The Geological Society of America
Special Paper 493
2012

A critique of probabilistic versus deterministic seismic hazard analysis with special reference to the New Madrid seismic zone

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ABSTRACT

Scientific understanding of earthquakes in the New Madrid seismic zone has advanced greatly in recent years, but these advances have resulted in neither better assessment of seismic hazard and risk nor better mitigation policy. The main reasons for this are (1) misunderstanding about the National Seismic Hazard Maps and (2) confusion about seismic hazard and risk. Seismic hazard and seismic risk are two fundamentally different concepts, even though they have often been used interchangeably. Both are used differently in policy decision making, but seismic risk is the deciding factor, not seismic hazard.

Even though the input parameters are scientifically sound, we contend that the National Seismic Hazard Maps produced for the New Madrid region are flawed because they were produced from probabilistic seismic hazard analysis (PSHA). PSHA is scientifically flawed: As a complex computer model, it could not pass a simple sensitivity test with a single input earthquake, and the annual probability of exceedance (i.e., exceedance probability in *one* year and a dimensionless quantity) has been erroneously interpreted and used as the annual frequency or rate of exceedance (i.e., the number of event exceedances per year and a dimensional quantity). Thus, the seismic hazard and resulting seismic risk estimates from PSHA can be viewed as artifacts, and the mitigation policies developed, the NEHRP (National Earthquake Hazards Reduction Program) provisions and resulting building codes in particular, are problematic.

Scenario seismic hazard analysis is a more appropriate approach for seismic hazard assessment, seismic risk assessment, as well as policy development in the New Madrid region.

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Wang, Z., and Cobb, J.C., 2012, A critique of probabilistic versus deterministic seismic hazard analysis with special reference to the New Madrid seismic zone, *in* Cox, R.T., Tuttle, M.P., Boyd, O.S., and Locat, J., eds., Recent Advances in North American Paleoseismology and Neotectonics East of the Rockies: Geological Society of America Special Paper 493, p. 259–275, doi:10.1130/2012.2493(13). For permission to copy, contact editing@geosociety.org.

INTRODUCTION

Recent earthquakes, particularly the 2010 Haiti and Chile earthquakes and the 2011 New Zealand and Japan earthquakes, have demonstrated that mitigation—better seismic design for buildings, bridges, and other infrastructure—is the most effective way to reduce seismic risk and avoid earthquake disasters. The Haiti earthquake (M 7.0) resulted in more than 220,000 deaths from massive building collapse, whereas the Chile earthquake (M 8.8) resulted in fewer than 200 deaths from building collapse. The low number of fatalities during the Chile earthquake was because of good seismic provisions for buildings. There was no major building collapse during the Japan earthquake (M 9.0) because of stringent seismic provisions for buildings; the great loss of life was caused by the tsunami generated by the quake (Takewaki, 2011). Building collapse during the M 6.1 New Zealand earthquake killed ~200 people (a surprisingly high number when considering mitigation efforts) due to strong ground shaking and widespread liquefaction (Hamburger and Mooney, 2011).

Development of mitigation policies, such as seismic provisions in building codes, is a complex process. For example, the NEHRP (National Earthquake Hazards Reduction Program) Recommended Provisions for Seismic Regulations for New Buildings and Other Structures, developed by the Building Seismic Safety Council (1998, 2004, 2009), became a national standard widely used by federal, state, and local governments as well as nongovernment organizations. As shown in Figure 1, the process for developing the NEHRP provisions is complex—It started with the National Seismic Hazard Maps, which depict ground-motion hazard in terms of the annual frequency or rate of exceeding a level of ground motion (Frankel et al., 1996, 2002; Petersen et al., 2008). Then, a group of engineers, seismologists, and others, using the maps and engineering science, developed a set of recommendations, including design ground motions, for seismic regulations for new buildings and other structures (BSSC, 1998, 2004, 2009). These recommendations were endorsed by the Federal Emergency Management Agency and thus became federal policy, with associated regulations, for seismic safety in the United States. The recommendations were also adopted by many state and local governments, as well as nongovernment organizations such as the International Building Code Council and the American Society of Civil Engineers, resulting in the International Building Code (IBCC, 2000) and ASCE/SEI 7–10 (2010).

Adoption of the NEHRP recommendations has created a disincentive for construction in some communities in the central and eastern United States, however, particularly in the New

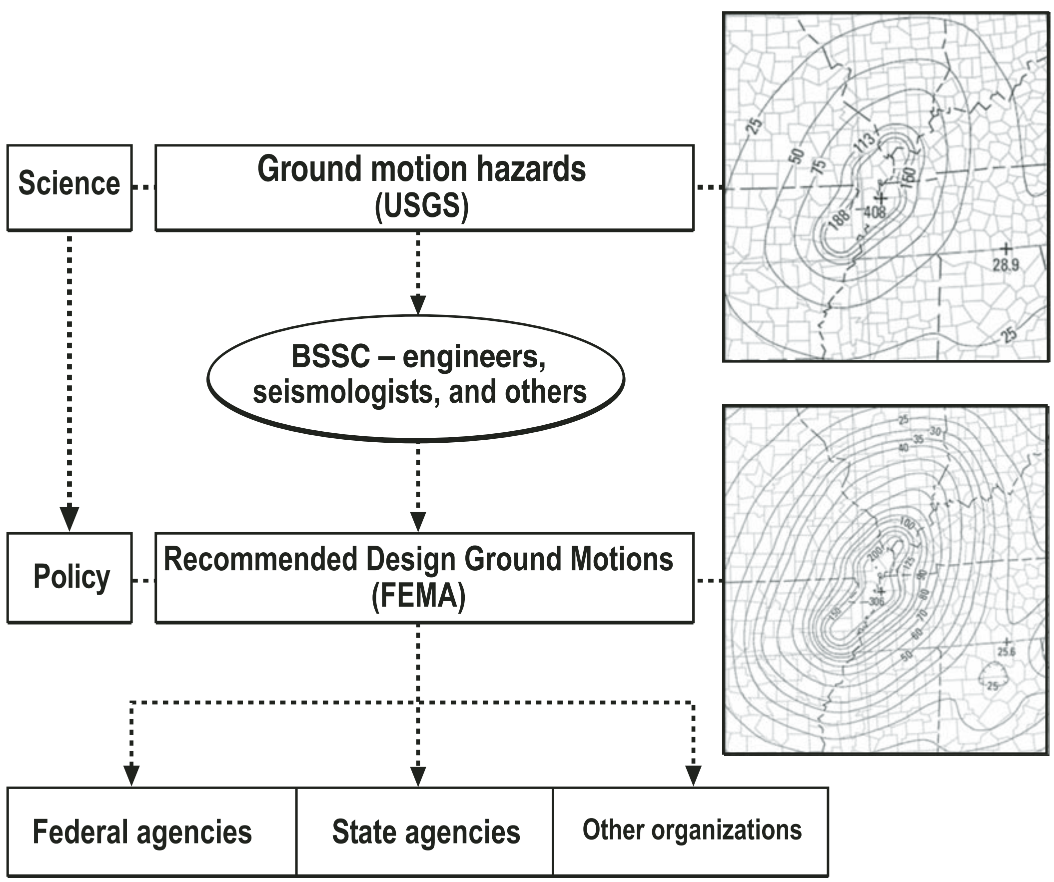

Figure 1. Flowchart for development of the National Earthquake Hazards Reduction Program recommended provisions. BSSC—Building Seismic Safety Council; FEMA—Federal Emergency Management Agency; USGS—U.S. Geological Survey.

Madrid region. For example, peak ground acceleration (PGA) of 0.8*g* would have to be considered for seismic design of a landfill at the Paducah Gaseous Diffusion Plant near Paducah, Kentucky, if the NEHRP hazard maps were used (Beavers, 2010). This high design ground motion required the U.S. Department of Energy to significantly strengthen its application for a permit from federal or state regulators to construct the landfill. The Structural Engineers Association of Kentucky (2002) found that if the International Residential Code of 2000 were adopted in Kentucky without revision, constructing residential structures in westernmost Kentucky, including Paducah, would require enlisting a design professional. The recommended seismic provisions in the building code for Memphis–Shelby County (MSC), Tennessee, had to be amended (2005 MSC Building Code of the 2005 Technical Codes for Memphis and Shelby County, Tennessee), as well as the recommended design ground motion for the residential building code for western Kentucky (SEAOK, 2002). The encumbrances on construction caused by the NEHRP provisions have led to intense debate, especially about the National Seismic Hazard Maps (Frankel, 2003, 2004, 2005; Stein et al., 2003a, 2003b; Wang, 2003, 2005a; Wang et al., 2005; Stein, 2010). At the heart of this debate is the simple question: How could the New Madrid region have a higher ground-motion hazard than the San Francisco Bay Area or Los Angeles?

