Pure Appl. Geophys.

DOI 10.1007/s00024-010-0148-3

Pure and Applied Geophysics

Seismic Hazard Assessment: Issues and Alternatives

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Abstract—Seismic hazard and risk are two very important concepts in engineering design and other policy considerations. Although seismic hazard and risk have often been used interchangeably, they are fundamentally different. Furthermore, seismic risk is more important in engineering design and other policy considerations. Seismic hazard assessment is an effort by earth scientists to quantify seismic hazard and its associated uncertainty in time and space and to provide seismic hazard estimates for seismic risk assessment and other applications. Although seismic hazard assessment is more a scientific issue, it deserves special attention because of its significant implication to society. Two approaches, probabilistic seismic hazard analysis (PSHA) and deterministic seismic hazard analysis (DSHA), are commonly used for seismic hazard assessment. Although PSHA has been proclaimed as the best approach for seismic hazard assessment, it is scientifically flawed (i.e., the physics and mathematics that PSHA is based on are not valid). Use of PSHA could lead to either unsafe or overly conservative engineering design or public policy, each of which has dire consequences to society. On the other hand, DSHA is a viable approach for seismic hazard assessment even though it has been labeled as unreliable. The biggest drawback of DSHA is that the temporal characteristics (i.e., earthquake frequency of occurrence and the associated uncertainty) are often neglected. An alternative, seismic hazard analysis (SHA), utilizes earthquake science and statistics directly and provides a seismic hazard estimate that can be readily used for seismic risk assessment and other applications.

1. *Introduction*

It is a daunting task to try to convey the science of seismology/geology to engineers, policy-makers, and the general public. It is essential to make every effort to convey the science clearly, accurately, and understandably because science is the basis for sound engineering design and other policy considerations. This is also the duty of professional seismologists/geologists.

It is often heard, "I am just a seismologist (or geologist) and this is what it is." It is also often heard, "The selection of an appropriate seismic hazard or risk for engineering design or policy consideration is not really a technical question, but rather a societal one." Clearly, there is a gap in understanding of seismic hazard and risk between the seismologists/geologists who assess them and engineers, policy-makers, and the general public who use these assessments. For example, the national seismic hazard maps produced by the U.S. Geological Survey using probabilistic seismic hazard analysis (PSHA), and showing the ground motions with 2, 5, and 10% probability of exceedance (PE) in 50 years, have been said to be the hazard maps that engineers want (FRANKEL *et al.*, 1996, 2000, 2002; PETERSEN *et al.*, 2008). By definition, ground motions with 2, 5, and 10% PE in 50 years represent seismic risk in a manner similar to flood and wind risk estimates in hydraulic and wind engineering (SACHS, 1978; GUPTA, 1989); but engineers may be using the national seismic hazard maps only because they represent the "best available science" (BSSC, 1998; LEYENDECKER *et al.*, 2000). Although it has been claimed that the national seismic hazard maps have been used in a variety of engineering designs, such as the International Building Code (ICC, 2006), the fact is that the USGS hazard maps have never been used directly in building design, and "the 2008 national seismic hazard maps should not be substituted for the model building code design maps nor should they be used with ASCE/SEI 41 or 31 for seismic rehabilitation or evaluation" (USGS, 2009). The gap in understanding of the national seismic hazard maps has made it difficult to use them for engineering design and other policy considerations in many communities in the

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central and eastern United States (Stein *et al.*, 2003; Wang *et al.*, 2003).

This paper examines the basic concepts of seismic hazard and risk first, because they are two important parameters for engineering design and policy consideration. The methodologies used to assess seismic hazard, as well as the associated science, will then be explored. The goal of this paper is to bridge the gap in understanding of seismic hazard and risk, as well as the associated science, between seismologists/geologists, engineers, policy-makers, and the general public, with the aim of achieving seismically safe and resilient communities.

2. *Seismic Hazard and Risk*

2.1. *Basic Concept*

Seismic hazard and risk are two of the most commonly used terms in engineering design and policy considerations. Although the two terms have often been used interchangeably, they are fundamentally different concepts (Reiter, 1990; Wang, 2006, 2007, 2009b). Seismic hazards are defined as "the potential for dangerous, earthquake-related natural phenomena such as ground shaking, fault rupture, or soil liquefaction" (Reiter, 1990, p. 3), or "a property of an earthquake that can cause damage and loss" (McGuire, 2004, p. 7). Seismic risk is defined as "the probability of occurrence of these consequences (i.e., adverse consequences to society such as the destruction of buildings or the loss of life that could result from seismic hazards)" (Reiter, 1990, p. 3), or "the probability that some humans will incur loss or that their built environment will be damaged" (McGuire, 2004, p. 8). In other words, seismic hazard describes the natural phenomenon or property of an earthquake, whereas seismic risk describes the probability of loss or damage that could be caused by a seismic hazard (Wang, 2009b). This difference is illustrated in Fig. 1, which shows that the Wenchuan earthquake and its aftershocks triggered massive landslides and rockfalls (seismic hazards). The driver and pedestrians shown in Fig. 1, who were vulnerable to the seismic hazards, were taking a risk, the probability of an adverse consequence: being struck by a rockfall. This example demonstrates that seismic risk is a probable outcome (or consequence) from interaction between a seismic hazard and vulnerability (something is vulnerable to the seismic hazard). Therefore, in general, seismic risk can be expressed qualitatively as

$$\text{Seismic risk} = \text{Seismic hazard}\Theta\text{Vulnerability}. \quad (1)$$

As shown in Eq. 1, high seismic hazard does not necessary mean high seismic risk, and vice versa.

Figure 1

Comparison of seismic hazard and risk. Seismic hazard: earthquake triggered rockfall. Vulnerability: car, its driver, and pedestrians. Consequence: struck by a rockfall. Seismic risk: the probability of being struck by a rockfall during the period that the car or pedestrians pass through the road section

There is no risk (i.e., no probability that the car or pedestrians could be hit by a rockfall) if the driver decides not to drive or pedestrians decide not to go through the road (i.e., no vulnerability). This example also demonstrates that engineering design or a policy for seismic hazard mitigation may differ from one for seismic risk reduction. Here, the seismic hazard (rockfall) may or may not be mitigated, but the seismic risk can always be reduced by either mitigating the seismic hazard (i.e., building barriers and other measures), reducing the vulnerability (i.e., limiting traffic or pedestrians), or both. Therefore, it is critical for engineers and decision-makers to clearly understand seismic hazard and risk.

