)$$

For example, a 2500 yr 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 they can 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 2500 yr return period (Frankel et al., 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 yr (input). The ground motion will not occur in 2500 yr because it is a consequence of the earthquake; rather, it will have a 20% probability of being exceeded

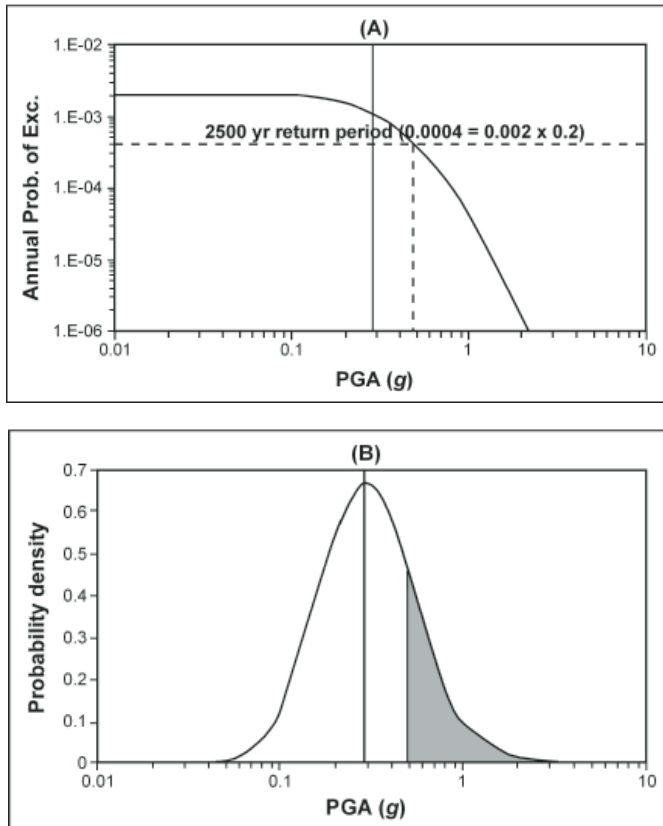


Figure 2. (A) Hazard (annual probability of exceedance) curve for a hypothetical characteristic earthquake of  $M = 7.5$  with average recurrence interval of 500 yr at a point 20 km from the epicenter. (B) Probability density (median peak ground acceleration [PGA] of 0.3g and a standard deviation [log] of 0.6 are assumed).

when the earthquake occurs in 500 yr. 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 it 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 the conclusions reached by the Aki Committee was that “the aggregated results of PSHA are not always easily related to the inputs” (NRC, 1988, p. 5). 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,

p. 1275). Wang et al. (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.

Frankel (2005, p. 474) offered a physical explanation for ground motion with a 2500 yr return period from a characteristic earthquake with a 500 yr recurrence interval. He stated “one of the five earthquakes expected to occur over the 2500 years will produce ground motions at that site greater than the 2% PE in 50 years (2500-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 2500 yr) is  $\sim 0.67$  ( $p \approx 1 - [1 - 0.2]^5$ ), not 1.0. This means that the PGA with a 2500 yr return period may not occur. An explanation similar to Frankel’s was offered by Holzer (2005) for ground motion with a 2500 yr return period from three characteristic earthquakes. Holzer’s explanation also contradicts the basics of PSHA (Wang, 2005).

As pointed out by Hanks (1997, p. 369), “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% probability of exceedance (PE) in 50 yr, are commonly considered in engineering design. In engineering risk analysis, a ground motion with 10%, 5%, or 2% PE in 50 yr means that a particular ground motion (an event) will occur at least once in 500, 1000, or 2500 yr (recurrence intervals) (Cornell, 1968; Milne and Davenport, 1969; Wang and Ormsbee, 2005; Wang et al., 2005). As shown by Frankel et al. (1996, 2002) and Frankel (2004), the ground motion with 2% PE in 50 yr is equivalent to the ground motion with a return period of 2500 yr (or annual probability of exceedance of 0.0004) derived from PSHA. As discussed earlier, the ground motion with a 2500 yr return period does not mean it will occur in 2500 yr; 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 yr 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 Wyssession, 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 Wyssession, 2003), the probability of  $n$  earthquakes of interest in an area or along a fault occurring during an interval of  $t$  years is

$$p(n, t, \tau) = \frac{e^{-t/\tau} (t/\tau)^n}{n!}, \quad (6)$$

where  $\tau$  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

$$p(0, t, \tau) = e^{-t/\tau}. \quad (7)$$

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

$$p(n \geq 1, t, \tau) = 1 - p(0, t, \tau) = e^{-t/\tau} = 1 - (1 - 1/\tau)^t. \quad (8)$$