The debate has attracted national attention. The Advisory Committee on Earthquake Hazards Reduction convened on 9 November 2010 in Memphis to address the concerns about the NEHRP recommendations. In a statement, ACEHR (2011, p. 1) acknowledged "the local community concerns," and stated that they assign "a high priority to addressing the issues raised about the high hazard levels and attendant costs" and recommended that "the NEHRP agencies engage other earthquake professionals in making a clear and defendable statement of current seismic risk and goals for reducing that risk in the New Madrid region." The statement also specifically recommended an examination of "the high hazard levels in USGS [U.S. Geological Survey] maps via an independent review for the New Madrid area" and recommended exploring "ways to improve communication of the hazards and their effects on structural design."

In response, the National Earthquake Prediction Evaluation Council organized an independent expert panel to review the current high earthquake hazard assigned to the New Madrid seismic zone (NMSZ). The Independent Expert Panel on New Madrid Seismic Zone Earthquake Hazards (2011, p. 1) released a report stating that "the lack of knowledge concerning the physical processes that govern earthquake recurrence intervals in the central United States, and whether large earthquakes will continue to occur at the same intervals as the previous three clusters of events," is the fundamental problem. The panel concluded that "evolution in our knowledge will change the estimated hazard from New Madrid main shocks in the next round of seismic hazard calculations; we infer that there are several factors that might reduce the estimated hazard." Furthermore, "it is likely that the estimated NMSZ hazard may decline moderately in the next hazard assessment due to improved knowledge of past earthquakes and current deformation." In other words, the panel expected the estimated hazard in the New Madrid seismic zone to be lower in the next round of hazard assessment.

This chapter examines seismic hazard and risk assessments and the science behind them, the methodologies used, and the policy implications for the New Madrid region. The goal is to facilitate the development of more effective mitigation policies.

SEISMIC HAZARD AND RISK

Risk is a term used in everyday decision making, in situations ranging from purchasing health insurance, to investing in a 401(k), to building a nuclear power plant, to fighting terrorism, to declaring war. An important associated term is *hazard.* Although hazard and risk have been used interchangeably, they are fundamentally different. Hazard is a natural or manmade phenomenon that has the potential to cause harm (i.e., social or economic consequences). Hurricanes, earthquakes, tornadoes, and floods are natural hazards, and car crashes, chemical spills, train derailments, and terror attacks are manmade hazards. Risk, on the other hand, is the probability of harm if someone or something is exposed to a hazard. Thus, seismic hazard is a natural phenomenon, such as ground shaking, fault rupture, or soil liquefaction, that is generated by an earthquake, whereas seismic risk is the probability that humans will incur loss or their built environment will be damaged if they are exposed to a seismic hazard (Reiter, 1990; McGuire, 2004; Wang, 2009, 2011). Seismic risk is an interaction between a seismic hazard and exposure of humans or their built environment. It can be expressed conceptually as

$$\textit{Seismic Risk} = \textit{Seismic Hazard} \times \textit{Exposure}. \tag{1}$$

As shown in Equation 1, high seismic hazard does not necessarily mean high seismic risk, and vice versa. There is no risk if there is no exposure, even if there is a high seismic hazard. Likewise, engineering design or a policy for seismic hazard mitigation may differ from one for seismic risk reduction. Seismic hazard may not be mitigated, but seismic risk can always be reduced by reducing exposure.

The differences between seismic hazard and risk, as well as their policy implications, are illustrated in Figure 2: Massive rockfalls (seismic hazards) were triggered by the main shock and aftershocks of the 2008 Wenchuan, China, earthquake (M 7.9) while a car and two pedestrians (exposures) were passing through the road section shown in the photo. The car driver and two pedestrians were taking a risk: possibly being injured or killed by rockfalls when they passed through the road section. The rockfall hazard may be difficult, even impossible, to mitigate along this road, but the risk (i.e., the possibility of injury and death) can always be reduced by reducing exposure (i.e., limiting traffic or pedestrians). There will be no risk if a driver decides not to drive or pedestrians decide not to walk on the road (i.e., no exposure). In general, seismic hazard such as fault rupture and

Figure 2. A comparison of seismic hazard and seismic risk. Seismic hazard: earthquake-triggered rockfalls. Exposure: car and its driver, and pedestrians. Seismic risk: the probability of being struck by a rockfall during the period that the car or pedestrians pass through the road section.

ground motion cannot be mitigated, and reducing exposure could also be difficult. Thus, the best way to reduce seismic risk is to reduce vulnerability (i.e., inability to withstand the effects of a seismic hazard) of the exposure, i.e., strengthen the built environment through better seismic design and construction. In other words, the most effective way to reduce seismic risk and avoid earthquake disaster is better seismic design and construction for buildings, bridges, and other infrastructure.

Seismic hazard and risk are conceptually (i.e., qualitatively) different. They play different roles in decision making. Furthermore, seismic risk is more important than seismic hazard in decision making. In order to make more informed or effective decisions, quantification is necessary. Seismic hazard is quantified through seismic hazard assessment, whereas seismic risk is quantified through seismic risk assessment.

Seismic Risk Assessment

Quantification of seismic risk is very complex and somewhat subjective, and it requires joint efforts from seismologists, engineers, and others. Seismic risk quantification not only depends on the desired physical measurements (e.g., magnitude, ground motion, fatalities, or economic loss), but also on the ways in which the hazard and exposure interact in time and space. Hazard and exposure could interact at a specific site (site-specific risk) or over an area (aggregated risk) (Malhotra, 2008). In order to estimate seismic risk, a model has to be assumed to describe the ways in which the hazard and exposure interact in time; several models, such as the Poisson, empirical, Brownian passage time, and time-predictable, have been used. Different models result in different estimations.

Currently, the most commonly used model in engineering risk assessment is the Poisson distribution. Under the Poisson assumption, an exposure (e.g., building) to a seismic hazard (e.g., a ground motion) is constant over the exposure's life t; seismic risk, expressed in terms of a probability P_T that the seismic hazard with a certain level or greater could occur at the exposure, can be estimated by

$$P_T = 1 - e^{-\frac{t}{\tau}}, \tag{2}$$

where τ is the average recurrence interval, or 1/τ is the average recurrence frequency of the seismic hazard with a certain level or greater. Equation 2 describes a quantitative relationship between seismic hazard, in terms of a certain level or greater with an average recurrence interval τ or frequency 1/τ, and seismic risk, in terms of the probability that the seismic hazard with a certain level or greater could occur at the exposure within the exposure's life. Equation 2 is used for risk calculation in earthquake engineering (Cornell, 1968, 1971; Milne and Davenport, 1969; McGuire, 2004; Luco et al., 2007), hydraulic engineering (Gupta, 1989), and wind engineering (Sachs, 1978).

Equation 2 is derived from the interactions between the hazard and exposure in time and space only, without consideration of physical interactions. In other words, Equation 2 can only determine the probability that the exposure could experience a certain level of hazard, not its vulnerability (i.e., inability to withstand the effects of a seismic hazard) nor the related level of damage or economic loss. The physical interaction between seismic hazard and exposure is complicated and determined from a fragility analysis. For example, for certain buildings, there is a relationship between ground motion and damage level, expressed as a fragility curve (Kircher et al., 1997). The damage level can also be related to a level of economic loss or fatality. Thus, seismic risk, in terms of the probability P_D of a level of damage from the exposure by a seismic hazard, can be estimated from

$$P_D = P_T \cdot P_V = (1 - e^{-\frac{t}{\tau}})P_V, \quad (3)$$

where P_V is the exposure's vulnerability to damage (i.e., probability of damage vs. a level of ground motion). As shown in Equation 3, reducing vulnerability P_V through strengthening the built environment will reduce risk.

Seismic Hazard Assessment

As a natural phenomenon, seismic hazard is quantified by three parameters: level of severity (physical measurement), spatial (where), and temporal (how often) measurement (Reiter, 1990; McGuire, 2004; Wang, 2009, 2011). A seismic hazard assessment determines these three parameters using scientific information obtained from instrumental, historical, and geologic observations. For example, peak ground acceleration (PGA) of 0.3*g* with a repeat time of 100 yr in San Francisco is a quantitative description of seismic hazard. The rockfall hazard shown in Figure 2 can be quantified as the falling of a rock with a mean diameter of 0.5 m or greater with an average occurrence frequency of once every hour along that road section. Thus, earthquake science, normally conducted by earth scientists, is the basis for seismic hazard assessment.

Many types of hazards could be caused by an earthquake (fault rupture), and they can be separated into two categories: primary and secondary hazards. Primary hazards are surface rupture and ground motion that are caused directly by a fault rupture. Strong ground motion could trigger a secondary hazard, such as ground-motion amplification, liquefaction, or a landslide under certain site conditions at a specific site. As shown in Figure 2, the ground motions from the main shock and aftershocks of the Wenchuan earthquake (M 7.9) triggered rockfalls along the road section. Ground-motion hazard normally affects large areas, whereas surface rupture is limited during an earthquake. Thus, ground-motion hazard is the main focus of a seismic hazard assessment. The U.S. National Seismic Hazard Maps (Frankel et al., 1996, 2002; Petersen et al., 2008) and ground-motion hazard maps (Street et al., 1996; Wang et al., 2007) depict ground-motion hazards on rock, based on earthquake sources and ground-motion attenuation relationships for rock. Secondary seismic hazards can be assessed if ground motion (input) and site conditions are known (Street et al., 1997, 2001; Bauer et al., 2001; Broughton et al., 2001; Rix and Romero-Hudock, 2001; Cramer et al., 2004, 2006; Wang, 2008). Secondary hazard assessment is often conducted alone or in combination with assessment of the primary ground-motion hazard at a local level. This effort is also referred to as microzonation (Wang, 2008). This paper focuses on primary ground-motion hazard assessment.