2.2. *Estimations*

The preceding discussions on seismic hazard and risk are in general, or qualitative, terms, which is insufficient for decision-making. As natural phenomenon, seismic hazard is quantitatively defined by three parameters: level of severity (physical measurement), spatial measurement (where), and temporal measurement (when or how often), as well as associated uncertainties. For example, the hazard in Fig. 1 can be quantified as a rockfall with a mean diameter of 0.5 m or larger that occurs every hour on average along the section of the road. Seismic hazards can also be quantified as an M7.5 earthquake (mean) with a recurrence interval of 500 years (mean) in the New Madrid Seismic Zone of the central United States, or a mean peak ground acceleration (PGA) of 0.3 g with a mean return period of 1,000 years in Memphis, TN. Seismic hazard is assessed from instrumental, historical, and geological observations. In other words, seismic hazard is assessed from earth sciences. How to assess seismic hazard will be discussed in detail later.

Seismic risk quantification is complicated and somewhat subjective because it depends on the desired measurement of consequence (i.e., outcome of physical interaction between the seismic hazard and vulnerability) and how the hazard and vulnerability interact in time and space. The hazard and vulnerability could interact at a specific site or over an area: so-called site-specific risk or aggregate risk (Malhotra, 2008). In general, seismic risk is quantified by four parameters: *probability*, *level of severity*, and *spatial* and *temporal* measurements (Wang, 2009b). For example, the Working Group on California Earthquake Probabilities (WGCEP, 2003) estimated that “there is a 62 percent probability of a major, damaging earthquake (M6.7 or greater) striking the greater San Francisco Bay Region (SFBR) over the next 30 years (2002–2031).” The October 17, 1989, Loma Prieta earthquake (M6.9) caused 62 deaths, about 4,000 injuries, and $10 billion in direct losses in the SFBR. Thus, the risk, in terms of an earthquake of M6.7 or greater, could also be expressed as a 62% probability of 60 or more deaths, 4,000 or more injuries, or $10 billion or more in direct losses over the next 30 years. These risk estimates are from all sources for an area such as SFBR. For an individual site or source, the risk estimate could be different. WGCEP (2003) estimated the risk in terms of modified Mercalli intensity (MMI); for example, the MMI of shaking at a given site with a 50% chance of being exceeded in 30 years. WGCEP (2003) estimated that in Oakland, CA, there is an 11% probability of an earthquake with M6.7 or greater occurring on the southern Hayward Fault over the next 30 years. WGCEP’s work shows that seismic risk estimate is very complicated and can be expressed in many different ways for different users.

In order to estimate seismic risk, a model has to be assumed or introduced to describe how the hazard and vulnerability interact in time. For example, several models (Poisson, Empirical, Brownian Passage Time, and Time-Predictable) have been used to describe earthquake occurrence in time and to estimate seismic risk. The most commonly used one in seismic risk estimation is the Poisson model (Cornell, 1968; WGCEP, 2003). If earthquake occurrence in time follows a Poisson distribution (Cornell, 1968; Wang, 2006, 2007), then seismic risk, expressed in terms of the probability of an earthquake exceeding a specified magnitude (M) at least once during a given exposure time t for a given vulnerability along a fault or in an area, can be estimated by

$$p(n \geq 1, t, \tau) = 1 - \mathrm{e}^{-t/\tau}, \tag{2}$$

where n and τ are the number and average recurrence interval of an earthquake with magnitude exceeding M. Equation 2 describes a quantitative relationship between seismic hazard (i.e., an earthquake of magnitude M or larger with an average recurrence interval τ) and seismic risk (i.e., the probability p that an earthquake of magnitude M or larger could occur during the exposure time t in the area), assuming that earthquake occurrence in time follows a Poisson distribution. The seismic risk estimate will be different if earthquake occurrence follows another distribution. Equation 2 can be used to estimate seismic risk for the car and pedestrians shown in Fig. 1. For the given seismic hazard, a rockfall with a mean diameter of 0.5 m or larger has a frequency of occurrence of one every hour on average along that section of the road. If it takes 3 min for the car to pass through the road section, and 20 min for the pedestrians, the risk for the car will be about a 5% probability of being struck by a rockfall with a diameter of 0.5 m or larger; for the pedestrians, about a 28% probability. The pedestrians will almost certainly be killed if they are struck by a rockfall of 0.5 m or larger in diameter, but the driver of the car may not be killed if the car is struck by a similar rockfall, because the body of the car could protect the driver. Thus, we assume that pedestrians will be killed (100% chance) if they are struck by a rockfall and that there is a 30% chance that the driver will be killed if the car is struck by a similar rockfall. The pedestrians have about a 28% probability of being killed, and the driver has about a 1.5% probability. These examples demonstrate that (1) time is a key element in risk estimation and (2) differences in physical characteristics of the vulnerabilities, i.e., the human body versus car or human body inside the car, result in different seismic risk estimation. The human body is more vulnerable to the rockfall hazard than the one inside the car. The car could be damaged, but the driver might not be injured if a rockfall struck the car.

The quantitative relationship between seismic hazard, vulnerability, and risk, as well as their roles in engineering design and policy considerations, can be illustrated through the following example. Figure 2 shows the modified Mercalli intensity experienced during the 1906 San Francisco earthquake (M7.8) in the Bay Area and the 1811–1812 New Madrid earthquake (M7.7) in the central United States. A much larger area was impacted by a similar earthquake in the central United States than in California because ground motion attenuates much slower in the older and harder rock in the central United States. In other words, a much larger area experienced a similar MMI in the central United States than in California. This does not mean that the central United States has higher seismic hazard, however, because the earthquake frequencies of occurrence are different. The frequency of occurrence of the M7.8 earthquake in the Bay Area is about 100–200 years, and about 500–1,000 years in the central United States. As shown in Fig. 2, in terms of seismic hazard, the Bay Area experienced either an M7.8 earthquake or an MMI VIII every 100–200 years, whereas the central United States experienced a similar earthquake or intensity every 500–1,000 years. It is not straight forward to make a decision whether to spend more resources for seismic hazard mitigation in the Bay Area or the central United States based on these seismic hazard comparisons (Table 1).