Equation 8 can be used to calculate the risk, expressed as  $x\%$  PE in  $Y$  years, for a given recurrence interval ( $\tau$ ) of earthquakes with a certain magnitude or greater. For example, the U.S. Geological Survey (2002) estimated a 7%–10% probability of a repeat of the 1811–1812 New Madrid earthquakes ( $M$  7.5–8.0) in 50 yr in the New Madrid region. This estimate was determined from Equation 8 and an average recurrence interval of ~500 yr, which was inferred from interpretation of paleoliquefaction records (Tuttle et al., 2002). Equation 8 can also be used to calculate the average recurrence interval ( $\tau$ ) of earthquakes with a certain magnitude or greater for a given risk level. For

example, 10%, 5%, and 2% PE in 50 yr are commonly used in earthquake engineering (BSSC, 1998; ICC, 2000). According to Equation 8, these risk levels are equivalent to 500, 1000, and 2500 yr recurrence intervals for earthquakes. For comparison, 1% PE in 1 yr and 2% PE in 1 yr are being considered for building designs for flood and wind, respectively (ICC, 2000). These risk levels are equivalent to 100 and 50 yr recurrence intervals for floods (100 yr flood) and wind storms, respectively.

In practice, knowledge of 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 (SA) in a given period are common measurements needed for a site. This is similar to the situation in flood and wind analyses whereby knowledge of 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 ( $\tau$ ), 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 here for developing a relationship between a ground-motion parameter and its recurrence interval (i.e., seismic hazard curve).

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

$$\text{Log}(N) = a - bM \text{ or } N = 10^{(a - bM)}, \quad (9)$$

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 8 has the same meaning as  $N$ . Therefore,

$$1/\tau = N = e^{2.303a - 2.303bM} \text{ or } 1/\tau = N = e^{-2.303a + 2.303bM}. \quad (10)$$

Estimations of the expected ground motion at a site are given 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

$$\text{Ln } Y = a_0 + f(M, R) + \varepsilon, \quad (11)$$

where  $\varepsilon$  is uncertainty ( $a_0$  is a constant). The uncertainty ( $\varepsilon$ ) can be modeled using a log-normal distribution with a standard deviation

( $\sigma$ ). From Equation 11,  $M$  can be expressed as a function of  $R$ ,  $\ln Y$ , and  $\epsilon$ :

$$M = f(R, \ln Y, \epsilon) \cdot (12)$$

Combining Equations 10 and 12 results in:

$$1/\tau = e^{2.303a - 2.303bf(R, \ln Y, \epsilon)} \text{ or } \tau = e^{-2.303a + 2.303bf(R, \ln Y, \epsilon)} \cdot (13)$$

Equation 13 describes a relationship between the ground motion ( $\ln Y$ ) with an uncertainty ( $\epsilon$ ) and its annual recurrence rate ( $1/\tau$ ) or recurrence interval ( $\tau$ ) at a distance ( $R$ ), i.e., a hazard curve. Equation 13 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  $M \geq 4.0$  known to have occurred in the New Madrid seismic zone (Bakun and Hopper, 2004). Two  $M 4.0$  earthquakes that occurred in 2003 have also been included in Table 1. As shown in the table, there is only one event with  $M = 6.0$  since the last 1811–1812 events, the 1843 Marked Tree, Arkansas, earthquake. This

TABLE 1. EARTHQUAKES WITH MAGNITUDE EQUAL TO OR GREATER THAN 4.0 IN THE NEW MADRID SEISMIC ZONE (FROM BAKUN AND HOPPER, 2004)

Date	Latitude (°N)	Longitude (°W)	M
16 December 1811	36.00	89.96	7.6
16 December 1811 "dawn"	36.25	89.50	7.0
23 January 1812	36.80	89.50	7.5
05 January 1843	35.90	89.90	6.2
17 February 1843	35.90	89.90	4.2
17 August 1865	35.54	90.40	4.7
19 November 1878	35.65	90.25	5.0
11 January 1883	36.80	89.50	4.2
04 November 1903	36.59	89.58	4.7
28 October 1923	35.54	90.40	4.1
07 May 1927	35.65	90.25	4.5
17 September 1938	35.55	90.37	4.4
02 February 1962	36.37	89.51	4.2
03 March 1963	36.64	90.05	4.7
17 November 1970	35.86	89.95	4.1
25a March 1976	35.59	90.48	4.6
25b March 1976	35.60	90.50	4.2
04 May 1991	36.56	89.80	4.1
30 April 2003	35.920	89.920	4.0
06 June 2003	36.87	88.98	4.0

