UNDERSTANDING SEISMIC HAZARD AND RISK: A GAP BETWEEN ENGINEERS AND SEISMOLOGISTS

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ABSTRACT

Seismologists often say that "this hazard or risk assessment represents the best available science" or "this is the number that engineers want." On the other hand, engineers often say that "we just need a number and we can design it" or "seismologists tell us that this is the best estimate." What seismologists provide may differ from what engineers really need for seismic design, however. Furthermore, the seismic hazard and risk provided may not represent the best available science. For example, although ground motions with 10, 5, and 2 percent probability of exceedance (PE) in 50 years have been said to represent the best available science, they are hard to explain and understand. The methodology used to derive those ground motions has been found to be inconsistent with modern earthquake science. In other words, the ground motions with 10, 5, and 2 percent PE in 50 years do not represent the best available science and are neither seismic hazard nor risk. Clearly, there is a gap between engineers and seismologists in defining and understanding seismic hazard and risk. This gap has hindered development of more cost-effective policy and engineering design in the United States, as well as in other countries. The consequence is obvious.

1. INTRODUCTION

Selection of a ground motion for engineering design and other considerations requires a clear understanding of seismic hazard and risk among stakeholders, seismologists and engineers in particular. Although seismic hazard and risk have often been used interchangeably, they are fundamentally different concepts (Wang, 2006, 2007). Seismic hazard describes natural phenomena caused by an earthquake that have the potential to cause harm, such as surface rupture, ground motion, ground-motion amplification, liquefaction, or induced landslide. Seismic hazard can be evaluated from instrumental, historical, and geological observations and is quantified by two parameters: a level of hazard and its recurrence interval or frequency: for example, an M7.5 earthquake with a recurrence interval of 500 years, and peak ground acceleration (PGA) of 0.3g with a return period of 1,000 years. Seismic risk, on the other hand, describes a probability of occurrence of a specific level of seismic hazard or loss over a certain time (e.g., 50 years), and is quantified by three parameters: probability, a level of hazard or loss, and exposure time. For example, a 5 percent probability that an M7.0 or greater earthquake could be expected in 50 years in an area and a 10 percent probability that 0.3g PGA could be exceeded in 50 years at a site are both seismic risk. The conceptual difference between seismic hazard and risk can be illustrated by a comparison of seismic hazard and risk in San Francisco and Memphis (Fig. 1).

Figure 1 shows that San Francisco and Memphis experienced a similar intensity (MMI VIII or greater) during the 1906 San Francisco earthquake and the 1811-1812 New Madrid earthquakes. The recurrence intervals of the M7.8 earthquakes are about 100 years in San Francisco and 500 to 1,000 years in Memphis. Let us consider two identical buildings (exposures) with a normal life of 50 years, one in San Francisco and one in Memphis. If we only consider seismic hazard, a similar intensity (MMI VIII or greater) may be used for seismic design for both buildings. If we consider seismic risk, however, higher design intensity should be used in San Francisco than in Memphis because seismic risk is much higher in San Francisco: about 39 percent chance of exceeding MMI VIII in 50 years versus about 5 to 10 percent chance. This example shows that a seismic design or mitigation policy based on seismic hazard assessment may differ from that based on seismic risk assessment. Moreover, a policy decision is based more on seismic risk, rather than seismic hazard. Therefore, it is necessary to clearly define seismic hazard and risk and how to assess them.