Several methods are used for seismic hazard assessment. The two most commonly used are probabilistic seismic hazard analysis (PSHA) and deterministic seismic hazard analysis (DSHA). PSHA and DSHA use the same seismological and geologic information, but they define and calculate seismic hazard differently. In PSHA, seismic hazard is defined as the ground motion with an annual frequency or rate of exceedance, and it is calculated from a mathematical model based on statistical relationships of earthquakes and ground motion (McGuire, 2004; 2008). In DSHA, seismic hazard is defined as the median or certain percentile (e.g., 84%) ground motion from a single earthquake or set of earthquakes, and it is calculated from simple statistics of earthquakes and ground motion (Krinitzsky, 1995, 2002).

A key component of any seismic hazard assessment is the ground-motion attenuation relationship, called the ground-motion prediction equation (GMPE).

Ground-Motion Prediction Equation

GMPE is a statistical relationship between a ground-motion parameter *Y* [i.e., PGA, PGV peak ground velocity], MMI [modified Mercalli intensity], or PSA [pseudo-response acceleration] at different periods) and earthquake magnitude *M*, source-to-site distance *R*, and uncertainty or residual δ, defined as

$$\ln(Y) = f(M, R) + \delta. \quad (4)$$

GMPE predicts ground motions in space (i.e., a spatial relationship), developed from a statistical analysis of ground-motion observations and/or theoretical ground-motion simulations (Campbell, 1981, 2003; Atkinson and Boore, 2006). The ground-motion uncertainty δ is modeled as a normal distribution with a standard deviation, σ (Bazzurro and Cornell, 1999; Atkinson and Boore, 2006; Abrahamson and Silva, 2008; Strasser et al., 2009). Equation 4 can also be expressed as

$$\ln(Y) = f(M, R) + \varepsilon\sigma, \quad (5)$$

where ε is the normalized residual, which is also a normal distribution with a constant standard deviation of 1 (Wang, 2011). The source-to-site distance *R* is measured as the shortest distance either to the surface rupture (R_{RUP}) or to the surface projection of the rupture (R_{JB}) (Atkinson and Boore, 2006; Abrahamson and Silva, 2008). GMPE has become the most important component in seismic hazard assessment because of its role in probabilistic seismic hazard analysis.

Probabilistic Seismic Hazard Analysis

The basic concepts and formulations of PSHA were developed by Cornell (1968, 1971) and computer coded by McGuire (1976). Later, PSHA gained acceptance by earth scientists and engineers for seismic hazard and risk assessments. In 1988, a panel, chaired by the late professor K. Aki, was appointed by the National Research Council with the charge "to assess the capabilities, limitations, and future trends of probabilistic seismic hazard analysis (PSHA) in the context of alternatives" (National Research Council, 1988, p. 87). The National Research Council panel identified many limitations with PSHA, particularly in how to capture earth science information. The panel found that "because the 'aggregated' results of PSHA are not always easily related to the inputs, PSHA may also obscure the unknown and uncertainties of earth sciences data and may lead to an unwarranted sense of accuracy in the value" (National Research Council, 1988, p. 5). In other words, PSHA may produce results that are obscurely related to scientific inputs. This can be demonstrated through a hypothetical site with a single characteristic earthquake (Fig. 3). As shown in Figure 3B, PSHA produces PGAs with annual frequencies of exceedance from 0.002 to 10^{-9} (1/yr) from a single input earthquake. The reciprocal of the annual frequency of exceedance was defined as the return period and has been interpreted and used as "the mean (average) time between occurrences of a seismic hazard—for example, a certain ground motion at a site" (McGuire, 2004). Thus, PSHA could produce PGAs with return periods of 500 yr to a billion years from a single input characteristic earthquake of magnitude M 7.5 and recurrence interval of 500 yr. Similarly, Frankel (2004, 2005) showed that PSHA can produce many ground motions from a single characteristic earthquake in the New Madrid seismic zone and San Andreas fault.

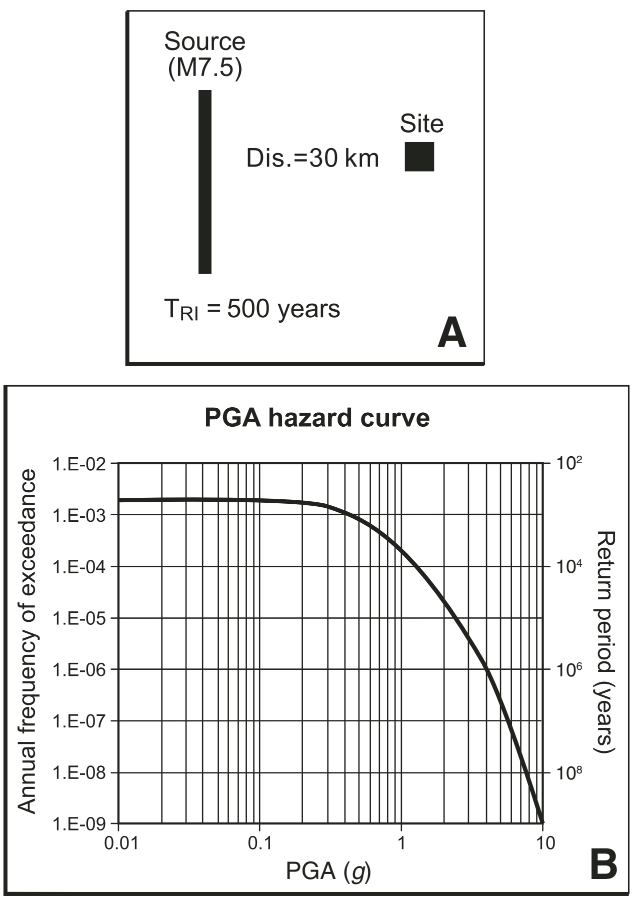

Figure 3. A hypothetical characteristic seismic source (A) and peak ground acceleration (PGA) hazard curve (B) at a site 30 km from the source.

However, one earthquake can generate only one ground motion at a site. For example, the 23 August 2011 Virginia earthquake (M 5.8) generated a strong ground motion that shook Washington, D.C., and damaged the Washington Monument (EERI, 2011). If the average recurrence interval of the Virginia earthquake (M 5.8) is 3000 yr, the return period (i.e., the average time between occurrences) of the ground motion generated by the earthquake at the Washington Monument must also be 3000 yr. From this perspective, the outputs (many ground motions) from a PSHA can be viewed as artifacts of the inputs (scientific data). As a computer model, PSHA cannot pass a simple sensitivity test with a single input earthquake, and it creates unknowns and uncertainties.

The unknowns and uncertainties related to PSHA have led to many disagreements about hazard estimates, such as those by the Lawrence Livermore National Laboratory and the Electric Power Research Institute in the early 1980s. In 1997, the Senior Seismic Hazard Analysis Committee was commissioned by the U.S. Nuclear Regulatory Commission, the U.S. Department of Energy, and the Electric Power Research Institute and charged "to review the present state-of-the art and improve on the overall stability of the PSHA process" (SSHAC, 1997, p. iii). The committee concluded that "many of the major potential pitfalls on executing a successful PSHA are procedural rather than technical in character" (SSHAC, 1997, p. xiv). The committee reviewed only the procedural implementation of PSHA. As a result, procedural guidelines, the SSHAC-97 guidelines, were established for executing a PSHA.

The most comprehensive PSHA studies, conducted according to the SSHAC-97 guidelines, have not always resulted in appropriate seismic hazard estimates, however. This was illustrated by the Yucca Mountain project (Stepp et al., 2001), which is the most comprehensive PSHA ever conducted according to SSHAC-97 guidelines in the United States. It resulted in extremely high ground-motion estimates for the Yucca Mountain nuclear waste repository: 11*g* PGA and 13 m/s peak ground velocity (PGV) at the rate of 10^{-8} per year or a return period of 100 m.y. (Hanks, 2011). These results triggered intense debates, discussion, and research by geologists, seismologists, and engineers, particularly among the top PSHA practitioners (Abrahamson and Bommer, 2005; McGuire et al., 2005; Abrahamson and Hanks, 2008). The ground-motion estimates were found to be inconsistent with precariously balanced rocks observed near the site and other geologic features (Brune and Whitney, 2000; Hanks, 2011). Brune and Whitney (2000) found that the Yucca Mountain region has not been subjected to ground acceleration larger than 0.3*g* during the last 75,000–80,000 yr, although the PSHA resulted in a PGA greater than 1.0*g* with a return period of ~80,000 yr (Stepp et al., 2001). The conclusion, after ~10 yr of debate and research, was that the ground motion for Yucca Mountain was overestimated (Abrahamson and Hanks, 2008; Hanks, 2011). Another comprehensive PSHA conducted in Switzerland using the SSHAC-97 guidelines also resulted in high ground-motion estimates and intense debate (Klügel, 2005a, 2005b, 2005c; Budnitz et al., 2005; Wang, 2005b). Thus, we contend it is not the procedural implementation of PSHA that causes the problems.

