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Understanding Seismic Hazard and Risk Assessments: An Example in the New Madrid Seismic Zone of the Central US

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UNDERSTANDING SEISMIC HAZARD AND RISK ASSESSMENTS: AN EXAMPLE IN THE NEW MADRID SEISMIC ZONE OF THE CENTRAL UNITED STATES

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ABSTRACT

Seismic hazard and risk are fundamentally different concepts. Seismic hazard describes phenomena generated by earthquakes that have potential to cause harm, but seismic risk is the likelihood (chance) of experiencing a specified level of seismic hazard in a given time exposure. Seismic hazard occurs naturally and can be evaluated from instrumental, historical, and geological observations. Seismic risk depends not only on the hazard and exposure, but also on models (i.e., time-independent [Poisson] and time-dependent ones) used to describe the occurrence of earthquakes. High seismic hazard does not necessarily mean high seismic risk, and vice versa.

Probabilistic seismic hazard analysis (PSHA) is a commonly used method to derive seismic hazard curve – a relationship between a ground motion parameter and its return period. The so-called return period in PSHA is a modification of the recurrence intervals of earthquakes using the probabilities of ground motions. The return period is not an independent temporal parameter, but it has been inappropriately treated as the mean recurrence interval of an independent event (ground motion) and used in seismic risk analysis. In the New Madrid Seismic Zone of the central United States, the mean recurrence interval of large earthquakes (~M7.5) is about 500 years, and the risk posed by such events or their ground motions (consequences) is about 10 percent probability of exceedance (PE) in 50 years. However, PSHA could predict ground motions with a range of return periods, up to 10^6 to 10^8 years, for the same earthquakes. In other words, use of PSHA could derive a range of risk estimates for a single earthquake. Thus, the use of PSHA for seismic risk analysis is not appropriate and confusing.

An alternative method, seismic hazard assessment (SHA), is presented in this paper. SHA is comparable to flood and wind hazard analyses and can be used for risk analysis in a similar way.

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Introduction

"Risk assessment is all about risk management. The only reason you do an assessment is because somebody has to make a risk-management decision" (Smith, 2005). Risk is something that everyone deals with every day and influences almost every aspect of decision-making. Although risk has different meanings and definitions among different professions and stakeholders, it can generally be quantified by three terms: probability, hazard (loss or other measurements), and time exposure. An example of risk from health sciences is the probability of getting cancer by smoking a pack of cigarettes per day (hazard) over lifetime (70 years on average). In the financial market, risk is defined as the probability of losing a certain amount of money (loss) over a period.

Seismic risk also has different meanings and definitions among different professions and stakeholders. "A single number is not a big enough concept to communicate the idea of risk" (Smith, 2005). For example, for seismologists, seismic risk is defined as the probability of earthquakes with a certain magnitude or greater striking at least once in a region during a specific period. For structural engineers, seismic risk is defined as the probability that ground motion (consequence of an earthquake) at a site of interest exceeds a specific level at least once in a given period (Cornell, 1968; Milne and Davenport, 1969). For an asset owner, seismic risk is the probability of damage (loss) caused by earthquakes in a specific period.

The difficulty in assessing seismic risk, as with risk posed by other natural events (e.g., hurricanes, winter storms, volcanic eruptions, etc.), is in characterizing hazard. Seismic hazard describes earthquakes or consequences of the earthquakes (i.e., ground motion, liquefaction, etc.) and their occurrence frequencies. Seismic hazards can be quantified from seismic hazard analysis, such as probabilistic seismic hazard analysis (PSHA) and deterministic seismic hazard analysis (DSHA). Seismic hazard analysis is based on statistics of earthquakes. What makes characterizing seismic hazards difficult is the paucity of observations, especially in the central and eastern United States, where no observations are available for large earthquakes. At least 13 sets of statistical parameters are used to describe ground-motion attenuations – relationships between ground motion, magnitude of an earthquake, and epicentral distance (EPRI, 2003). All these attenuation relationships were based on computer modeling and few observations from small and moderate earthquakes. These different attenuation relationships predict significantly different ground motions.

Seismic hazard estimates can be dramatically different if different methods and statistical parameters are used. The same is true for seismic risk estimates. Hence, it is worthwhile to review the definitions and methodologies of seismic risk and seismic hazard analyses. Seismic hazard and risk being estimated in the New Madrid Seismic Zone will be reviewed and discussed.

Seismic Risk

In earthquake engineering, risk was originally defined as the probability that Modified Mercalli Intensity (MMI) or ground motion at a site of interest will exceed a specific level at least once in a given period, a definition that is analogous to flood and wind risks (Cornell, 1968; Milne and Davenport, 1969). The risk calculation is based on a

Poisson model, which assumes that earthquake occurrence is independent of time and independent of the past history of occurrences or nonoccurrences. Although the Poisson model may not be the best model for earthquake occurrence, especially large earthquake occurrence in which the tectonic stress is released when a fault fails and must rebuild before the next one can occur at that location (Stein and Wysession, 2003), it is the standard model for seismic risk analysis, as well as for other types of risk analysis.