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 4.0 and 5.0 in the New Madrid seismic zone (Stein and Newman, 2004). The  $a$  and  $b$  values are estimated to be  $\sim 3.15$  and  $1.0$ , respectively. The  $b$  value of  $1.0$  is consistent with that used in the national seismic hazard maps (Frankel et al., 1996, 2002). Figure 3 also shows that recurrence intervals

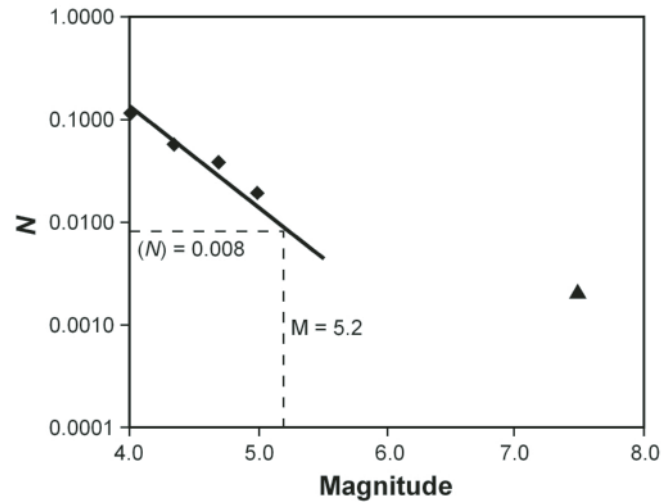


Figure 3. Magnitude-frequency (Gutenberg-Richter) curve for the New Madrid seismic zone. Diamond—historical rate, triangle—geological (paleoliquefaction) rate.

for large earthquakes ( $M \geq 6.0$ ) would be quite long,  $\sim 700$  yr for  $M 6.0$ ,  $7000$  yr for  $M 7.0$ , and  $70,000$  yr for  $M 8.0$ , if these  $a$  and  $b$  values are assumed to be applicable for large earthquakes in the New Madrid seismic zone. This is not consistent with paleoseismic interpretations by Tuttle et al. (2002): an average recurrence interval of  $\sim 500$  yr 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 et al., 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  $M 5.5$  (Fig. 2), and (2) the large earthquake ( $M 7.6$ ) is characteristic. For  $a = 3.15$  and  $b = 1.0$ :

$$1/\tau = e^{7.254 - 2.303M} \text{ for } 4.0 \leq M \leq 5.5 \cdot (14)$$

Equation 14 describes a hazard curve in terms of earthquake magnitude and its annual recurrence rate. For  $M = 4.85$ , Equation 14 results in an annual recurrence rate ( $1/\tau$ ) of  $\sim 0.02$  or a recurrence interval ( $\tau$ ) of  $50$  yr, which means that at least one earthquake with magnitude equal to or greater than  $4.85$  would be expected to occur in  $50$  yr. Similarly, Equation 14 results in an annual recurrence rate of  $\sim 0.01$  or a recurrence interval of  $100$  yr if  $M = 5.15$ . Hence, according to Equation 8, we can calculate risks for the New Madrid area; i.e., there is about a  $63\%$  PE in  $50$  yr that the area will be hit by at least one earthquake with  $M = 4.85$  or greater, and about a  $39\%$  PE in  $50$  yr that the area will be hit by at least one earthquake with  $M = 5.15$  or greater.

The estimated risk of a large earthquake ( $\sim M 7.5$ ) hitting the New Madrid area is  $\sim 10\%$  PE in  $50$  yr (USGS, 2002). Figure 4 is the earthquake probability (risk) map for the New Madrid area

generated from the U.S. Geological Survey earthquake hazard Web site (eqint.cr.usgs.gov/eq/html/eqprob.html).