PSHA is a mathematical formulation derived from a rigorous probability analysis of the distribution of earthquake magnitudes, locations, and ground-motion attenuation (McGuire, 2008). As shown by Cornell (1968, 1971), the exceedance probability for a given ground motion *y* can be obtained from a probability analysis of GMPE (Eq. 5) for seismic source *j*:

$$P_j[Y \geq y] = \iint \{1 - \Phi(\frac{\ln y - \ln y_{mr}}{\sigma_j})\} f_{M,j}(m) f_{R,j}(r) dmdr, \quad (6)$$

where $\ln y_{mr} = f(m,r)$, $1 - \Phi(x)$ is the exceedance probability for ground-motion uncertainty δ, and $f_{Mj}(m)$ and $f_{Rj}(r)$ are the probability density functions (PDFs) for earthquake magnitude *M* and source-to-site distance *R*, respectively. $P_j[Y \geq y]$ describes the spatial uncertainty, because GMPE predicts ground motions in space. According to Cornell (1968, 1971), if earthquake occurrence in time follows a Poisson distribution with an average rate of v_j (per year) for seismic source *j*, Equation 2 can be used to estimate the probability that ground motion *Y* exceeds a given value *y* during a time interval of *t*:

$$P_{j,t}[Y \geq y] = 1 - e^{-P_j[Y \geq y] v_j t}. \quad (7)$$

For a small probability (say, ≤ 0.05), Equation 7 can be approximated (e.g., through the use of a Taylor series expansion) as

$$P_{j,t}[Y \geq y] \approx P_j[Y \geq y] v_j t. \quad (8)$$

For *t* = 1 yr, the annual probability of exceedance (i.e., the probability of exceedance in one year) is equal to

$$P_{j,t=1\,year}[Y \geq y] \approx v_j \cdot t(1\,year) P_j[Y \geq y] = v_j P_j[Y \geq y]. \quad (9)$$

As shown in Equation 9, the annual probability of exceeding a given ground motion at a site is approximately equal to the product of the annual probability for earthquakes, v_j (per year) × *t*(1 yr), and the exceedance probability for a given ground motion *y*, $P_j[Y \geq y]$. Thus, the total annual probability of exceedance for a given ground-motion *y* at a site from all seismic sources can be obtained from the "total probability theorem" (Cornell, 1968, 1971; McGuire, 2008) by

$$P_a[Y \geq y] = \sum_j v_j P[Y \geq y] = \sum_j v_j \iint \{1 - \Phi(\frac{\ln y - \ln y_{mr}}{\sigma_j})\} f_{M,j}(m) f_{R,j}(r) dmdr. \quad (10)$$

Equation 10 is derived under three preconditions:

1. Earthquake occurrence in time follows a Poisson distribution.
2. There is a small probability of occurrence (say, ≤0.05).
3. *t* = 1 yr.

In other words, Equation 10 is not mathematically valid if any of the three preconditions is not satisfied. Cornell (1968, 1971) defined the reciprocal of the annual probability of exceedance,

$$T_{RP} = \frac{1}{P_a[Y \geq y]} = 1/\{\sum_j v_j \iint [1 - \Phi(\frac{\ln y - \ln y_{mr}}{\sigma_j})] f_{M,j}(m) f_{R,j}(r) dmdr\}, \quad (11)$$

as the return period. Equations 10 and 11 are the core of PSHA (Cornell, 1968, 1971; McGuire, 2004, 2008).

As shown in Equation 9, the *annual* probability of exceedance is the exceedance probability in one year: a probability and dimensionless quantity. As defined in Equation 11, the return period T_{RP} is also a dimensionless quantity, because the reciprocal of a dimensionless quantity is still dimensionless. For example, the reciprocal of a probability of 0.01 (or 1%) is 100, which means the chance is 1 in 100. As implied by the title, *Engineering Seismic Risk Analysis*, Cornell (1968) defined the seismic risk as the annual probability of exceedance for a ground motion or intensity at a site. In other words, as it was developed by Cornell (1968), PSHA derives seismic risk estimate in terms of the annual probability of exceedance for a given ground motion at a site.

Unfortunately, the annual probability of exceedance has been erroneously interpreted and used as the annual frequency or rate of exceedance and a *dimensional quantity* with the unit of per year (1/yr), and the return period was erroneously interpreted as the average recurrence time with the unit of years in PSHA (McGuire, 2004, 2008). This error resulted from a simple mathematical mistake: forgetting the precondition of *t* = 1 yr (annual) shown in Equation 9. In other words, the unit of v_j (per year) has been cancelled out by the precondition of *t* = 1 yr, which is not written explicitly in Equations 10 and 11. This mathematical error was committed by Cornell (1968) and led to the seismic risk analysis, in terms of the annual probability of exceedance for a given ground motion at a site, becoming a seismic hazard analysis, in terms of the frequency or rate of exceedance for a given ground motion at a site. For example, the annual probabilities of exceedance of 0.002, 0.001, and 0.0004 have been erroneously used as the frequencies of 0.002, 0.001, and 0.004 per year (Frankel et al., 1996, 2002). The reciprocal of the annual probabilities of exceedance of 0.002, 0.001, and 0.0004 means that the chances of occurrence in one year are 1 in 500, 1000, and 2500, respectively, not the average recurrence times of 500, 1000, and 2500 yr. Similarly, the annual probability of exceedance of 10^{-8} means extremely low probability or that the chance of occurrence in one year is 1 in 100 million. However, the annual probability of exceedance of 10^{-8} was interpreted as a rate of 10^{-8} per year (Stepp et al., 2001; Hanks, 2011). Annual probability of exceedance and annual frequency (rate) of exceedance have been widely used interchangeably (Frankel, 2004, 2005; Independent Expert Panel on New Madrid Seismic Zone Earthquake Hazards, 2011; Kerr, 2011). We wish to emphasize that probability is a dimensionless quantity, and thus is not equivalent to frequency (a dimensional quantity with the unit of "per year"), and these terms should not be used interchangeably.

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." As shown in this section, PSHA produces outputs that are not consistent with earth science (scientific inputs), and its mathematics are inappropriate. Furthermore, recent studies also found that PSHA has other inherent problems (Anderson and Brune, 1999; Wang et al., 2003, 2005; Wang, 2007, 2011; Wang and Zhou, 2007). For example, PSHA, Equation 10, is developed from the assumption that earthquake occurrence in time follows a Poisson distribution. Earthquake occurrence, for large earthquakes in particular, does not follow a Poisson distribution. Also, PSHA is based on a single point-source model for earthquakes (Cornell, 1968), which is not valid for the large earthquakes that are of safety concern. A large earthquake is considered to be a complex finite fault rupture in modern seismology.

Therefore, we contend that PSHA is scientifically flawed, and its results are artifacts.

Deterministic or Scenario Seismic Hazard Analysis

Deterministic seismic hazard analysis (DSHA) has been widely used in seismic hazard assessment, especially for engineering purposes. DSHA develops a particular seismic scenario upon which a ground-motion hazard evaluation is based. The scenario consists of the postulated occurrence of an earthquake of a specified size at a specified location. DSHA uses four basic elements (Reiter, 1990; Krinitzsky, 1995, 2002):

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

For example, the ground motion specified for bridge design in California is partly determined by the deterministic ground motion from the maximum credible earthquake (Mualchin, 2011). The ground motion for building seismic design in coastal California is capped by a deterministic ground motion close to major fault sources (BSSC, 1998, 2009). DSHA has also been widely used in the New Madrid region for a variety of purposes. Street et al. (1996) and Wang et al. (2007) used DSHA to develop ground-motion hazard maps for bridge and highway seismic design in Kentucky. Haase and Nowack (2011) developed scenario ground-motion hazard maps for Evansville, Indiana.

DSHA determines the ground motion from a single or several scenario earthquakes that have maximum impact. It addresses the ground motion from individual (i.e., maximum magnitude, maximum probable, or maximum credible) earthquakes. Seismic hazard derived from DSHA has a clear physical and statistical meaning. Recent efforts in DSHA have focused on computer simulation for ground-motion hazard quantification (Wang et al., 2007; Irikura and Miyake, 2011; Zuccolo et al., 2011). The advantages of DSHA include:

1. The derived ground motion has an easily understood physical and statistical meaning.
2. The results are easily understood by earth scientists, engineers, and others.
3. It utilizes ground-motion simulation.