Now, let's consider seismic risk for two identical buildings with a normal life of 50 years, one in San Francisco and one in Memphis (Fig. 2). If the earthquake occurrences follow a Poisson distribution, we can use Eq. 2 to estimate seismic risk in terms of the probability that the buildings could be hit by an M7.8 earthquake or experience MMI VIII during their 50 year lifespan. According to Eq. 2, the probability of the building in San Francisco being hit by an M7.8 earthquake or experiencing an MMI VIII will be about 22–39% during its 50 year life; the probability of the building in Memphis being hit by a similar earthquake or experiencing a similar MMI will be about 5–10% (Table 1). A recent study (KIRCHER *et al*., 2006) shows that a repeat of the 1906 San Francisco earthquake (M7.8) could cause more than $150 billion in losses in the Bay Area. A similar size earthquake (M7.7) in the New Madrid Seismic Zone could also cause huge losses in the central United States, but the losses there would not be as large as in the Bay Area because the vulnerabilities (i.e., people and the built environments) are much higher in the Bay Area than in the central United States. The seismic risk comparisons (Table 1) make it easy to understand why the most resources for seismic hazard mitigation and risk reduction in the

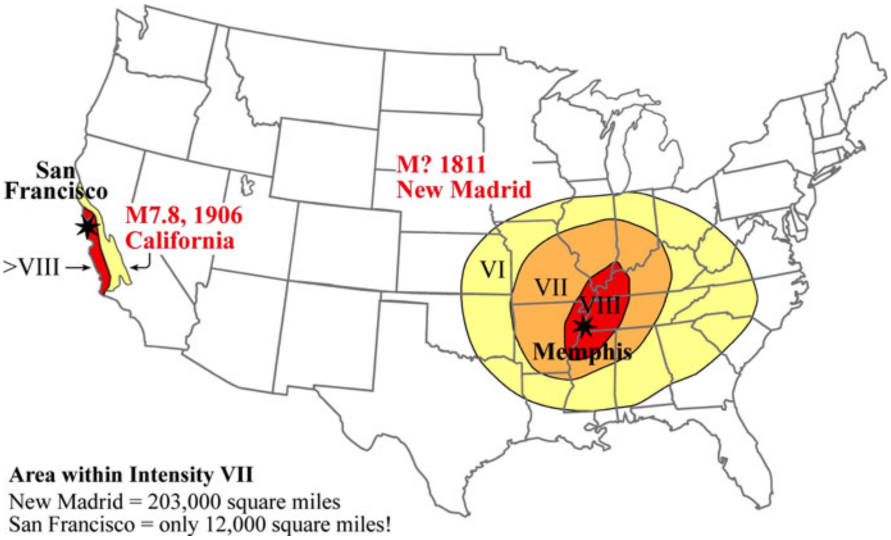

Figure 2
Seismic hazard and risk comparison between the central United States and the San Francisco Bay area, CA

Table 1

Seismic hazard and risk comparisons between San Francisco and Memphis

Location	Seismic hazard	Seismic risk
San Francisco	M7.8 or MMI VIII every 100–200 years	22–39% probability of M7.8 or MMI VIII being exceeded in 50 years
Memphis	M7.7 or MMI VIII every 500–1,000 years	5–10% probability of M7.7 or MMI VIII being exceeded in 50 years

United States have been allocated to California, the Bay Area in particular. The risk comparisons also demonstrate that requiring similar or higher seismic design load for buildings in Memphis or the central United States than for similar buildings in San Francisco is not a good engineering practice or policy decision.

In summary, seismic hazard and risk are two fundamentally different concepts and play quite different roles in engineering design and policy decision-making. It is seismic risk, not seismic hazard, that engineering designs, insurance premiums, or other policy decisions are based on. For example, the risk analyses carried out by Luco (2008) have been recommended to develop the so-called risk-targeted earthquake ground motion for the NHERP provisions by the Building Seismic Safety Council (BSSC) (Kircher *et al.*, 2008). Qualitatively, seismic hazard describes the natural phenomenon or property of an earthquake, whereas seismic risk describes the probability of consequence from the interaction between seismic hazard and vulnerability. Quantitatively, seismic hazard is defined by three parameters: level of severity, and spatial and temporal measurements, whereas seismic risk is defined by four parameters: probability, a measurement of consequence, and spatial and temporal measurements. Seismic hazard is assessed from instrumental, historical, and geological observations (i.e., from earthquake science). Estimation of seismic risk is much more complicated and somewhat subjective, because it depends on how the hazard and vulnerability interact physically in time and space. Detailed estimation of seismic risk is beyond earthquake science and requires cooperation with other disciplines, engineering in particular.

3. Seismic Hazard Assessment

As discussed in the previous section, seismic hazard is quantified by three parameters: level of severity, and spatial and temporal measurements. Thus, the purpose of a seismic hazard assessment is to determine these three parameters from instrumental, historical, and geological observations. Two methods are commonly used for seismic hazard assessment: probabilistic seismic hazard analysis (PSHA) and deterministic seismic hazard analysis (DSHA). PSHA and DSHA use the same seismological and geological information, but define and calculate seismic hazard fundamentally differently. In PSHA, seismic hazard is defined as the ground motion with an annual probability of exceedance and calculated from a so-called triple integration (a mathematical model) based on statistical relationships of earthquake and ground motion. In DSHA, seismic hazard is defined as the maximum ground motion from a single earthquake or set of earthquakes and calculated from simple statistics of earthquake and ground motion. A key component for seismic hazard assessment including both PSHA and DSHA is the ground motion attenuation relationship or the so-called ground motion prediction equation (GMPE). Thus, in this section, GMPE will be briefly discussed first.