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

$$\ln Y = c_1 + f_1(M) + f_2(M, r_{\text{rup}}) + f_3(r_{\text{rup}}) + \varepsilon_a + \varepsilon_e, \quad (15)$$

where  $r_{\text{rup}}$  is the closest distance to fault rupture,  $\varepsilon_a$  is aleatory (randomness) uncertainty, and  $\varepsilon_e$  is epistemic uncertainty. For  $r_{\text{rup}} \leq 70$  km, PGA of 0.2, and SA of 1.0 s:

$$\ln(\text{PGA}) = 0.0305 + 0.633M - 0.0427(8.5 - M)^2 - 1.591 \ln R + (-0.00428 + 0.000483M)r_{\text{rup}} + \varepsilon_a + \varepsilon_e, \quad (16)$$

$$\ln(\text{SA}_{0.2s}) = -0.4328 + 0.617M - 0.0586(8.5 - M)^2 - 1.320 \ln R + (-0.00460 + 0.000337M)r_{\text{rup}} + \varepsilon_a + \varepsilon_e, \quad (17)$$

$$\ln(\text{SA}_{1.0s}) = -0.6104 + 0.451M - 0.2090(8.5 - M)^2 - 1.158 \ln R + (-0.00255 + 0.000141M)r_{\text{rup}} + \varepsilon_a + \varepsilon_e, \quad (18)$$

and

$$R = \sqrt{r_{\text{rup}}^2 + [c_7 \exp(c_8 M)]^2}. \quad (19)$$

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

$$\sigma_{\ln Y} = \begin{cases} c_{11} + c_{12}M & \text{for } M < 7.16 \\ c_{13} & \text{for } M \geq 7.16 \end{cases}. \quad (20)$$

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

By combining the ground-motion attenuation relationships (Equations 16, 17, and 18) and the Gutenberg-Richter relationship (Equation 14), 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 ( $\varepsilon = 0.0$ ) hazard curves for PGA, 0.2 s SA, and 1.0 s SA at a site 30 km from the source. As shown already, there is significant uncertainty ( $\sigma \approx 0.66\text{--}0.90$ ) in the predicted ground motions, and the uncertainty depends on magnitude and distance.