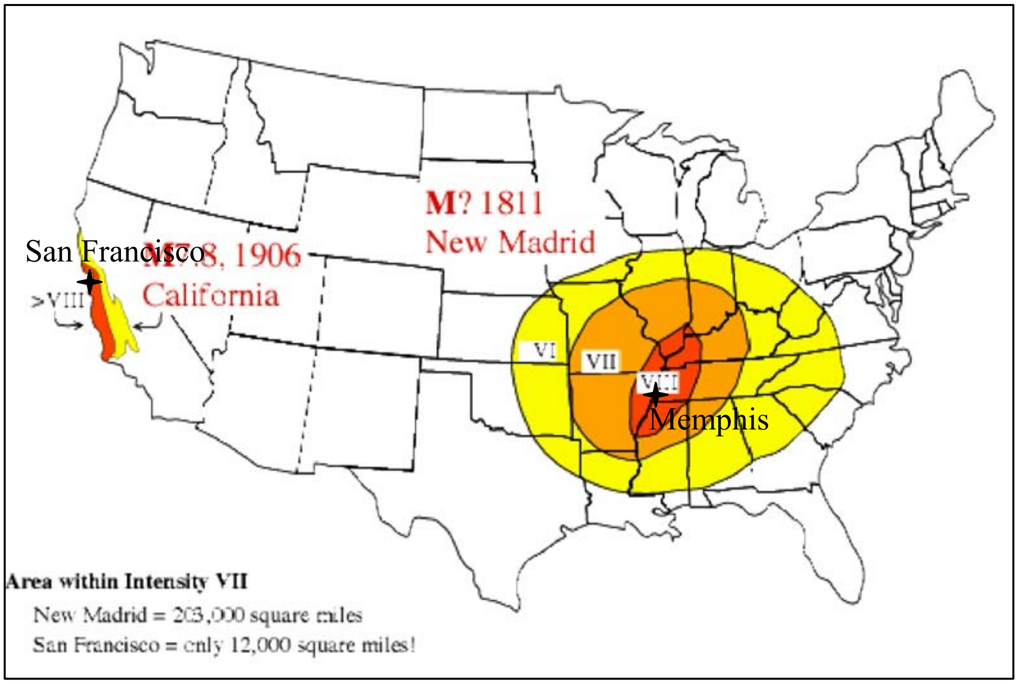

Figure 1. A conceptual comparison of seismic hazard and risk in Memphis and San Francisco.

2. SEISMIC RISK

Definition of seismic risk is more broad and subjective than definition of seismic hazard. Although seismic risk can generally be defined as the probability of occurrence of the adverse consequences to society (Reiter, 1990; McGuire, 2004), it has different meanings for different stakeholders (Smith, 2005). For example, engineers are interested in the probability that a specific level of ground motion at a site of interest could be exceeded in a given period, a definition that is analogous to flood and wind risk (Sacks, 1978; Gupta, 1989), whereas insurance companies are more interested in the probability that a specific level of losses in a region or at a specific site could be exceeded in a given period. In general, seismic risk is quantified by three parameters: probability, level of hazard or consequence to society, and exposure (time and vulnerability) (Wang, 2006, 2007). In order to estimate seismic risk, we have to assume a model (distribution) for the probability of earthquake occurrence in time. One commonly used distribution is the Poisson model (Cornell, 1968; Milne and Davenport, 1969; Stein and others, 2006). Under the assumption of a Poisson distribution, seismic risk, expressed in terms of a probability of earthquakes exceeding a specified magnitude (M) in a given exposure time (t), can be estimated by

$$p(n \geq 1, t, \tau) = 1 - e^{-t/\tau}, \tag{2.1}$$

where τ is the average recurrence interval of an earthquake with magnitude of M or greater or ground motion of a certain level or greater. Eqn. 2.1 were used to calculated seismic risks in San Francisco and Memphis, about 39 and 5 to 10 percent chance of exceeding MMI VIII in 50 years in the previous section. Eqn. 2.1 describes a quantitative relationship between seismic hazard and risk under the assumption of a Poisson distribution for earthquake occurrence in time. In other words, seismic risk is an interaction between a seismic hazard (i.e., an earthquake of M7.8 or greater or MMI VIII or greater with a recurrence interval of 100 years) and an exposure (i.e., a building with a life of 50 years). In general, seismic risk can be expressed as

$$Seismic\ Risk = Seismic\ Hazard\ x\ Exposure\,. \tag{2.2}$$

Thus, high seismic hazard does not necessary mean high seismic risk if exposure is lower, and vice versa.

As shown in Eqn. 2.1, in order to estimate seismic risk, we need to know seismic hazard in terms of a level of hazard (i.e., earthquake magnitude, ground motion or MMI at a site, and damage or loss) and its exceedance frequency ($1/\tau$) or recurrence interval (τ). This is the main purpose of a seismic hazard analysis, PSHA in particular.