According to the Poisson model (Cornell, 1968; Stein and Wysession, 2003), the probability of n earthquakes of interest occurring in an area or along a fault during an exposure time (t) in year is

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

where τ is the average recurrence interval (or average recurrence rate, $1/\tau$) of earthquakes equal to or greater than a specific magnitude (M). The probability that no earthquake will occur is

$$p(0,t,\tau) = e^{-t/\tau}. \tag{2}$$

The probability of at least one (one or more) earthquake equal to or greater than a specific magnitude (M) occurring within t years is

$$p(n \geq 1,t,\tau) = 1 - p(0,t,\tau) = 1 - e^{-t/\tau}. \tag{3}$$

Eq. 3 can be used to calculate risk, expressed as X percent PE in t years, for a given average recurrence interval (τ) of earthquakes of a certain magnitude (M) or greater. For example, for an average recurrence interval of about 500 years of an M7.0 earthquake or larger, the risk that the area will be struck by at least one such event is about 10 percent probability in 50 years. Eq. 3 can also be used to calculate the average recurrence interval τ of earthquakes with a certain magnitude (M) or greater for a given PE in a specific time. For example, for 10, 5, and 2 percent PE in 50 years that are commonly considered in earthquake engineering (BSSC, 1998; ICC, 2000), Eq. 3 gives τ of 500, 1,000, and 2,500 years, respectively, for earthquakes with a certain magnitude or greater. In another words, ground motions with 10, 5, and 2 percent PE in 50 years are equivalent to the motions with 500-, 1,000-, and 2,500-year recurrence intervals. For comparison, 1 percent PE in 1 year is usually considered for building design for floods (ICC, 2000). According to Eq. 3, this risk level is equivalent to large floods of 100-year recurrence interval (100-year flood). Similarly, 2 percent PE in 1 year is usually considered for building design for wind (ICC, 2000) which is equivalent to strong wind of 50-year recurrence interval.

The above calculations are for natural events (earthquakes, hurricanes, volcanic eruptions, winter storms, etc.) only, and are expressed in terms of the event magnitude (M7.5 earthquake, Category 5 hurricane, e.g.) with X percent PE in t years. In other words, the level of hazard is expressed in terms of earthquake magnitude. For engineering purposes, the level of hazard in terms of ground motion (peak ground acceleration [PGA] and response accelerations) is desired, however. In another words, engineers need to know the consequences of earthquakes at a given point. This is similar to the situation in flood and wind engineering, in which the consequences of floods and winds, such as peak discharge and 3-second gust wind speed, must be known for specific sites. The consequences of natural events and their occurrence intervals (τ) are generally determined through hazard analyses (i.e., seismic hazard analysis in seismology and flood-frequency analysis in hydrology).

Probabilistic Seismic Hazard Analysis (PSHA)

PSHA is the most used method to assess seismic hazard and risk for input into various aspects of public and financial policy. For example, the U.S. Geological Survey used PSHA to develop the national seismic hazard maps (Frankel and others, 1996, 2002). These maps are the basis for national seismic safety regulations and design standards, such as the NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures (BSSC, 1998) and the 2000 International Building Code (ICC, 2000). It has been concluded that PSHA inherits intrinsic drawbacks and is not appropriate to be used (Wang and others, 2003, 2005; Wang and Ormsbee, 2005; Wang, 2005a, 2005b, 2006). For the purpose of demonstrating the fundamental difference between PSHA and the new method (Wang, 2006) to be discussed later, it is necessary to briefly review the basic concepts of PSHA here.

PSHA was originally developed by Cornell in 1968 for estimating engineering risk in comparison with the analogous flood or wind problem. A similar method was also developed by Milne and Davenport (1969). Cornell (1971) extended his method to incorporate the possibility that ground motion at a site could be different for different earthquakes of the same magnitude at the same distance (i.e., ground motion uncertainty). A FORTRAN algorithm of Cornell's method (Cornell, 1971) was developed by McGuire in 1976 and has been the standard PSHA ever since. There is a fundamental difference between the formulations in Cornell (1968) and those in Cornell (1971); the former does not include ground-motion uncertainty, whereas the latter does, but incorrectly.

In PSHA, an annual probability of exceedance (γ) of a ground-motion amplitude y is (McGuire, 1995),

$$\gamma(y) = \sum_i v_i \iiint f_M(m) f_R(r) f_\varepsilon(\varepsilon) P[Y > y \mid m, r, \varepsilon] \, dm\,dr\,d\varepsilon \, , \tag{4}$$

where v_i is the activity rate for seismic source i; $f_M(m)$, $f_R(r)$, and $f_\varepsilon(\varepsilon)$ are earthquake magnitude, source-to-site distance, and ground motion density functions, respectively; ε is ground motion uncertainty; and $P[Y>y|m,r,\varepsilon]$ is the probability that Y exceeds y for a given m and r. The triple integration in equation (4) is very complicated, and a numerical solution is required. For characteristic seismic sources, Eq. 4 can be simplified as

$$\gamma(y) = \sum_i \frac{1}{T_i} P_i(Y > y) \, , \tag{5}$$

where T_i is the average recurrence interval of the characteristic earthquake for source i, and $P_i(Y \geq y)$ is the probability that the ground motion (Y) from source i will exceed y.