The biggest criticism of DSHA is that it "does not take into account the inherent uncertainty in seismic hazard estimation" (Reiter, 1990, p. 225), but actually DSHA accounts for all the inherent uncertainty explicitly for each scenario earthquake. For example, the maximum credible earthquake (MCE) ground motion is usually taken at a mean plus one standard deviation (i.e., 84th percentile) in the scatter of recorded earthquake ground motions (Krinitzsky, 1995, 2002; Silva and Darragh, 2011). The weakness of DSHA is that "frequency of occurrence is not explicitly taken into account" (Reiter, 1990, p. 225). The temporal characteristic of earthquakes (i.e., recurrence interval or frequency and its associated uncertainty) is not addressed, even though it is an integral part of seismic hazard and must be considered in engineering design and other policy considerations. As pointed out by Wang et al. (2004), however, a scenario earthquake can always be associated with a recurrence interval and its uncertainty. For example, the average recurrence interval of the New Madrid scenario earthquake is ~500–1000 yr (Haase and Nowack, 2011). This recurrence interval can be used to estimate seismic risk with Equations 2 and 3. Thus, DSHA contains/includes some elements of probability (Yeats et al., 1997).

SEISMIC HAZARD, RISK, AND MITIGATION POLICY

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, Missouri, was the closest settlement to the epicenters of a series of at least three large earthquakes during a 3 mo period in 1811–1812 (Nuttli, 1973). Although the New Madrid seismic zone has been well studied, particularly through the NEHRP program, the basic physical processes that govern earthquake recurrence are still not clear. For example, several models for New

Madrid earthquake occurrence have been proposed, including sequences initiated by erosion of Mississippi River sediments, glacial unloading, and thermal events from the upper mantle (Zoback, 1992; Newman et al., 1999; Kenner and Segall, 2000; Calais et al., 2010). The estimated magnitudes for the 1811–1812 earthquakes range from M 6.8 to 8.2, and the estimated recurrence intervals range from 500 yr to several thousand years (Nuttli, 1973; Tuttle et al., 2002; Hough and Page, 2011).

Only limited ground-motion recordings from moderate and strong earthquakes (M_W 4.5 to 6.0) are available to develop ground-motion prediction equations in the intraplate region of the central and eastern United States. So the GMPEs developed for this part of the country were developed from theoretical ground-motion simulations, constrained by limited observations from moderate to strong earthquakes (Somerville et al., 2001; Campbell, 2003; Atkinson and Boore, 2006; Wang and Lu, 2011).

The USGS Seismic Hazard Maps

The U.S. Geological Survey produced the National Seismic Hazard Maps, which display earthquake ground motions for various exceedance probability levels across the United States, including in the New Madrid seismic zone. The maps have been applied in seismic provisions of building codes, insurance rate structures, risk assessments, and other public policy. The maps were produced from a comprehensive consensus process involving many geologists, seismologists, engineers, and others (Frankel et al., 1996, 2002; Petersen et al., 2008). The first step in the process was to build an input database that reflects the scientific understanding of earthquakes. Figure 4 shows the input parameters for the New Madrid seismic zone (Petersen et al., 2008). The second step was to perform a PSHA to generate seismic hazard curves on a grid of sites across the United States. Figure 5 shows 0.2 s response acceleration hazard curves for Memphis, New Madrid, Paducah, and San Francisco from the 2008 national hazard mapping (Petersen et al., 2008). These curves provide a range of ground motion, from 0.001 to 5.0*g* for 0.2 s pseudo-response accelerations, versus a range of annual frequencies of exceedance, from 1.0 to 0.00001 (1/yr). Three points on the curves corresponding to annual frequencies of exceedance of 0.002, 0.001, and 0.0004 (1/yr) were picked to produce the National Seismic Hazard Maps (Petersen et al., 2008). Figure 5 shows New Madrid to have a higher ground-motion hazard than San Francisco at the annual frequency of exceedance of 0.0001 (1/yr) or less. The reciprocals of the annual frequencies of exceedance of 0.002, 0.001, and 0.0004 (1/yr), the return periods of 500, 1000, and

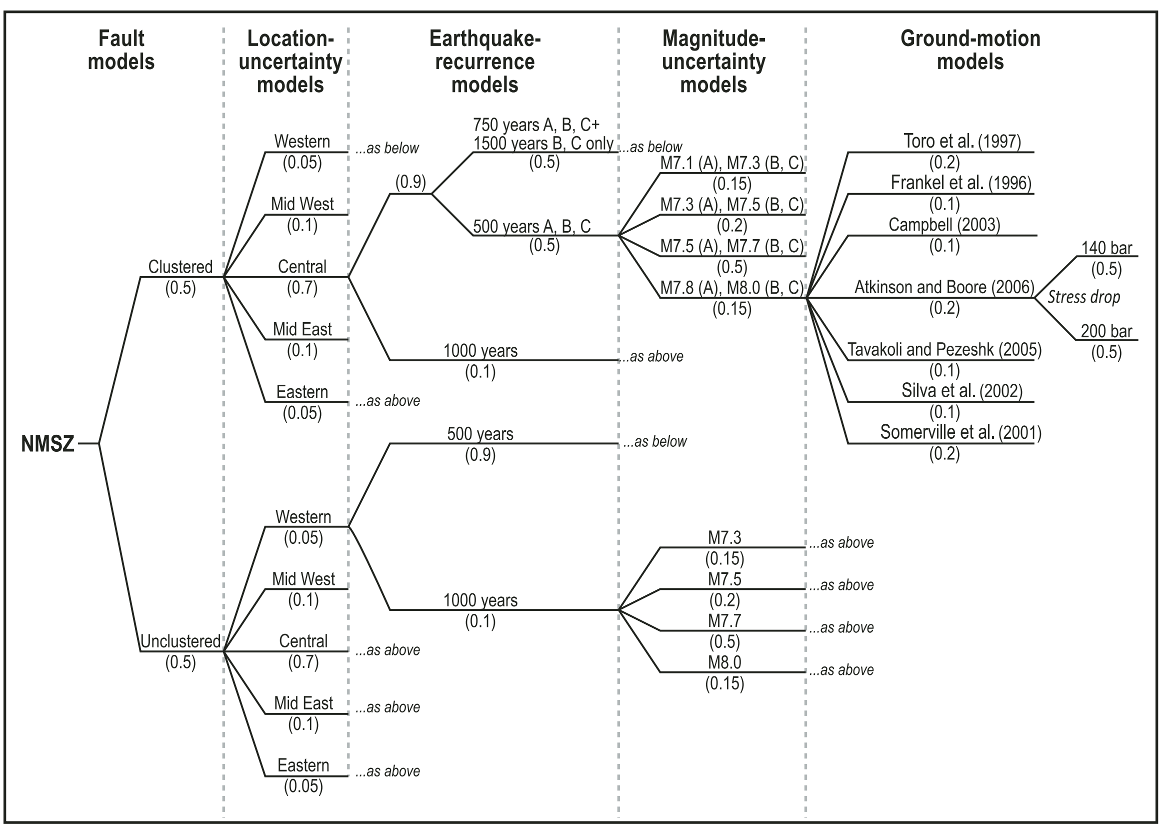

Figure 4. Input parameters (logic tree) for the New Madrid seismic zone (NMSZ) from Petersen et al. (2008).