3. PROBABILISTIC SEISMIC HAZARD ANALYSIS

PSHA was developed in the 1970's for estimating seismic risk, with the aim of accounting for uncertainties in earthquake source, wave propagation path, and site conditions (Cornell, 1968, 1971). A FORTRAN algorithm of Cornell's method (Cornell, 1968, 1971) was developed by McGuire in 1976 and has become the standard PSHA used since then. Thus, modern PSHA is often referred to as the Cornell-McGuire method (Bommer and Abrahamson, 2006). The goal of PSHA is to derive a seismic hazard curve; i.e., a relationship between a ground motion parameter and its frequency of exceedance, utilizing some statistical relationships in seismology and their probability distributions (Cornell, 1968, 1971).

The most important statistical relationship used in PSHA is the ground-motion attenuation relationship. In modern seismology, ground motion Y is modeled as a function of magnitude M and source-to-site distance R with uncertainty E:

$$\ln(Y) = f(M,R) + E\,. \tag{3.1}$$

The uncertainty E is also modeled as a normal distribution with a zero mean and standard deviation $\sigma_{ln,Y}$ (Campbell, 1981, 2003; Joyner and Boore, 1981; Boore and others, 1997; Atkinson and Boore, 2006). Thus, the uncertainty of ground motion Y is a log-normal distribution (Fig. 2). Therefore, Eqn. 3.1 can be rewritten as

$$\ln(Y) = f(M,R) + n\sigma_{\ln,Y}\,, \tag{3.2}$$

where n (a constant) is a number of standard deviations ($\sigma_{ln,Y}$) measured as the difference relative to the median ground motion $f(M,R)$ (Fig. 2). R is either measured as the closest distance to the surface projection of the rupture surface (R_{JB}) or the closest distance to the rupture surface (R_{RUB}). The ground-motion attenuation relationship describes a spatial relationship between a ground-motion parameter and earthquake magnitude and source-to-site distance.

The key step in PSHA is to estimate the exceedance probability for a given ground motion (y), $P[Y \geq y]$, from a ground-motion attenuation relationship, Eqn. 3.1 or 3.2. As shown by Benjamin and Cornell (1970), estimating the exceedance probability for a functional distribution with multiple variables, such as the ground-motion attenuation relationship (i.e., Eqn. 3.1), is very difficult, even impossible. According to Benjamin and Cornell (1970), the joint probability density function for M, R, and E is

$$f_{M,R,E}(m,r,\varepsilon) = f_M(m)\,f_R(r)\,f_E(\varepsilon)\,, \tag{3.3}$$

if and only if M, R, and E are independent random variables. Here $f_M(m)$, $f_R(r)$, and $f_E(\varepsilon)$ are the probability density functions (**PDF**) for M, R, and E, respectively. Then, the exceedance probability $P[Y \geq y]$ can be evaluated from

$$P[Y \geq y] = \iiint f_M(m) f_R(r) f_E(\varepsilon) H[\ln Y(m,r,\varepsilon) - \ln y] dm dr d\varepsilon \ , \tag{3.4}$$

where $H[\ln Y(m,r,\varepsilon)-\ln y]$ is the Heaviside step function, which is zero if $\ln Y(m,r,\varepsilon)$ is less than $\ln y$, and 1 otherwise (McGuire, 1995). Because E is assumed to follow a normal distribution, **PDF** for E is

$$f_E(\varepsilon) = \frac{1}{\sqrt{2\pi}\sigma_{\ln,y}} \exp[-\frac{(\ln y - \ln y_{mr})^2}{2\sigma^2_{\ln,y}}] \qquad -\infty \leq \varepsilon \leq +\infty \, , \tag{3.5}$$

where $\ln(y_{mr}) = f(m,r)$. **PDF** for M is determined by the earthquake occurrence frequency relationship, such as the Gutenberg-Richter relationship. The truncated Gutenberg-Richter relationship is

$$\lambda = \frac{1}{\tau} = e^{\alpha - \beta M} \qquad m_0 \leq M \leq m_{\max} \, , \tag{3.6}$$

where λ is the cumulative number of earthquakes with magnitude equal to or greater than M occurring yearly, α and β are constants, and m_0 and m_{max} are the lower and upper bounds of earthquake magnitude, respectively. **PDF** for M is

$$f_M(m) = \frac{\beta e^{-\beta(m-m_0)}}{1 - e^{-\beta(m_{\max}-m_0)}} \qquad m_0 \leq m \leq m_{\max} \ . \tag{3.7}$$