3.1. Ground Motion Prediction Equation

GMPE describes a relationship between a ground motion parameter Y (i.e., PGA, PGV, MMI, or PSA at different periods), earthquake magnitude M, source-to-site distance R, and uncertainty or residual δ as

$$\ln(Y) = f(M, R) + \delta. \tag{3}$$

Figure 3a shows the schematic relationship of GMPE. As shown in Fig. 3a, GMPE predicts ground motions in space (i.e., a spatial relationship). The ground motion uncertainty δ is modeled as a normal distribution with a standard deviation, σ (Fig. 3) (Campbell, 1981, 2003; Bazzurro and Cornell, 1999; Atkinson and Boore, 2006; Abrahamson and Silva, 2008; Strasser *et al.*, 2009). Thus, Eq. 3 can also be expressed as

$$\ln(Y) = f(M, R) + \varepsilon\sigma, \tag{4}$$

where ε is the normalized residual, which is also a normal distribution with a constant standard deviation of 1 (Fig. 3b) and independent of M and R (Bazzurro and Cornell, 1999). 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}) (Fig. 4) (Campbell, 1981, 2003; Atkinson and Boore, 2006; Abrahamson and Silva, 2008). In addition, many different functional forms have been used. For example, Atkinson and Boore (2006) used the following functional form for hard rock in the central and eastern United States:

$$f(M, R) = c_1 + c_2 M + c_3 M^2 + (c_4 + c_5 M) f_1 + (c_6 + c_7 M) f_2 + (c_8 + c_9 M) f_0 + c_{10} R_{\mathrm{RUB}}, \tag{5}$$

where c_1, c_2,…c_{10} are constants; $f_0 = \max(\log(R_0/R_{\mathrm{cd}}), 0)$; $f_1 = \min(\log R_{\mathrm{cd}}, \log R_1)$; $f_2 = \max(\log(R_{\mathrm{cd}}/R_2), 0)$; $R_0 = 10$ km; $R_1 = 70$ km; $R_2 = 140$ km.

Silva *et al.* (2002) used the functional form of

$$f(M, R) = c_1 + c_2 M + (c_6 + c_7 M)\ln(R_{JB} + e^{c_4}) + c_{10}(M - 6)^2. \tag{6}$$

As shown in Eqs. 3 through 6, GMPE is a statistical tool for predicting and forecasting based on ground motion data. Furthermore, as shown by Youngs *et al.* (1995), Abrahamson and Silva (1997), Boore *et al.* (1997), and Strasser *et al.* (2009), σ depends on M or R, or both. In other words, δ depends on M or R, or both, whereas ε does not (standardized normal distribution with a constant standard deviation of 1) (Wang, 2009a).

3.2. Probabilistic Seismic Hazard Analysis

Two approaches for PSHA being developed with the aim to estimate seismic risk in late 1960s (Cornell, 1968; Milne and Davenport, 1969). In his landmark paper, Cornell (1968) developed a theoretical relationship between a ground motion parameter (i.e., MMI, PGA, or others) and annual probability of exceedance at a site of interest based on the statistical relationships of earthquakes and ground motion, i.e., Gutenberg–Richter relationship

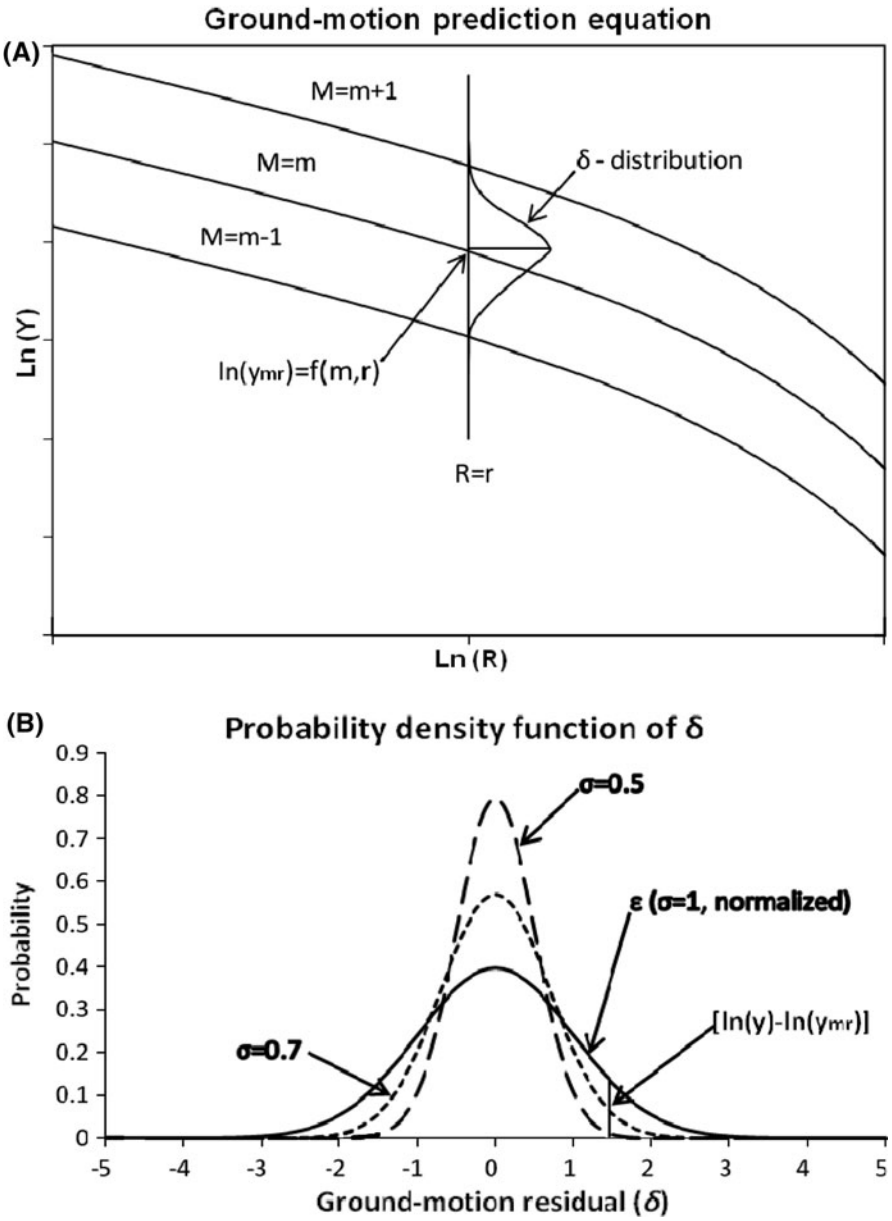

Figure 3
Schematic relationship of GMPE (**a**) and uncertainty distribution (**b**)

and GMPE. Milne and Davenport (1969) derived an empirical relationship between a ground motion parameter and frequency of occurrence from historical observations of earthquakes, which is quite similar to those that are commonly used in flood and wind hazard analyses today (Sachs, 1978; Gupta, 1989). In other words, the Cornell approach is theoretical, and the Milne-Davenport approach is empirical. Currently, the Cornell approach or the so-called Cornell–McGuire method (Cornell, 1968, 1971; McGuire, 2004) is the dominant one used in seismic hazard assessment in the United States, as well as in the rest of the world. PSHA is universally referred to as the Cornell approach or Cornell–McGuire approach in current seismic hazard assessments. In this paper, PSHA is referred to as the

Cornell approach or so-called Cornell–McGuire method.