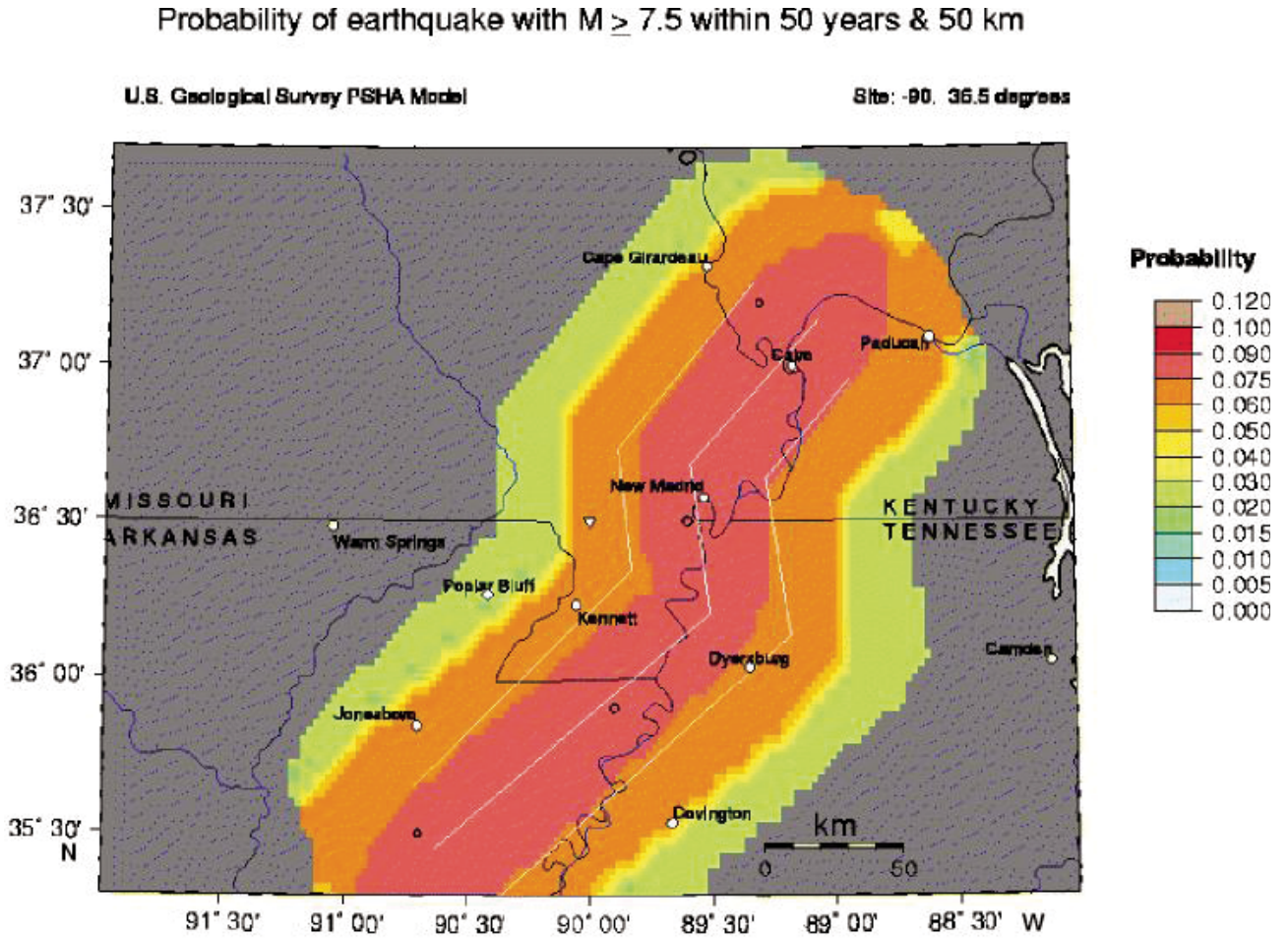




TABLE 2. COEFFICIENTS  $c_7$ ,  $c_8$ ,  $c_{11}$ ,  $c_{12}$ , AND  $c_{13}$  OF CAMPBELL'S (2003) ATTENUATION

Coefficients	PGA	0.2 s SA	1.0 s SA
$c_7$	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

Note: PGA—peak ground acceleration; SA—response acceleration.

The uncertainty can be estimated in the hazard analysis by adding a total uncertainty ( $\epsilon \neq 0.0$ ) to the attenuation relationship. Also shown in Figures 5, 6, and 7 are the hazard curves with 16% and 84% confidence levels (i.e.,  $\pm 1\sigma$ ). These hazard curves (Figs. 5, 6, and 7) are similar to those derived in 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  $\sim 0.07g$  has an annual recurrence rate of 0.008, or recurrence interval of 125 yr. This PGA (0.07g) could occur at least once in a 125 yr period because it is a consequence of an earthquake with magnitude equal to 5.2 or greater (Fig. 3).

As shown in Figures 5–7, the median ground motions with the annual recurrence rate of 0.002 are significant: 0.44g PGA, 0.59g 0.2 s SA, and 0.26g 1.0 s SA, respectively. According to these results, the characteristic earthquake (M 7.0–8.0) is of safety concern in the New Madrid area. The risk posed by the characteristic earthquake is  $\sim 10\%$  PE in 50 yr. There is no knowledge on large earthquakes or ground motions generated by the earthquakes that have recurrence intervals much longer than 500 yr in the New Madrid area. In another words, there is no information on the earthquakes or ground motions with PE much

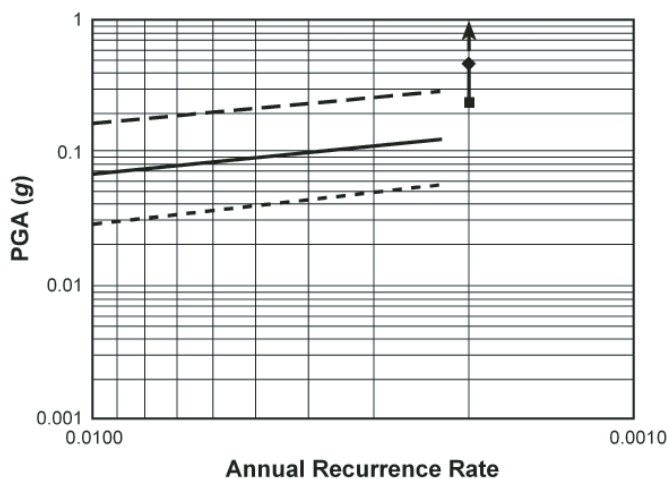


Figure 5. Peak ground acceleration (PGA) hazard curves at a site 30 km from the New Madrid faults. Diamond—median (mean) PGA, square—PGA with 16% confidence, and triangle—PGA with 84% confidence from the characteristic earthquake of M = 7.5.