Determination of **PDF** for R is very complicated, not only depending on the geometric configuration of the fault and site, but also on the source model (i.e., single point versus finite fault). If the fault and site geometric configuration is as in Figure 3, according to Cornell (1968), $f_R(r)$ for a point source is equal to

$$f_R(r) = \frac{r}{L\sqrt{r^2 - 40^2}} \qquad d \leq r \leq r_0 \ . \tag{3.8}$$

In Figure 3, R is epicentral distance. Thus, $P[Y \geq y]$ can be evaluated if the fault and site geometric configuration, source model, and earthquake occurrence frequency relationship are known. This leads to the basic formulation of PSHA for a point-source model (Cornell, 1968, 1971; McGuire, 1976, 2004), or the so-called Cornell-McGuire method (Bommer and Abrahamson, 2006):

$$\gamma(y) = \sum vP[Y \geq y] = \sum v \iint \{1 - \int_0^y \frac{1}{\sqrt{2\pi}\sigma_{\ln,y}} \exp[-\frac{(\ln y - \ln y_{mr})^2}{2\sigma^2_{\ln,y}}] d(\ln y)\} f_M(m) f_R(r) dm dr \, , \tag{3.9}$$

where γ is the annual probability of exceedance for a ground motion $Y \geq y$, and v is the activity rate and equal to

$$v = e^{\alpha - \beta m_0} \, . \tag{3.10}$$

The inverse of the annual probability of exceedance ($1/\gamma$), called the return period (t_r), is equal to

$$t_r(y) = 1/(\sum v \iint \{1 - \int_0^y \frac{1}{\sqrt{2\pi}\sigma_{\ln,y}} \exp[-\frac{(\ln y - \ln y_{mr})^2}{2\sigma^2_{\ln,y}}] d(\ln y)\} f_M(m) f_R(r) dm dr) \, . \tag{3.11}$$

If only a single characteristic earthquake with a recurrence interval of T_0 is considered, Eqn. 3.11 becomes

$$t_r(y) = \frac{T_0}{1 - \int_0^y \frac{1}{\sqrt{2\pi}\sigma_{\ln,y}} \exp(-\frac{(\ln y - \ln y_{mr})^2}{2\sigma^2_{\ln,y}}) d(\ln(y))} \, . \tag{3.12}$$

The denominator in Eqn. 3.12 is the exceedance probability of ground motion at given r and m (the shaded area in Figure 2). Figure 4 shows a PGA hazard curve (solid line) for a site 40 km from a characteristic earthquake of M7.5

with a recurrence interval of 250 years. As shown in Figure 4, a range of return period, from 250 to 100 million years or longer, could be "created" by using the ground-motion uncertainty in PSHA (Eqn. 3.12). The ground motion uncertainty is a spatial relationship (Anderson and Brune, 1999). In other words, PSHA uses the spatial distribution to extrapolate temporal distribution (return periods), or the so-called *ergodic* assumption, "treating spatial uncertainty of ground motions as an uncertainty over time at a single point" (Anderson and Brune, 1999). The *ergodic* assumption is resulted from the invalid mathematical formulation of PSHA (Wang and Zhou, 2007).

As shown above, the Cornell-McGuire method was developed for a point-source model of earthquake with the pre-condition of independency of the ground-motion uncertainty (E). A point-source model was common in the 1970's, but is no longer considered valid today. An earthquake is considered a finite fault in modern seismology, particularly in the ground-motion attenuation relationships (Campbell, 1981, 2003; Joyner and Boore, 1981; Boore and others, 1997; Atkinson and Boore, 2006). Therefore, the Cornell-McGuire method is not based on a valid earthquake physical source model. Furthermore, Wang and Woolery (2008) have shown that there is a dependency of the ground-motion uncertainty on R for the finite fault source. In other words, the mathematical formulation of PSHA is not valid (Wang and Zhou, 2007). Thus, the results from PSHA do not have clear physical meaning and the seismic hazard and risk derived from PSHA are numerical "creations" (Wang and others, 2003, 2005; Wang, 2005, 2006, 2007; Wang and Ormsbee, 2005).