PSHA was developed from earthquake science in the 1970s under three fundamental assumptions: (a) equal likelihood of earthquake occurrence (single point) along a line or over an areal source, (b) constant-in-time average occurrence rate of earthquakes, and (c) Poisson (or "memory-less") behavior of earthquake occurrences (Cornell 1968, 1971). It is very important to note that the basic equation for PSHA was derived from mathematical statistics. According to mathematical statistics (Benjamin and Cornell, 1970; Mendenhall *et al.*, 1986; Wang and Zhou, 2007), if and only if M, R, and δ are independent random variables, the joint probability density function for GMPE, Eq. 3, is

$$f_{M,R,\Delta}(m,r,\varepsilon) = f_M(m)f_R(r)f_\Delta(\delta), \tag{7}$$

where $f_{M,j}(m)$, $f_{R,j}(r)$, and $f_\Delta(\delta)$ are the probability density function (PDF) for earthquake magnitude (M), epicentral or hypocentral distance (R_{EPI} *or* R_{HYP}) (Fig. 4), and ground motion uncertainty δ, respectively. The exceedance probability $P[Y \geq y]$ for seismic source j is

$$\begin{aligned} P_j[Y\geq y] &= \iiint f_{M,R,\Delta}(m,r,\delta)H\big[\ln Y(m,r,\delta) \\ &\quad -\ln y\big]\mathrm{d}m\mathrm{d}r\mathrm{d}\delta \\ &= \iiint f_{M,j}(m)f_{R,j}(r)f_{\Delta,j}(\delta)H\big[\ln Y(m,r,\delta) \\ &\quad -\ln y\big]\mathrm{d}m\mathrm{d}r\mathrm{d}\delta, \end{aligned} \tag{8}$$

where $H[\ln Y(m,r,\delta) - \ln y]$ is the Heaviside step function, which is zero if $\ln Y(m,r,\delta)$ is less than $\ln y$, and 1 otherwise. Because ground motion uncertainty δ follows a normal distribution (Fig. 3 and Eq. 4), Eq. 8 can be rewritten as

$$\begin{aligned} &P_j[Y\geq y] \\ &= \iint\left\{1-\int_0^y \frac{1}{\sqrt{2\pi}\sigma_j}\exp\left[-\frac{(\ln y-\ln y_{mr})^2}{2\sigma_j^2}\right]\mathrm{d}(\ln y)\right\} \\ &\quad \times f_{M,j}(m)f_{R,j}(r)\mathrm{d}m\mathrm{d}r \\ &= \iint\left\{1-\Phi\left(\frac{\ln y-\ln y_{mr}}{\sigma_j}\right)\right\}f_{M,j}(m)f_{R,j}(r)\mathrm{d}m\mathrm{d}r, \end{aligned} \tag{9}$$

where $\ln(y_{mr}) = f(m,r)$, $\Phi(x)$ is the cumulative probability function for δ and equal to the area under the probability distribution curve from $-\infty$ to $[\ln(y) - \ln(y_{mr})]$ (Fig. 3b), and $1 - \Phi(x)$ is the exceedance probability for δ and equal to the area under the probability distribution curve from $[\ln(y) - \ln(y_{mr})]$ to ∞ (Fig. 3b).

Under of the assumption of Poisson (or "memory-less") behavior of earthquake occurrences (Cornell 1968, 1971), seismic risk in terms of the probability that ground motion Y exceeds a given value y during a time interval of t if earthquake (event) occurs with average rate of v_j (per year) from source j is

$$P_{j,t}[Y\geq y] = 1 - \mathrm{e}^{-P_j[Y\geq y]v_j t}. \tag{10}$$

Equation 10 can be obtained from Eq. 2 by substituting τ with $1/(v_j Pj[Y \geq y])$. For small risk (say ≤ 0.05) (Cornell, 1968, 1971), Eq. 10 can be approximated as

$$P_{j,t}[Y\geq y] = P_j[Y\geq y]v_j t. \tag{11}$$

For $t = 1$ year, annual probability of exceedance (probability of exceedance in 1 year) is equal to

$$P_{j,t=1}[Y\geq y] = v_j P_j[Y\geq y]. \tag{12}$$

It is worth to emphasize here that $t = 1$ year is neglected on the right side of Eq. 12. Otherwise, the probability (dimensionless) could be equal to the frequency (unit of 1/time) in Eq. 12. Therefore, total risk in terms of the annual probability of exceedance $\gamma(y)$ for a given ground motion y from all seismic sources is

$$\begin{aligned} \gamma(y) &= \sum_j v_j \iint\left\{1-\Phi\left(\frac{\ln y-\ln y_{mr}}{\sigma_j}\right)\right\} \\ &\quad \times f_{M,j}(m)f_{R,j}(r)\mathrm{d}m\mathrm{d}r. \end{aligned} \tag{13}$$

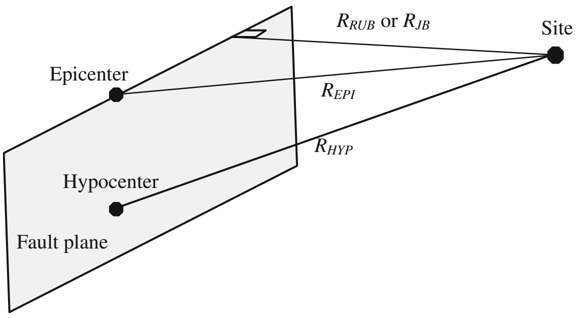

Figure 4
Schematic geometry of earthquake fault and source-to-site distances

Equation 13 is basic hazard calculation equation of PSHA (Cornell, 1968, 1971; McGuire, 2004).