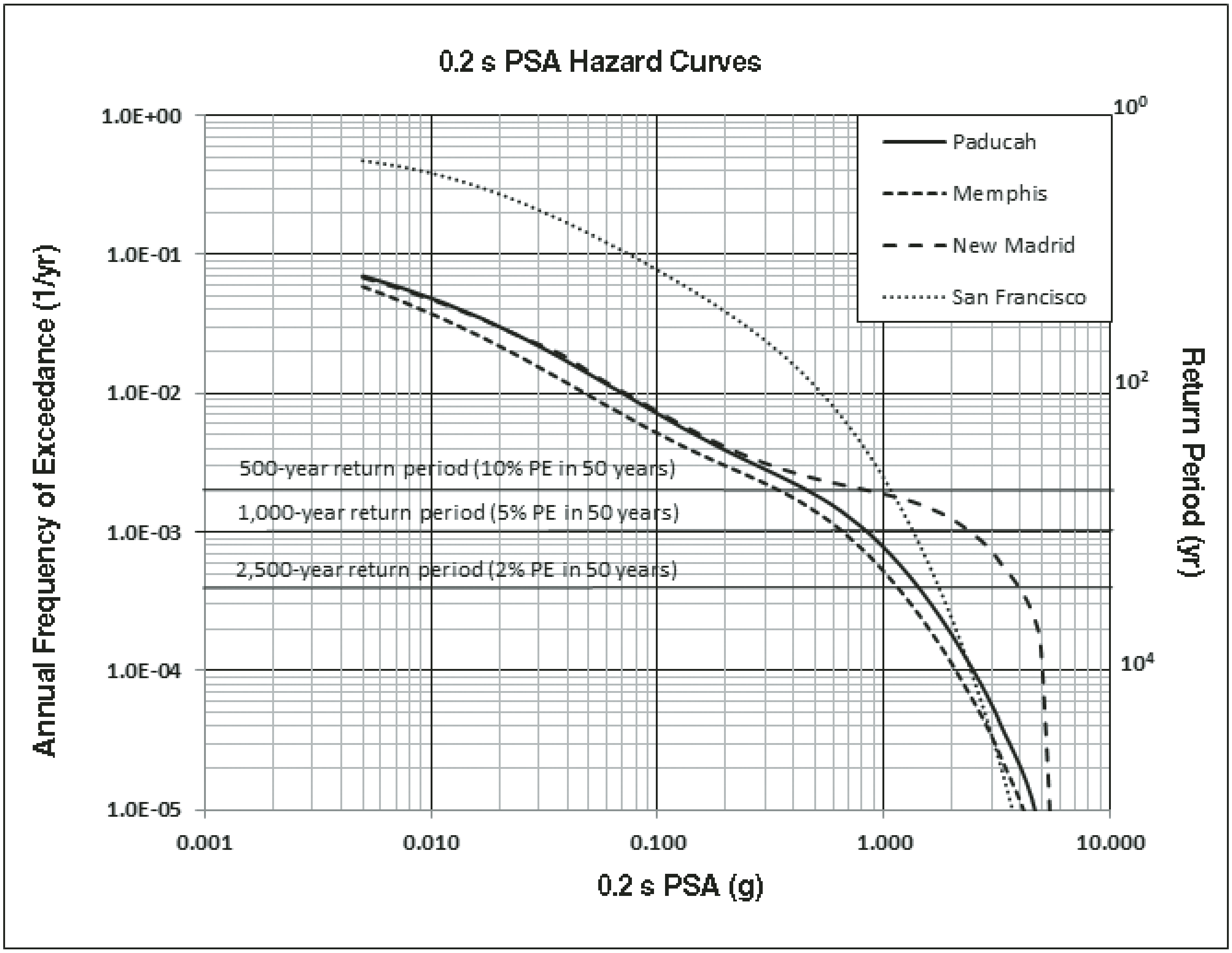

Figure 5. 0.2 s response acceleration hazard curves for Memphis (35.15°N, 90.05°W), New Madrid (36.25°N, 89.50°W), Paducah (37.10°N, 88.60°W), and San Francisco (37.80°N, 122.40°W) from the 2008 National Seismic Hazard Maps (Petersen et al., 2008). PE—probability of exceedance; PSA—pseudo-response acceleration.

2500 yr, were used to calculate seismic risk in terms of probabilities of exceedance of 10%, 5%, and 2% for buildings with an average life of 50 yr (Frankel et al., 1996, 2002; BSSC, 1998, 2009; Frankel, 2004, 2005; Petersen et al., 2008). The hazard curves have also been used to calculate mean annual frequency of building collapse and building collapse probability over a life of 50 yr (McGuire, 2004; Luco et al., 2007; BSSC, 2009).

As discussed earlier herein, PSHA determines the annual probability of exceedance for a given ground motion at a site. We contend that it is mathematically inappropriate to interpret and/or use the annual probability of exceedance as the annual frequency or rate of exceedance. It is also mathematically inappropriate to interpret and/or use the reciprocal of the annual probability of exceedance as the average time between occurrences of a given ground motion. Thus, we assert that the National Seismic Hazard Maps have not been understood and used correctly. Even though the input database is scientifically sound, the hazard curves and maps from the national seismic hazard mapping project (Frankel et al., 1996, 2002; Petersen et al., 2008) can be viewed as artifacts because they are produced from PSHA, which is not the appropriate scientific approach.

Therefore, the application of the National Seismic Hazard Maps for seismic provisions of building codes, insurance rate structures, risk assessments, and other public policy is problematic.

Scenario Seismic Hazard Map

Scenario or deterministic seismic hazards have been assessed in the New Madrid area. For example, Street et al. (1996), Wang et al. (2007), and Haase and Nowack (2011) developed ground-motion hazard maps corresponding to specific New Madrid earthquake scenarios. Figure 6 is a median PGA hazard map for

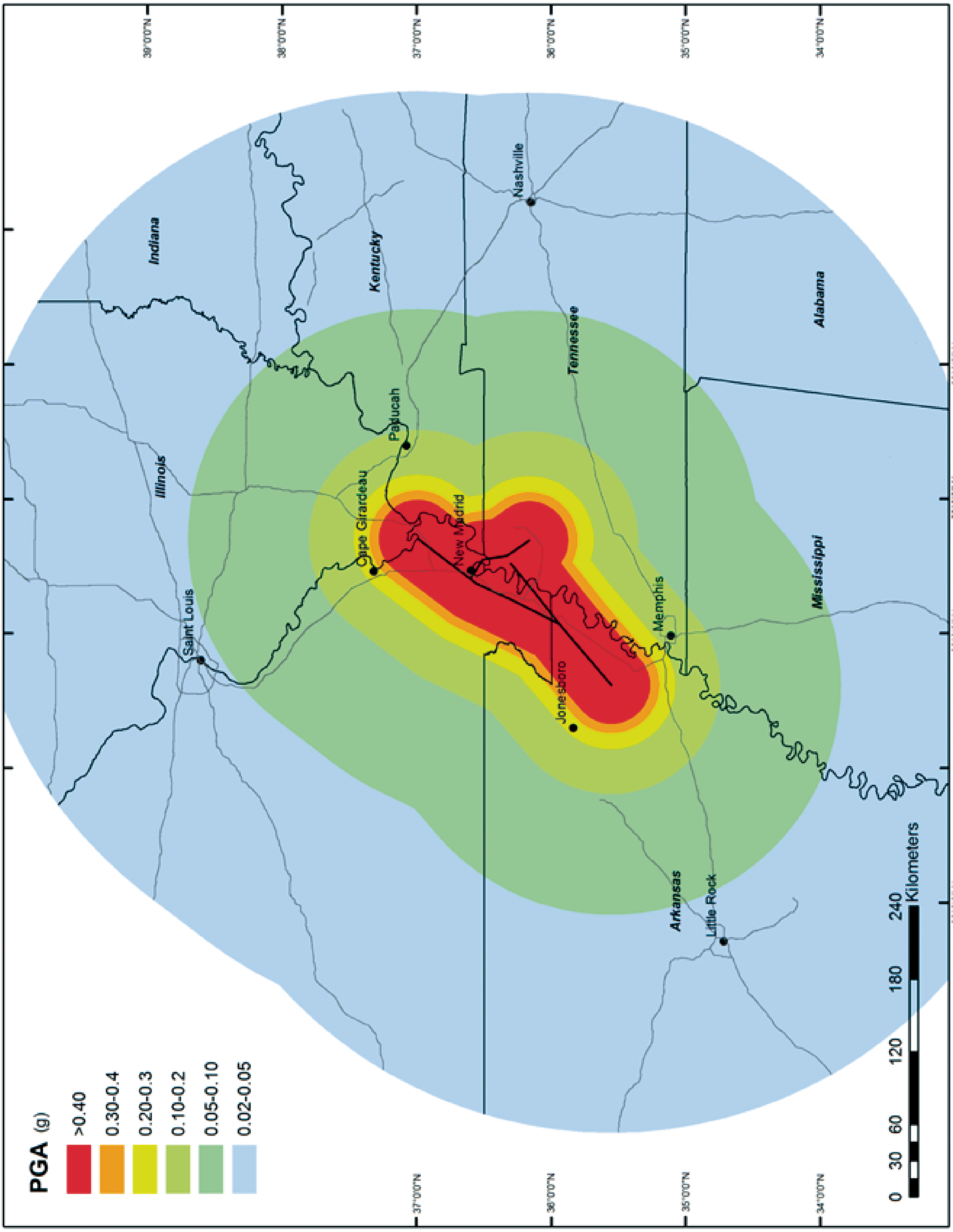

Figure 6. Peak ground acceleration (PGA; median) hazard map for a scenario earthquake of M 7.7 along the New Madrid faults of Johnston and Schweig (1996).

the New Madrid faults based on a scenario earthquake of M 7.7 with a recurrence interval of 500–1000 yr. Campbell's (2003) GMPE was used to produce the map. The map shows that Memphis and Paducah could experience a similar PGA of ~0.2*g* if the scenario earthquake occurs along the New Madrid faults. These scenario seismic hazard maps can be used for engineering seismic design and other policy considerations. For example, they have been used for seismic design of bridges and highway structures in Kentucky (Wang et al., 2007). The ground motion from a M 7.6 scenario earthquake in the New Madrid seismic zone was used for seismic design of a landfill at the Paducah Gaseous Diffusion Plant near Paducah, Kentucky (Beavers, 2010).