Here are few examples to illustrate the problems of PSHA. Although the annual probability of exceedance or return period defined in PSHA is not a temporal measure (Wang and others, 2003, 2005; Wang, 2005, 2006, 2007; Wang and Ormsbee, 2005), the annual probability of exceedance has been interpreted and used as "the frequency (the number of events per unit of time)" or the return period as "the mean (average) time between occurrences of a seismic hazard, for example, a certain ground motion at a site, or a certain level of damage or loss" (McGuire, 2004). The return period has been equated to the average recurrence interval (τ) in Eqn. 2.1 to estimate seismic risk, and this is exactly how the ground motions with 10, 5, and 2 percent PE in 50 years are calculated (Frankel and others, 1996, 2002; Frankel, 2004; McGuire, 2004; Petersen and others, 2008). By definition, the ground motions with 10, 5, and 2 percent PE in 50 years are seismic risk, but they are called seismic hazard (Frankel and others, 1996, 2002; Frankel, 2004; Petersen and others, 2008). Even PSHA practitioners could not understand what the real meaning of the ground motions with 10, 5, and 2 percent PE in 50 years is (Frankel, 2004, 2005). Thus, the selection of the ground motion with 2 percent PE in 50 years for seismic design consideration in the United States became "the number that engineers want" or "what seismologists tell us is the best estimate."

As shown in Figure 4, PSHA could derive ground motion with a return period of 1 million years or longer, even from a single characteristic earthquake that is assumed to occur every 250 years on average. This explains how the extremely high ground motion (5.0g PGA or larger) at Yucca Mountain, Nev., and physically impossible ground motion at nuclear power plants in Switzerland were derived from PSHA (Stepp and others, 2001; Klügel, 2005). The ground motion with a return period of 1 million years or longer is a numerical "creation" of PSHA from the ground-motion uncertainty because there are only a few hundred years of instrumental and historical records and 10,000 years of geologic records (Holocene age) available (Wang, 2005, 2006, 2007). PSHA practitioners have even argued about the ways to "create" the ground motion with a long return period (McGuire and others, 2005; Abrahamson and Bommer, 2005; Musson, 2005).

4. SEISMIC HAZARD ASSESSMENT

An alternative approach, called seismic hazard assessment (SHA), was developed by Wang (2006, 2007) with the aim of deriving a hazard curve that can be used for seismic risk assessment. This approach directly utilizes the ground-motion attenuation and earthquake occurrence frequency relationships (i.e., Eqns. 3.1 and 3.6). From Eqn. 3.1, M can be expressed as a function of R, $\ln Y$, and E as

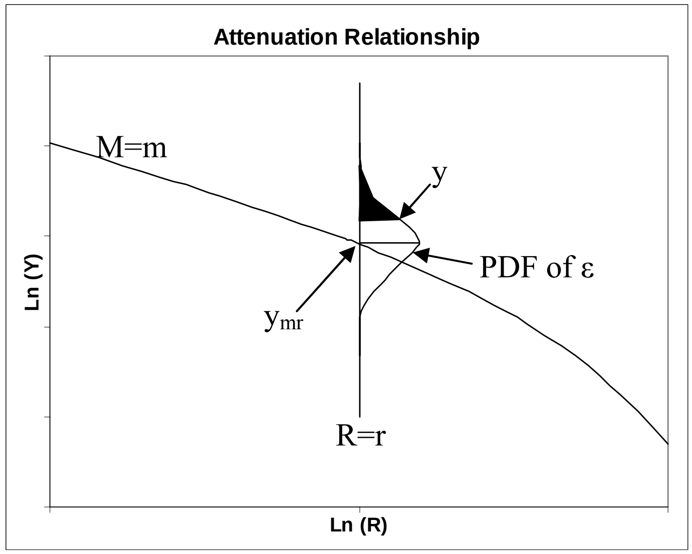

Figure 2. Ground-motion attenuation relationship.