Although PSHA has become the most widely used method for seismic hazard assessment, recent studies (Wang and Zhou, 2007; Wang, 2008, 2009a) showed that:

1. PSHA is not based on a valid earthquake source model. As shown in Eq. 13, a probability density function, $f_{R,j}$ (r), was introduced to describe the distribution of an earthquake (a single point) along the fault line or over the fault plane (Fig. 4) (Cornell, 1968; McGuire, 2004). In other words, PSHA was based on a single point source model for an earthquake, an assumption (a) of Cornell (1968). Today, however, an earthquake is considered a complex finite fault rupture. For example, the great Sumatra earthquake of December 26, 2004, had a rupture length of more than 1,200 km with a width of about 200 km. The May 12, 2008, Wenchuan, China, earthquake (M7.9) had a rupture length of about 300 km (Li *et al.*, 2008). In particular, a finite fault and only one single distance (i.e., the closest distance from site to fault rupture either R_{RUB} or R_{JB}) are considered in GMPE (Fig. 4) (Campbell, 1981, 2003; Silva *et al.*, 2002; Atkinson and Boore, 2006; Li *et al.*, 2008). In other words, the distance R being considered in PSHA is different from the one being considered in GMPE (Fig. 4). Thus, the probability density function, $f_{R,j}$ (r), in Eq. 13 is not appropriate for a finite fault.
2. The ground motion uncertainty, δ, is not treated correctly in PSHA. As shown by Wang and Zhou (2007), Eq. 13 is valid only if M, R, and δ are independent random variables. As discussed early, however, δ depends on M or R, or both. Therefore, δ is not treated correctly in the mathematics of PSHA. This incorrect treatment of the ground motion uncertainty has led to the so-called *ergodic* assumption, "treating spatial uncertainty of ground motions as an uncertainty over time at a single point" (Anderson and Brune, 1999). As shown in Eq. 13, the standard deviation σ is a key parameter that influences hazard calculation, and becomes a critical parameter at low annual probability of exceedance (10^{-4} or less) in particular (Abrahamson and Bommer, 2005; McGuire *et al.*, 2005; Musson, 2005; Bommer and Abrahamson, 2006; Strasser *et al.*, 2009). This incorrect treatment of δ also explains why σ becomes so important in PSHA that much effort has been dedicated to the study of σ, including how to split it into aleatory and epistemic parts, or how to quantify uncertainty of uncertainty (Bommer, 2003; Bommer *et al.*, 2004; Bommer and Abrahamson, 2006; Strasser *et al.*, 2009).

As shown in Eqs. 10–13, the annual probability of exceedance means the probability of exceedance in 1 year, and is dimensionless. However, the annual probability of exceedance has been interpreted and used as "the frequency (the number of events per unit of time) with which a seismic hazard will occur" (McGuire, 2004, p. 7), and the reciprocal of the annual probability of exceedance has been defined as the average return period (Cornell, 1968, 1971) and 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, p. 8). These definitions and interpretations of the annual probability of exceedance and return period are incorrect because the annual probability of exceedance and its reciprocal are dimensionless. In other words, the defined return period does not carry a unit of time, but a numerical number. This incorrect definition or interpretation of the return period has led PSHA to numerically "create" infinite ground motion events with return periods of 500 to a billion years from a single earthquake (event) with a recurrence interval of 500 years (Fig. 5). But ground motion at a site is a consequence of an earthquake; it should have the same temporal characteristics as the earthquake—the same frequency of occurrence (i.e., 0.04 per year) or interval (500 years). This example also explains how the extremely high ground motion (5.0 g PGA or larger) with a return period of 100 million years at Yucca Mountain, NV, and physically impossible ground motion at nuclear power plants in Switzerland could be numerically "created" by PSHA from a few hundreds years of instrumental and historical records and 11,000 years of geologic records (Holocene age) on earthquakes (Stepp *et al.*, 2001; Klügel, 2005).

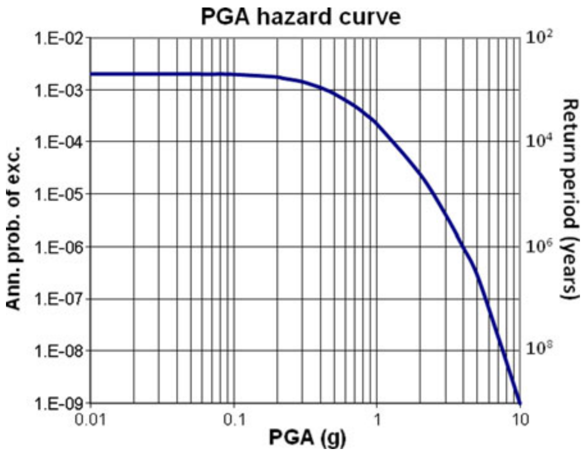

Figure 5
PGA hazard curve at a site 30 km from a single characteristic earthquake of M7.5 with a recurrence interval of 500 years

Thus, PSHA becomes a purely numerical "creation" with no physical or mathematical basis. In other words, seismic hazard or risk defined in PSHA is an artifact.

3.3. *Alternative Approach*

An alternative approach, called seismic hazard analysis (SHA), has been developed (Wang, 2006, 2007) to derive a hazard curve that is not only consistent with modern earthquake science, but also can be used for seismic risk assessment. This approach directly utilizes the statistical relationships of earthquake frequency of occurrence (the Gutenberg–Richter relationship) and GMPE.