Seismic Risk and Mitigation Policy

Figure 7 compares the modified Mercalli intensity during the 1906 San Francisco earthquake (M 7.8) in the Bay Area with the intensity during the 1811–12 New Madrid earthquakes (M 7.7) in the central United States (USGS). The impact area was much larger for the central United States event than for the similar-magnitude event in California because ground motion attenuates much more slowly in the older and harder rocks in the central United States. This does not mean that the central United States has higher seismic hazards, however, because the earthquake occurrence frequencies are different. The occurrence frequency of the M 7.8 earthquake along the San Andreas fault is ~200 yr, and that of the M 7.7 earthquake along the New Madrid fault is ~500–1000 yr (Petersen et al., 2008). As shown in Figure 7, the Bay Area experiences either an earthquake of M 7.8 or intensity of MMI VIII about every 200 yr (Frankel, 2004), whereas the central United States experiences a similar earthquake or intensity about every 500–1000 yr. It is not a straightforward comparison in terms of seismic hazard between the Bay Area and the New Madrid area. In other words, seismic hazard information alone is not sufficient to make engineering or policy decisions.

As stated in the NEHRP provisions, "one of the goals of the Federal Emergency Management Agency (FEMA) and the National Earthquake Hazards Reduction Program (NEHRP) is to encourage design and building practices that address the earthquake hazard and minimize the resulting risk of damage and injury" (BSSC, 2009). Thus, seismic risk estimates are essential for policies to mitigate damage and injury. Consider seismic risk for two identical buildings with a normal life of 50 yr, one in San Francisco and one in Paducah (Fig. 7): If earthquake occurrence follows a Poisson distribution, Equation 2 can be used to estimate the probability that the buildings could be hit by an M 7.8 earthquake or experience MMI VIII intensity during their lives. The resulting probabilities are ~22% for the building in San Francisco and ~5%–10% for the building in Paducah. The building in San Francisco faces about two to four times higher risk than the same building in Paducah. In other words, the site-specific seismic risk (a single building) in San Francisco is two to four times higher than in Paducah. This site-specific risk comparison shows that it is not a good policy to require a similar or even higher design ground motion for a building in Paducah than in San Francisco.

A study by Scawthorn et al. (2006) shows that a repeat of the 1906 San Francisco earthquake (M 7.8) could cause more than $150 billion in losses (aggregated) in the Bay Area. Assuming rupturing of all three fault segments, a New Madrid earthquake of M 7.7 could cause more than $300 billion in losses (aggregated) (Elnashai et al., 2009). The resulting annualized loss due to these particular earthquake sources in the New Madrid region is $0.3 to $0.6 billion, and $0.75 billion in the Bay Area. The resulting risk in the New Madrid region is $300 billion with a 5%–10% probability in 50 yr, and $150 billion with 22% probability in 50 yr in the Bay Area. The San Francisco Bay Area has much more exposure than that in the New Madrid region. In the vicinity of

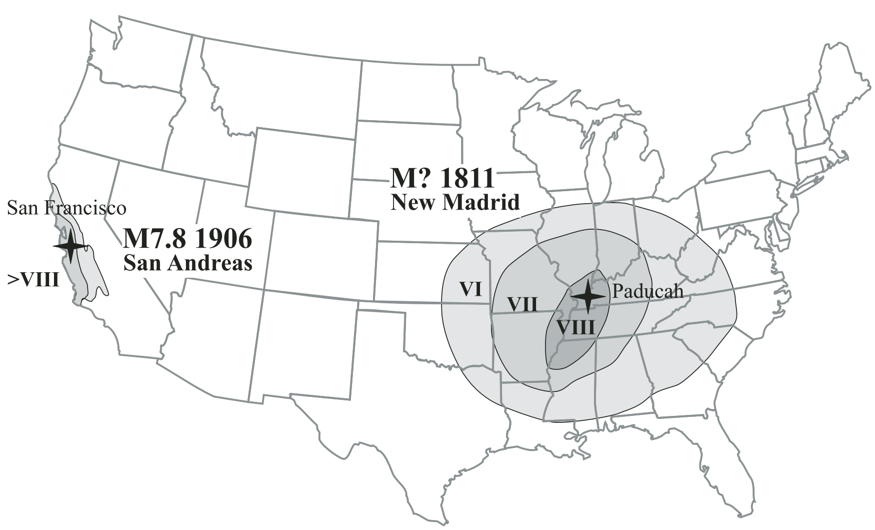

Figure 7. Seismic hazard and risk comparison between the New Madrid region and the San Francisco Bay Area, and seismic hazard and risk comparison between an identical building in San Francisco and Paducah.

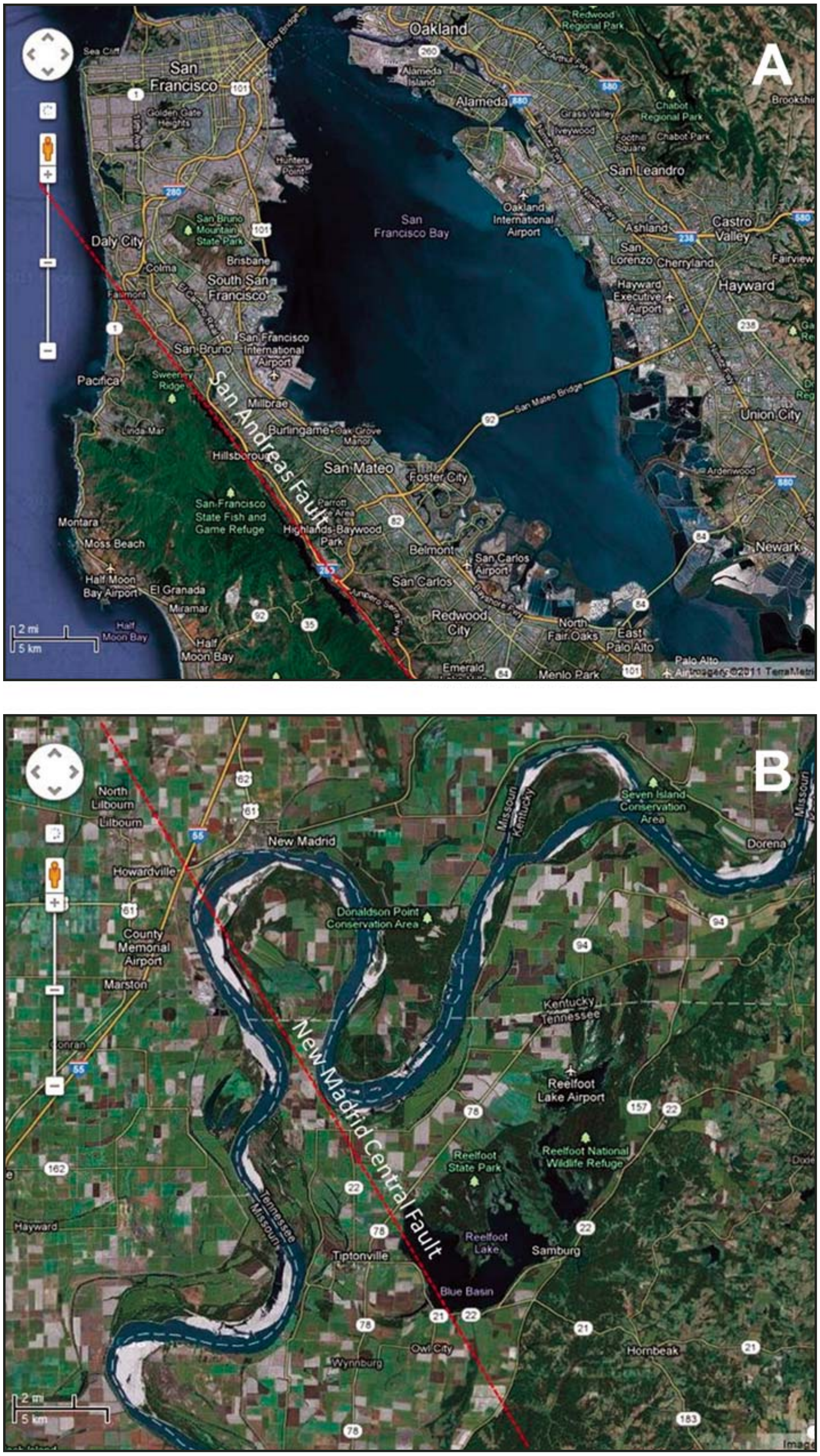

Figure 8. Google map comparison between the San Francisco Bay Area (A) and the central New Madrid area (B). The red dashed line shows the location of the San Andreas fault and the central New Madrid fault.

the San Andreas fault, there are significant exposures (Fig. 8A), including the San Francisco International Airport, while in the vicinity of the central New Madrid fault, there are fewer exposures (Fig. 8B). We contend that the loss estimate ($300 billion) for the New Madrid scenario is on the high side, and the aggregated risk is higher in the San Francisco Bay Area than the New Madrid region. It is a good policy to allocate more resources for seismic hazard mitigation in the San Francisco Bay Area than in the New Madrid region.