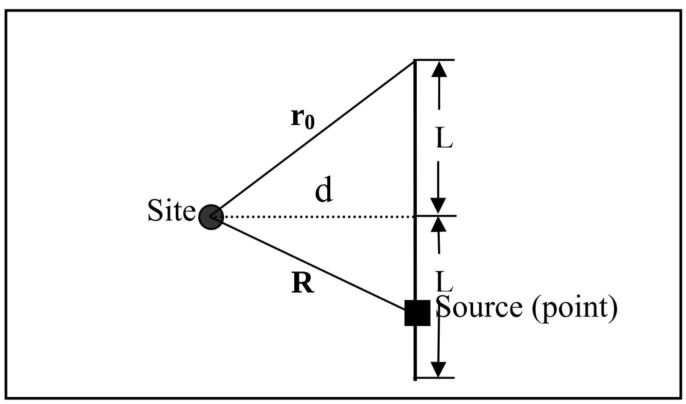

Figure 3. Geometric configuration for a hypothetical line source and site.

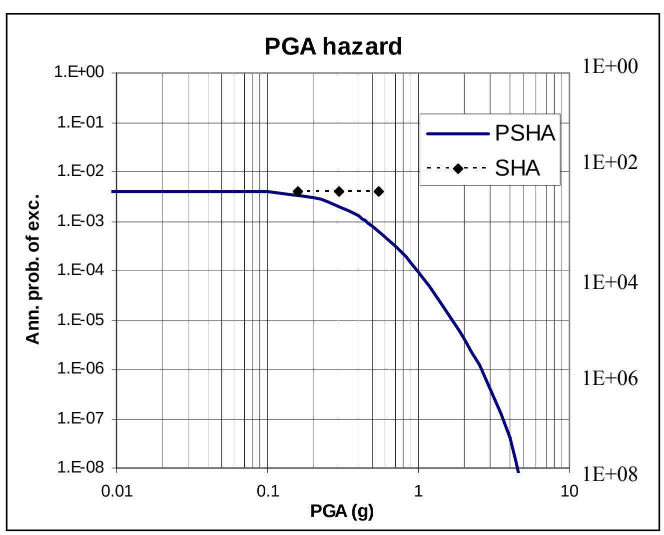

Figure 4. PGA hazard curve at a site 40 km from a single characteristic earthquake of M7.5 with a recurrence interval of 250 years. A median PGA of 0.3g and standard deviation (log) of 0.6 were assumed.

$$M = g(R, \ln Y, E)\,. \tag{4.1}$$

Combining Eqns. 3.6 and 4.1 results in

$$\tau = e^{-\alpha + \beta g(R, \ln Y, E)}\,. \tag{4.2}$$

Eqn. 4.2 describes a relationship between the ground motion (ln*Y*) with an uncertainty (*E*), the recurrence interval (τ), and distance (*R*); i.e., a hazard curve. If only a single characteristic earthquake is considered, Eqn. 4.2 becomes

$$\tau = T_0\,. \tag{4.3}$$

The PGA hazard for a site 40 km from a characteristic earthquake of M7.5 with a recurrence interval of 250 years calculated from SHA is shown in Figure 4. In comparison with PSHA, the PGA hazard derived from SHA is consistent with its input; i.e., a single earthquake that is assumed to occur every 250 years on average. SHA also gives a level of uncertainty explicitly.

Figure 5 shows a PGA hazard curve at a site 30 km from the New Madrid Seismic Zone in the central United States. The PGA hazard curve was derived from the historical earthquakes with magnitudes between M4.0 and M5.0 in the New Madrid Seismic Zone (Bakun and Hopper, 2004) and the ground-motion attenuation relationship of Campbell (2003). A characteristic earthquake of M7.5 with a recurrence interval of 500 years was also used. As shown in Figure 5, the levels of uncertainty of PGA are derived explicitly. The hazard curves with 16 percent and 84 percent confidence levels are equivalent to the hazard curves with median plus/minus one standard deviation. The result from SHA (hazard curve) is similar to those derived by flood-frequency analysis (Gupta, 1989; Wang and Ormsbee, 2005) and wind-frequency analysis (Sacks, 1978). From Figure 5, we can get a median PGA of 0.44g with annual exceedance rate of 0.002 or recurrence interval of 500 years. Using this recurrence interval, Eqn. 2.1 will give a 10 percent PE in 50 years for the median PGA of 0.44g. This median PGA is directly generated from the characteristic earthquake of M7.5.