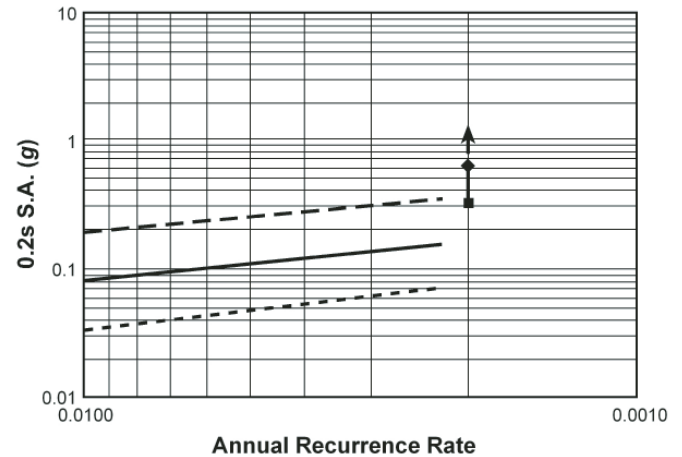


Figure 6. Hazard curves for 0.2 s response acceleration (SA) at a site 30 km from the New Madrid faults. Diamond—median (mean) 0.2 s SA, square—0.2 s SA with 16% confidence, and triangle—0.2 s SA with 84% confidence from the characteristic earthquake of M = 7.5.

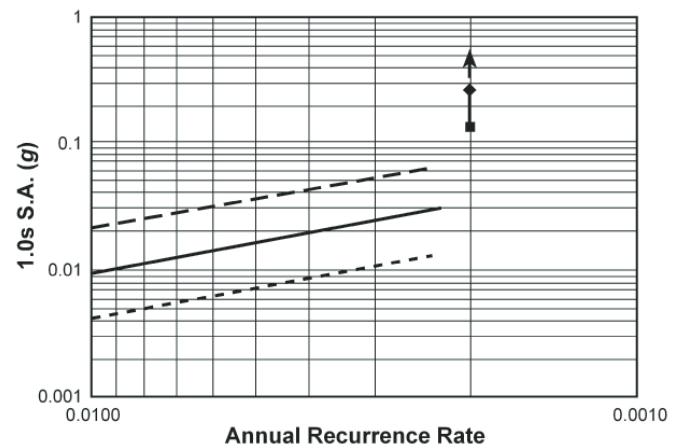


Figure 7. Hazard curves for 1.0 s response acceleration (SA) at a site 30 km from the New Madrid faults. Diamond—median (mean) 1.0 s SA, square—1.0 s SA with 16% confidence, and triangle—1.0 s SA with 84% confidence from the characteristic earthquake of M = 7.5.

less than 10% in 50 yr, such as 2% PE or less in 50 yr, in the New Madrid area. However, PSHA has derived the ground motions with 2% or less PE in 50 yr (Frankel et al., 1996, 2002; Frankel, 2005). These ground motions are numerically created by using the ground-motion uncertainty.

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 13. For example, for the annual recurrence rate of 0.002 or 10% PE in 50 yr, PGA and SA can be generated according to Equation 13 using a ground-motion attenuation relationship, such as Campbell's (2003) attenuation relationship. Figure 8 shows median PGA, 0.2 s SA, and 1.0 s SA maps for the New Madrid area.