The New Madrid region also faces other natural hazards, particularly weather-related hazards such as tornados, floods, and ice storms. For example, on 5–6 February 2008, tornados killed 57 people and caused more than $400 million in property damage in Arkansas, Tennessee, and Kentucky, all part of the New Madrid region. A massive ice storm struck several states in the New Madrid region on 26–29 January 2009 (Fig. 9) and caused 36 fatalities and more than $0.5 billion in damage in Kentucky alone. Between 25 and 28 April 2011, tornados killed 236 people and caused more than $3 billion in damage in Alabama. On 22 May 2011, a deadly tornado killed 141 people and caused more than $3 billion in damage in Joplin, Missouri, and in May 2011, a historic flood inundated many areas from southern Illinois all the way down to Louisiana and caused more than $1 billion in damage. We suggest that tornados, floods, ice storms, and other weather-related hazards pose an even higher risk in the New Madrid region than earthquakes do. Therefore, a comprehensive mitigation policy that addresses all natural hazards—tornados, floods, ice storms, and earthquakes in particular—is needed for the New Madrid region. This will require a comprehensive assessment of all the hazards and risks.

This lack of a comprehensive assessment of all the hazards and risks makes it difficult to develop and implement a sound mitigation policy for earthquakes, although it is certain that the region is facing seismic hazards and risk. As shown in Figure 1, the development of a seismic mitigation policy starts with seismic hazard maps. Therefore, as part of a prudent and conservative approach, we recommend that ground-motion hazards from large New Madrid earthquakes, such as shown in Figure 6, be considered for engineering design and other policies for the region.

SUMMARY AND CONCLUSIONS

Seismic hazard and seismic risk are two important concepts used in the development of mitigation measures and policy. They have often been used interchangeably, even though they are fundamentally different. The differences between seismic hazard and seismic risk are of practical significance in earthquake engineering and other related decision making because measures for seismic hazard mitigation are different from measures for seismic risk reduction. Seismic hazards, fault rupture and ground motion in particular, cannot be mitigated, but seismic risk can always be reduced, either through limiting exposure or strengthening the exposure (limiting vulnerability). Limiting exposure

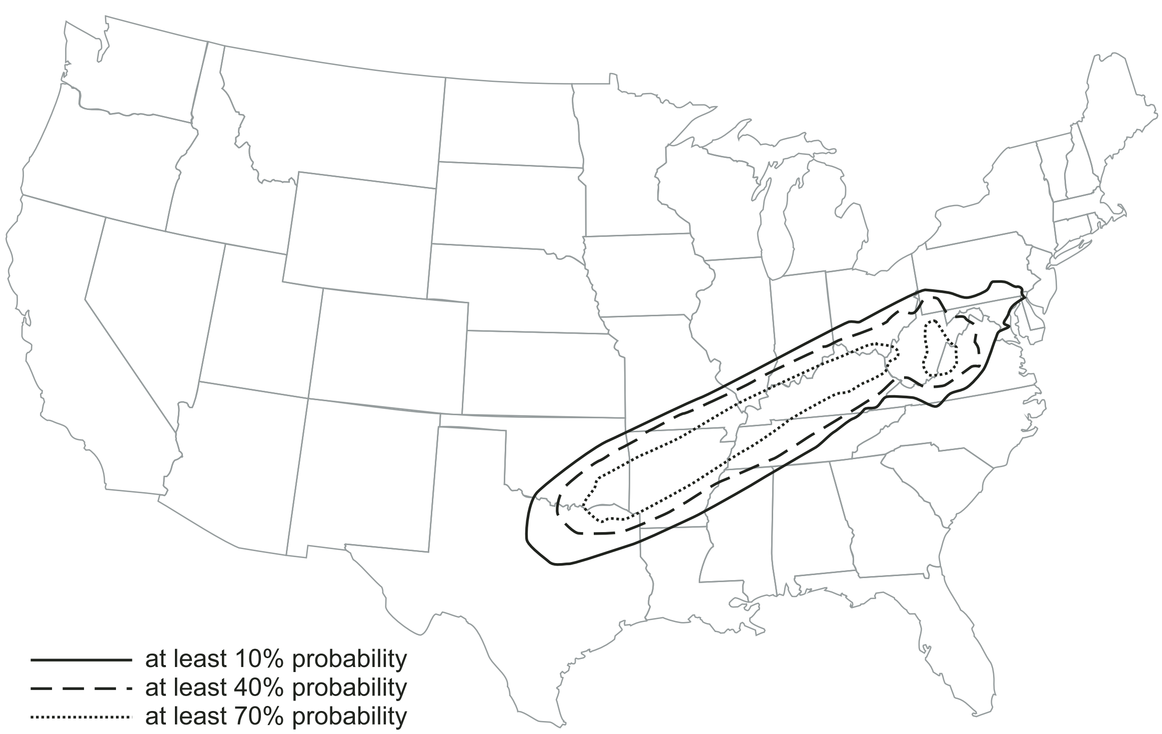

Figure 9. Location of the ice storm of 26–28 January 2009, in the central United States (NOAA, 2009).

often is not a practical choice for society because demand for economic development is always high. Thus, the most viable approach for reducing seismic risk is to strengthen the built environment through better seismic design and construction. In other words, the best way to prevent earthquake disaster is to build better seismic-resistant buildings and infrastructure.

The understanding of earthquakes in the New Madrid seismic zone has advanced greatly through scientific studies, particularly those supported by the NEHRP program. These studies have provided scientific information for seismic hazard assessment, which has been the basis for seismic risk assessment and mitigation policy for the region. There are significant problems with seismic hazard assessment, however, particularly with the National Seismic Hazard Maps. The maps were produced from PSHA using input parameters derived from a comprehensive consensus process involving many geologists, seismologists, engineers, and others.

We assert that PSHA is scientifically flawed. As a complex computer model, it does not pass a simple sensitivity test with a single input earthquake: One earthquake could generate many ground motions at a site. A mathematical error was committed in the original PSHA formulation (Cornell, 1968): forgetting the precondition of $t = 1$ yr (annual). This mathematical error led to equating the annual probability of exceedance (a dimensionless quantity) to the annual frequency or rate of exceedance (a dimensional quantity with unit of 1/yr) or equating the reciprocal of the annual probability of exceedance (i.e., return period) to the average time between occurrences of a ground motion. Even though the numbers are equivalent, 1% (0.01) = 1% (0.01), 1% (0.01) in one year is not equal to 1% (0.01) per year because the dimensions are not equal. The reciprocal of 1% (0.01) is 100 and means that the chance of occurrence is 1 in 100, not the average recurrence time in years.

Thus, we view the hazard curves and maps from the national seismic hazard mapping project as artifacts, even though the input database is scientifically sound. The National Seismic Hazard Maps have not been interpreted and used correctly. In other words, the annual probabilities of exceedance, such as 0.002, 0.001, and 0.0004, have been erroneously interpreted and used as the frequencies (rates) of 0.002, 0.001, and 0.0004 per year, respectively, or the reciprocal of the annual probabilities of exceedance of 0.002, 0.001, and 0.0004 have been erroneously interpreted and used as the return periods of 500, 1000, and 2500 yr. The reciprocal of the annual probabilities of exceedance of 0.002, 0.001, and 0.0004 should be regarded as the chances of 1 in 500, 1000, and 2500 in one year, respectively. Thus, we also view seismic risks derived from the hazard curves and maps as artifacts. Therefore, the application of the National Seismic Hazard Maps for seismic provisions of building codes, insurance rate structures, risk assessments, and other public policy is problematic.

Other approaches, such as scenario/deterministic seismic hazard analysis, should be considered for seismic hazard assessment in the New Madrid area. Currently, the deterministic ground motion is used in engineering design for bridge and highway structures in California (Mualchin, 2011). The ground motion for building seismic design in coastal California is capped by a deterministic ground motion closer to the active faults (BSSC, 1998, 2009). Therefore, as a prudent and conservative approach, we recommend scenario/deterministic seismic hazards from large New Madrid earthquakes be considered for engineering design and other policies for the region.

The New Madrid region also faces other significant hazards and risks, particularly tornadoes, floods, and ice storms. Therefore, a comprehensive mitigation policy to address all natural hazards and risks is needed for the New Madrid region. This will require a comprehensive assessment of all natural hazards and risks, which has not yet been attempted. This hinders the development of effective mitigation policies for the region. It is also noted that mitigation measures toward seismic hazards also mitigates the other natural hazards. In other words, mitigation of any natural hazard will improve the resilience of the community.

ACKNOWLEDGMENTS

We thank Meg Smath of the Kentucky Geological Survey for editorial help. We appreciate comments and suggestions from volume co-editor Randel Cox, John Steinmetz, and an anonymous reviewer, which helped to improve the manuscript greatly.

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Manuscript Accepted by the Society 15 June 2012

Geological Society of America Special Papers

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Geological Society of America Special Papers 2013;493; 259-275
doi:10.1130/2012.2493(13)

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