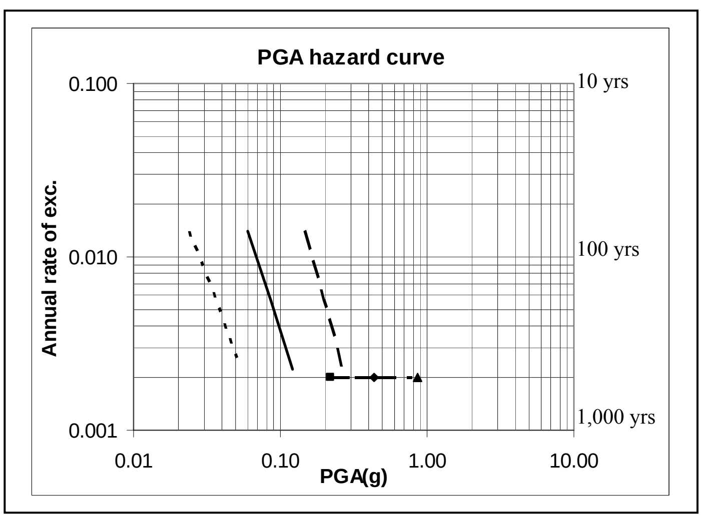

Figure 5. PGA hazard curves at a site 30 km from the New Madrid faults. Solid line─median PGA, short-dashed line─16 percent confidence, long dashed line─84 percent confidence. Diamond─median (mean) PGA, square─PGA with 16 percent confidence, and triangle─PGA with 84 percent confidence for the characteristic earthquake of M7.5.

This example also shows that SHA and DSHA derive the same results for a single characteristic earthquake. As shown by Reiter (1990), Kramer (1996), and Krinitzsky (2002), only ground motion(s) from a single or few earthquakes that have maximum impacts at a site is desired in deterministic seismic hazard analysis (DSHA). The earthquake(s) could be a characteristic event, a maximum credible earthquake, maximum considered earthquake, or scenario earthquake. As pointed out by Wang and others (2004), these earthquakes can always be associated with a recurrence interval. Therefore, DSHA is a special case of SHA.

Figure 6 shows a PGA hazard curve for the historical earthquakes in San Francisco from 1769 to 2001 and the ground-motion attenuation relationship of Boore and others (1997). It also shows the PGA hazard curve in San Francisco (N37.775/W122.418) from the 2002 National Seismic Hazard Mapping project (Frankel an others, 2002). As shown in Figure 6, SHA provides a PGA hazard curve that is consistent with the input data: an interval of about 230 years which means a recurrence interval of about 230 years for ground motion exceedance. In contrast to SHA, PSHA could derive PGA with return period of 100,000 years although the recurrence intervals of the large and characteristic earthquakes in San Francisco area are in the order of a few hundred years (Frankel and others, 2002). There is no knowledge of or information about an earthquake with a 100,000 years recurrence interval in the input data (Frankel and others, 2002). The ground motion with 100,000 years return period is a purely numerical "creation" of PSHA.

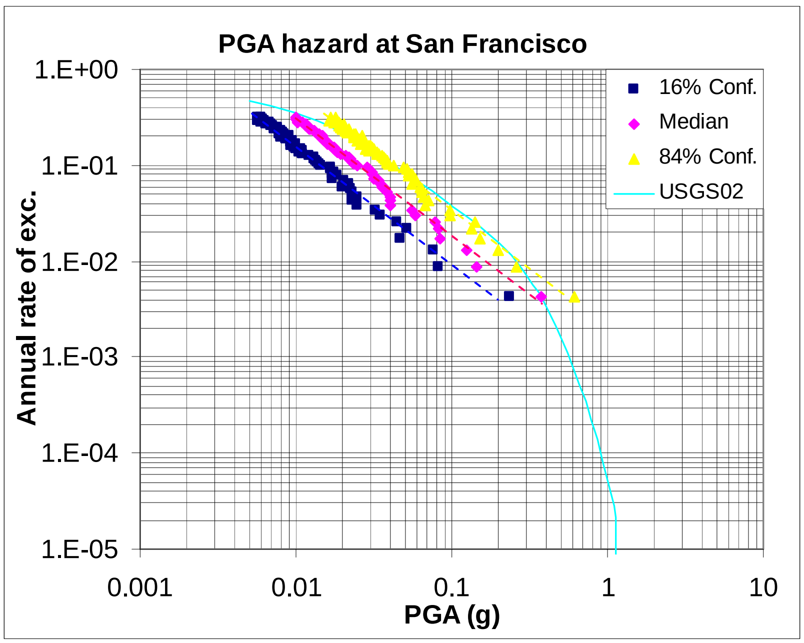

Figure 6. PGA hazard curve for San Francisco.