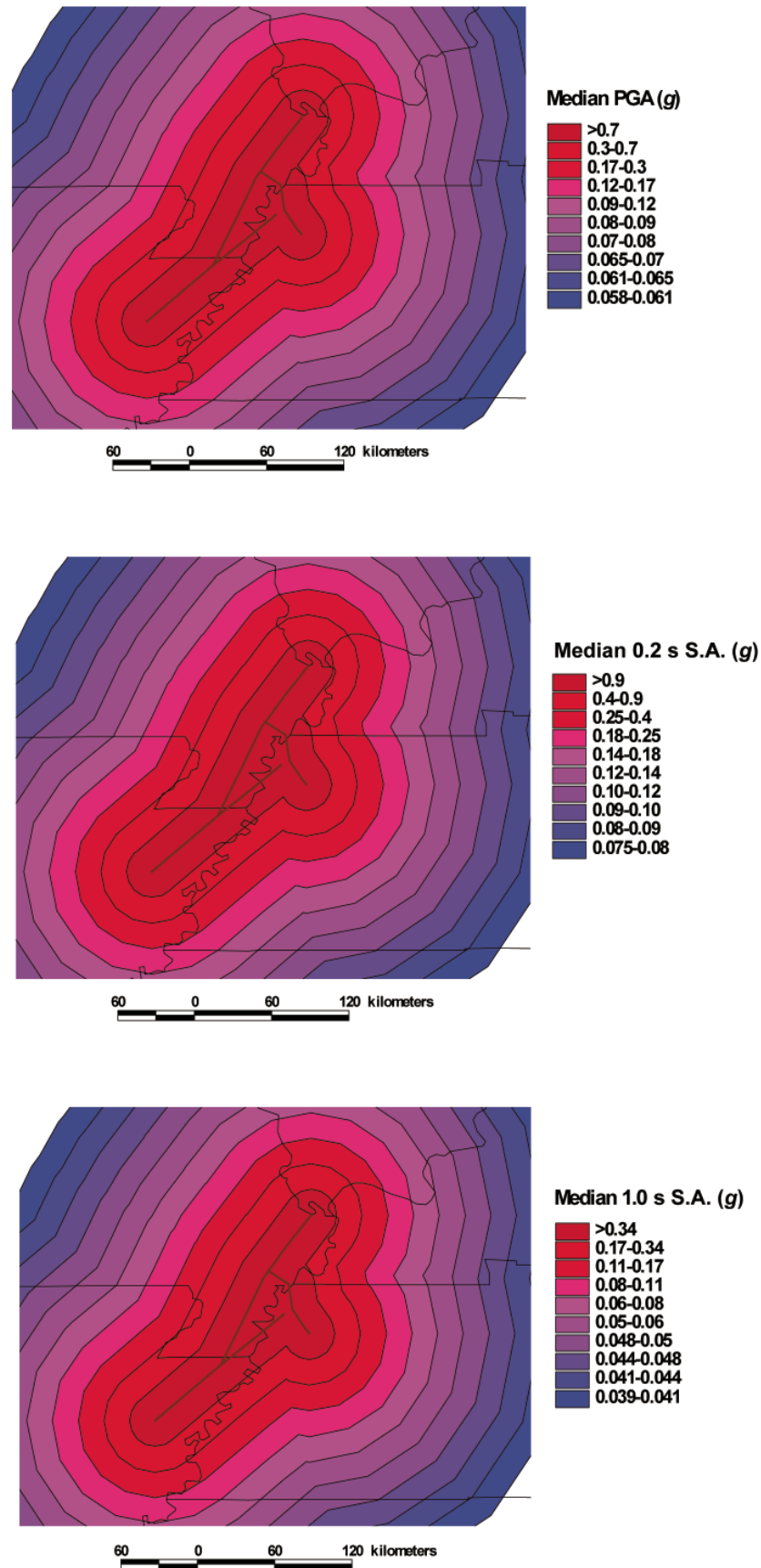


Figure 8. Median peak ground acceleration (PGA) (top), 0.2 s response acceleration (SA) (middle), and 1.0 s SA (bottom) with 10% PE in 50 yr for the New Madrid seismic zone. The New Madrid faults of Johnston and Schweig (1996) and attenuation relationship of Campbell (2003) were used.

## DISCUSSION

Estimations of seismic hazard and risk depend 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 the 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 the occurrence 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; seismic hazard is defined 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). Although PSHA has been widely used in seismic hazard and risk assessments, the return period derived from PSHA is not an independent temporal parameter but a mathematical extrapolation of the recurrence interval of earthquakes and the uncertainty of ground motion. Thus, PSHA is not appropriate for use in seismic hazard and risk assessments (Wang and Ormsbee, 2005).

A new method (SHA) for estimating seismic hazards (ground motions) at a point of interest is proposed here. 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 et al., 1996; Toro et al., 1997; Somerville et al., 2001; Campbell, 2003). For example, the uncertainty in focal depth was treated as an aleatory uncertainty in the attenuation relationship of Toro et al. (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 ( $M < 6.0$ ). 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 7.5–8.0 to be 7–10% PE in 50 yr (risk). This estimate was based on an average recurrence interval of ~500 yr, interpreted from paleoliquefaction records (Tuttle et al., 2002). The SHA method results in risk estimates (Fig. 8) that are consistent with the estimates of the U.S. Geological Survey (2002).

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