In seismology, earthquake occurrence generally follows the Gutenberg–Richter distribution (relationship),

$$\lambda = \frac{1}{\tau} = e^{\alpha - \beta M} \quad m_0 \leq M \leq m_{\max}, \tag{14}$$

where λ is the cumulative number of earthquakes with magnitude equal to or greater than M occurring per year (i.e., frequency of occurrence), α and β are constants, and m_0 and $m_{\max}$ are the lower and upper bounds of earthquake magnitude. Figure 6a shows the Gutenberg–Richter curve derived from the historical earthquakes with magnitudes between M4.0 and M5.0 in the New Madrid Seismic Zone (Bakun and Hopper, 2004) and a characteristic earthquake of M7.5 with a recurrence interval of 500 years. From Eq. 4, M can be expressed as a function of R, ln Y, and $\varepsilon\sigma$:

$$M = g(R, \ln Y, \varepsilon\sigma). \tag{15}$$

Combining Eqs. 14 and 15 results in

$$\tau = \frac{1}{\lambda} = e^{-\alpha + \beta g(R, \ln Y, \varepsilon\sigma)}. \tag{16}$$

Equation 16 describes a relationship between the recurrence interval (τ) or frequency (λ), the ground motion (ln$Y$) with an uncertainty ($\varepsilon\sigma$), and the fault distance (R): i.e., a hazard curve. Figure 6b is a PGA hazard curve for a site 30 km from the New Madrid Seismic Zone in the central United States (Wang, 2006, 2007). GMPE of Campbell (2003) was used. As shown in Fig. 6b, the levels of uncertainty are derived explicitly. The hazard curves with 16% and 84% confidence levels are equivalent to the hazard curves with median plus/minus one standard deviation. The result from SHA (hazard curve) is similar to results derived by flood-frequency analysis (Gupta, 1989; Wang and Ormsbee, 2005) and wind-frequency analysis (Sachs, 1978).

As shown in Fig. 6a, there are not enough instrumental and historical records in the New Madrid Seismic Zone to construct a complete Gutenberg–Richter curve. The geological records (paleoliquefaction) were used to constrain the rate for the large earthquakes. The rate of the large earthquakes is not consistent with the rate inferred from the small to moderate instrumental and historical earthquakes (Fig. 6a). For this situation, a single characteristic earthquake can be considered for the seismic source. For a single earthquake of magnitude M with a recurrence interval of T_C, Eq. 16 becomes

$$\tau = \frac{1}{\lambda} = T_C. \tag{17}$$

This means that only one return period, T_C, is derived from one single earthquake. As shown in Fig. 6b, only one return period, 500 years, is derived from the characteristic earthquake of M7.5 with a recurrence interval of 500 years. The corresponding PGA can have many values with different uncertainty levels (i.e., a median PGA of 0.44 g, median − 1σ PGA of 0.21 g, and median + 1σ PGA of 0.89 g). Thus, the

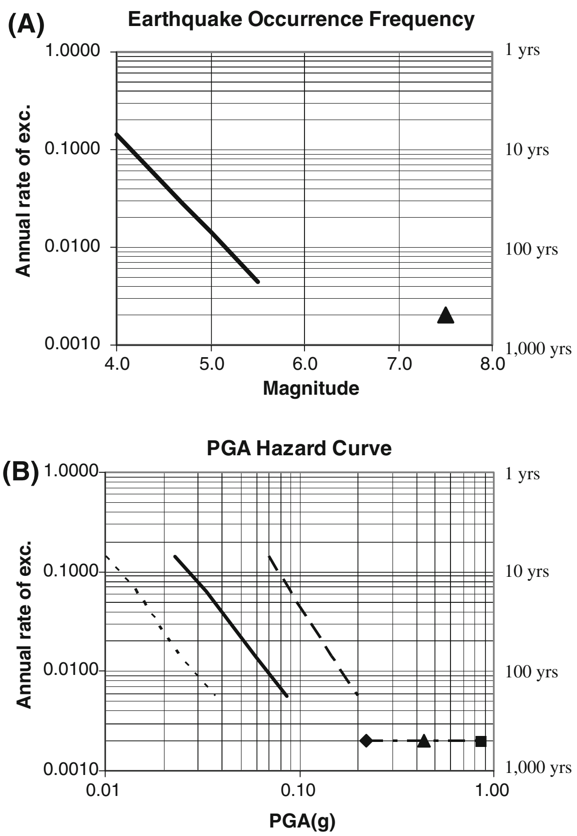

Figure 6

Earthquake magnitude and frequency of occurrence (Gutenberg–Richter) curve (**a**) and PGA hazard curves at a site 30 km from the New Madrid faults (**b**). *Solid line* median PGA, *short-dashed line* median $-$ 1σ (or 16% confidence), *long dashed line* median + 1σ (or 84% confidence), *triangle* median PGA, *filled diamond* median $-$ 1σ PGA, and *filled square* median + 1σ PGA for the characteristic earthquake of M7.5

temporal characteristic of ground motion derived from SHA is consistent with that of the input earthquakes. For a single earthquake, this example also demonstrates that hazard calculation in SHA is the same as in DSHA (Reiter, 1990; Krinitzsky, 1995, 2002). In other words, DSHA is a special case of SHA (Wang, 2006, 2007).

SHA calculates seismic hazard at a point of interest in terms of ground motion and its frequency of occurrence, as well as associated uncertainty level, directly from the earthquake frequency of occurrence curve (Gutenberg–Richter relationship) and GMPE. The hazard curves derived from SHA are comparable to those derived from flood-hazard analysis in hydraulic engineering and wind-hazard analysis in wind engineering, and have a similar meaning as well. Seismic risk estimated using SHA is comparable to the risk posed by other natural hazards such as floods and wind.

4. Discussion

The world is full of uncertainties, ranging from personal health, the financial market, and natural disasters (i.e., earthquake, hurricane, flood, and others), to simple measurements of location and time. Any decision is made under a certain degree of uncertainty. Therefore, dealing with uncertainty is a way of life. Risk is one of the most important concepts for dealing with uncertainty in everyday decision making. Another important concept associated with risk is hazard. Although hazard and risk have often been used interchangeably, they are fundamentally different (Wang, 2009b). Similarly, seismic hazard and risk are also fundamentally different. Seismic hazard is an earthquake-related natural phenomenon such as ground shaking, fault rupture, or soil liquefaction, whereas seismic risk is a probable outcome (or consequence) of interaction between a seismic hazard and vulnerability (something is vulnerable to the seismic hazard). As a natural phenomenon, seismic hazard is quantified by three parameters: a level of severity (physical measurement), temporal and spatial measurements. Thus, the purpose of seismic hazard assessment is to quantify seismic hazard and its associated uncertainties in time and space from the instrumental, historical, and geological observations (i.e., from earthquake science), and to provide a base for seismic risk assessment.