5. DISCUSSION

Dealing with uncertainty is a way of life because the world is full of it. Risk is an important concept for characterizing and managing uncertainty. Another important concept associated with risk is hazard. Although hazard and risk have often been used interchangeably, they are fundamentally different. In general, hazard describes a natural or man-made phenomenon that could cause harm to society, while risk describes a probability of such harm if someone or something is exposed to the hazard. In other words, risk describes an interaction relationship between a hazard and exposure. Hazard may or may not be mitigated, but risk can be reduced. Therefore, risk plays a more important role in decision-making.

Similarly, seismic hazard describes a natural phenomenon associated with an earthquake (i.e., fault rupture, ground motion, and liquefaction) that could cause harm and is quantified by two parameters (a level of measurement and its occurrence frequency), whereas seismic risk describes a probability of harm if someone or something is exposed to a seismic hazard and is quantified by three parameters (a probability, level of measurement, and exposure time). Seismic hazard may or may not be mitigated. For example, fault rupture and ground motion cannot be mitigated because tectonic movement (the main cause of earthquakes) cannot be stopped, but liquefaction at a site can be mitigated by engineering measures. Seismic risk can be reduced through either mitigation of seismic hazard or reduction of exposure or both.

The main goal of a seismic hazard analysis is to estimate the seismic hazard that can be used for seismic risk assessment. This is especially true for PSHA. PSHA was developed for seismic risk assessment and considers all uncertainties in earthquake source, path, and site conditions (Cornell, 1968, 1971; McGuire, 1976, 2004). This is why PSHA is so appealing and has become the dominant method for seismic hazard and risk assessment throughout the world. Another advantage of PSHA is that it could provide a seismic hazard estimate to satisfy any need or requirement because its end result is a curve that provides a range of hazard (i.e., 0.0 to 10.0g PGA). As shown in this paper, however, PSHA is based on an invalid earthquake physical model (point source) and incorrect mathematical formulation. Therefore, seismic hazard and risk derived from PSHA are difficult to explain and understand. Furthermore, the use of PSHA has led to both overly conservative and unsafe engineering design and policy, which has a significant consequence to society. The ground motion with 10 percent PE in 50 years was selected as the design ground motion in China (Hu and Gao, 2004); it indicates 0.1 to 0.15g PGA in the Wenchuan earthquake area. The recorded PGA was in the range of 0.3 to 0.6g in the epicentral area of the Wenchuan earthquake. This is one of the reasons that so many building were damaged and collapsed in the Wenchuan earthquake. Furthermore, PSHA has also been used in seismic hazard and risk assessment for nuclear facilities (SFNSI, 1999; USNRC, 2007). The consequence of using PSHA is significant.

As an alternative, SHA utilizes earthquake occurrence frequency and modern ground-motion attenuation relationships directly. SHA calculates seismic hazard from all earthquake sources, but considers all uncertainties explicitly. Thus, hazard estimates from SHA are consistent with modern science. The hazard curve derived from SHA is similar to those derived from flood-frequency and wind-frequency analyses (Sacks, 1978; Gupta, 1989; Wang and Ormsbee, 2005) and has the same meaning (Wang, 2006, 2007). SHA can be directly used for risk assessment. Also, SHA is similar to the approaches of Milne and Davenport (1969) and Stein and others (2006).

6. CONCLUSION

Selection of a level of seismic hazard or risk for engineering design is complicated. It depends not only on science, but also on social, economic, and other issues. A good seismic design should be based on sound science, however. Therefore, it is essential for seismologists and engineers to understand seismic hazard and risk, as well as the science behind them. Unfortunately, there is clear gap between seismologists and engineers in understanding of seismic hazard and risk, particularly those derived from PSHA. Although PSHA has been the most widely used method in seismic hazard and risk assessments, it is not based on modern science. This is why seismic hazard and risk derived from PSHA are so difficult to explain and understand. The use of PSHA may not result in sound and safe seismic design. As an alternative, SHA provides scientifically consistent seismic hazard and risk estimates.

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