As implied by its name, the acclaimed superior ability to account for all uncertainties has made PSHA a dominant method for seismic hazard assessment in the United States, as well as the rest of the world. It was found, however, that PSHA is not based on valid physics and mathematics and the resulting hazard estimate does not have a clear physical and statistical meaning (Wang and Zhou, 2007; Wang, 2009a). Furthermore, as shown in this paper, the annual probability of exceedance defined in PSHA is the probability of exceedance in 1 year, and is dimensionless. The return period, defined as the reciprocal of the annual probability of exceedance (Cornell, 1968, 1971), is also dimensionless. However, the annual probability of exceedance has been interpreted and used as "the frequency (the number of events per unit of time) with which a seismic hazard will occur" (McGuire, 2004, p. 7), and the return period 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, p. 8). Therefore, PSHA is a pure numerical "creation" or model without physical and mathematical bases.

The results derived from PSHA are all artifact and difficult to understand and use. This can explain why the most important effort in current PSHA practice is on how to count, re-count, and split uncertainties, but not on earthquake physics and statistics (SSHAC, 1997; Abrahamson and Bommer, 2005; McGuire *et al.*, 2005; Musson, 2005; Bommer and Abrahamson, 2006; Strasser *et al.*, 2009). In other words, practice of PSHA becomes a personal belief, but not a science. If they are purely academic, the problems with PSHA may not be of concern. However, the problems with PSHA have far reaching implications for society; from seismic design of buildings, bridges, nuclear power plants, to earthquake insurance premiums. For example, according to a PSHA study by Stepp *et al.* (2001), which is one of the most comprehensive PSHA studies in the world, a PGA of 10 g might have to be considered for engineering design of nuclear repository facility at Yucca Mountain in Nevada. The use of the national seismic hazard maps which were produced from PSHA (Frankel *et al.* 1996, 2002; Petersen *et al.*, 2008) could lead to a similar or even higher design ground motion in Memphis, TN, and Paducah, KY (Stein *et al.*, 2003; Wang *et al.*, 2003). On the other hand, the Chinese national seismic design ground motion (PRCNS, 2001), which was also derived from PSHA, was found to be too low in the Wenchuan, China earthquake area (Xie *et al.*, 2009). This is one of the reasons why the losses from the Wenchuan earthquake were so high.

Although the biggest criticism of DSHA is that "it (DSHA) does not take into account the inherent uncertainty in seismic hazard estimation" (Reiter, 1990, p. 225), the truth is that DSHA accounts for all the inherent uncertainty explicitly. For example, the maximum credible earthquake (MCE) ground motion is usually taken at a mean + 1 standard deviation (i.e., 84th percentile) in the scatter of recorded earthquake ground motions (Krinitzsky, 1995, 2002; Mualchin, 1996; Klügel *et al.*, 2006). The weakness of DSHA is that "frequency of occurrence is not explicitly taken into account" (Reiter, 1990, p. 225). In other words, the temporal characteristic of ground motion (i.e., occurrence interval or frequency and its associated uncertainty) is not addressed or often neglected in DSHA. The temporal characteristic of ground motion is an integral part of seismic hazard and must be considered in engineering design and other policy consideration. One of the improvements for DSHA is to address the temporal characteristics. Actually, as pointed out by Wang *et al.* (2004), a deterministic earthquake can always be associated with a recurrence interval and its uncertainty.

SHA directly utilizes earthquake statistical relationships, earthquake frequency of occurrence (Gutenburg-Richter relationship), and GMPE to predict ground motion at a point of interest. The hazard curves derived from SHA are comparable to those derived from flood-hazard analysis in hydraulic engineering and wind-hazard analysis in wind engineering, and have a similar meaning. Seismic risk estimated using SHA is comparable to the risk posed by other natural hazards such as hurricanes, winter storms, and volcanic eruptions. As discussed earlier, SHA depends on the earthquake frequency of occurrence relationship. As pointed out by Krinitzsky (Krinitzsky, 1993a, b), there may not be enough earthquake records to construct a reliable frequency relationship for a specific seismic source zone, particularly for a fault zone. Therefore, SHA may not be applicable to areas where earthquake records are scarce or seismicity is low. For the areas with limited earthquake records, a single or a few earthquakes (i.e., maximum credible earthquake, maximum considered earthquake, or maximum design earthquake) are often considered for engineering design and other policies. Under this situation, SHA and DSHA are the same. Therefore, DSHA is a special case of SHA.

5. Conclusion

Seismic hazard assessment is an effort to quantify seismic hazard and its associated uncertainty by earth scientists. As for any natural or man-made events, such as hurricanes and terrorist attacks, an earthquake has a unique position in time and space. In other words, how to quantify the temporal and spatial characteristics of seismic hazard is the core of a seismic hazard assessment. Although PSHA has been proclaimed as the best method and is used widely for seismic hazard assessment, neither the physical model nor the mathematical formulation is valid. In other words, PSHA is a purely numerical "creation" with no physical or mathematical basis. Thus, PSHA should not be used for seismic hazard assessment, and use of PSHA could lead to either unsafe or overly conservative engineering design, with dire consequences for society.

On the other hand, even though DSHA has been labeled as an unreliable approach, it actually has been more widely used for seismic hazard assessment. In California, the design ground motion for bridges and buildings was determined from DSHA, not PSHA (Mualchin, 1996; Kircher *et al.*, 2008). DSHA has clear earthquake physics and statistics. The biggest criticism of DSHA, particularly by PSHA proponents, has been its inability to account for uncertainty. This is not true, however. DSHA accounts for all the inherent uncertainty in an explicit and appropriate way. The biggest drawback of DSHA is that the temporal characteristics (i.e., the recurrence interval or frequency of ground motion) are often time neglected. This is one of the areas that need to be addressed or improved in DSHA.

As an alternative, SHA utilizes all aspects of earthquake science and statistics to provide a seismic hazard estimate that can be readily used for seismic risk assessment and other applications. The limitation of SHA is that there may not be enough earthquake records to construct a reliable earthquake frequency of occurrence relationship in areas where earthquake records are scarce or seismicity is low. SHA and DSHA are the same for areas where only a single or a few earthquakes (i.e., maximum credible earthquake, maximum considered earthquake, or maximum design earthquake) are considered.

Acknowledgments

I thank Meg Smath of the Kentucky Geological Survey for editorial help. I appreciate comments and suggestions from Kelin Wang. I also appreciate the comments and suggestions from Kojiro Irikura and two anonymous reviewers, which help to improve the manuscript greatly.

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(Received March 26, 2009, revised December 16, 2009, accepted March 31, 2010)