The inverse of annual probability of exceedance ($1/\gamma$), called the return period, is often used: for example, a 2,500-year return period (the inverse of annual probability of exceedance of 0.0004). The return period has been erroneously equated to the average recurrence interval (τ) of earthquakes and used to calculate seismic risk (Frankel and others, 1996, 2002; Frankel, 2005). As shown in Eqs. 4 and 5, the return period is a function of the recurrence intervals of earthquakes and the probabilities that the ground motion will exceed a specific value if the earthquakes occur. In other words, the return period is a modification of the recurrence intervals (time-domain characteristics) of earthquakes using the uncertainty of ground-motion measurement at a site (spatial characteristics) without physical basis (Wang and Ormsbee, 2005; Wang, 2005a, b). This can be clearly seen for a single characteristic seismic source:

$$\gamma(y) = \frac{P[Y > y)}{T} \quad or \ \mathrm{Re}\,turn\ Period = \frac{T}{P[Y > y]}. \tag{6}$$

As shown in Eq. 6, the return period is equal to the actual recurrence interval of an earthquake divided by the probability of ground motion. For example, a return period of 2,500 years is equal to a recurrence interval of about 500 years for earthquakes with magnitude similar to the 1811−1812 New Madrid event (M7.0−8.0) divided by 20 percent probability that the ground motion will be exceeded in the New Madrid Seismic Zone (Frankel, 2004; Wang and others, 2003, 2005).

These calculations clearly show that the return period defined in PSHA is not equivalent to the recurrence interval of earthquakes. Therefore, it is not appropriate to use the return period for estimating seismic risk (Eq. 3). Furthermore, PSHA also inherits several obvious drawbacks as discussed in Wang and others (2003), Wang and Ormsbee (2005), Wang (2005a, b), and Wang (2006).

Seismic Hazard Assessment

An alternative method, called seismic hazard assessment (SHA), was proposed by Wang (2006) and is briefly described here. Similar to flood occurrences in hydrology, earthquake occurrences follow the well-known Gutenberg-Richter magnitude-frequency relationship:

$$Log(N) = a - bM \ or \ N = 10^{a-bM}, \tag{7}$$

where N is the cumulative number of earthquakes with magnitude equal to or greater than M occurring yearly, and a and b are constants. Eq. 7 can be rewritten as

$$N = e^{2.303a-2.303bM} \quad or \ \frac{1}{N} = e^{-2.303a+2.303bM}. \tag{8}$$

The Gutenberg-Richter relationship describes the relationship between the average recurrence rate (N) or recurrence interval ($1/N$) and earthquakes equal to or greater than a specific magnitude (M). Therefore,

$$\tau = \frac{1}{N} = e^{-2.303a+2.303bM}. \tag{9}$$

Eqs. 3 and 9 determine seismic risk in terms of earthquake magnitude (M) with X percent PE in t years. Also, in seismology, observed ground motion at a site with an epicentral distance R from an earthquake of magnitude M can be described by (Campbell, 1981)

$$\ln Y = a_0 + f(M,R) + \varepsilon, \tag{10}$$

where a_0 is a constant, ε is uncertainty, and f is a function of M and R. The uncertainty (ε) can be modeled using a log-normal distribution with a standard deviation (σ). From Eq. 10, M can be expressed in terms of R, $\ln Y$, and ε as

$$M = M(R, \ln Y, \varepsilon). \tag{11}$$

Combining Eqs. 9 and 11 results in

$$\tau = e^{-2.303a+2.303bM(R,\ln Y,\varepsilon)}. \tag{12}$$

Eq. 12 describes a relationship between the ground motion ($\ln Y$) with an uncertainty (ε), the earthquake recurrence interval (τ), and distance (R); i.e., a hazard curve. Eqs. 3 and 12 together determine seismic risk in terms of ground motion (Y) of X percent PE in t years with an uncertainty (ε) or confidence level.

Hazard and Risk in the New Madrid Seismic Zone

Seismicity in the New Madrid Seismic Zone is currently quite low, as compared with California. The straight line in Fig. 1 shows the Gutenberg-Richter relationship for earthquakes with magnitudes between M4.0 and M5.0 in the New Madrid Seismic Zone (Bakun and Hopper, 2004). The *a* and *b* values are estimated to be about 3.15 and 1.0, respectively. The *b* value of 1.0 is consistent with that used in the national seismic hazard maps (Frankel and others, 1996, 2002). If we extend the straight line in Fig. 1 to large magnitude, it would predict very long recurrence intervals for large earthquakes, about 700 years for M6.0, 7,000 years for M7.0, and 70,000 years for M8.0. This is not consistent with paleoseismic interpretations by Tuttle and others (2002). Frankel and others (1996, 2002) treated these large earthquakes as characteristic events, even though it is difficult to determine whether they are characteristic (Stein and Newman, 2004).

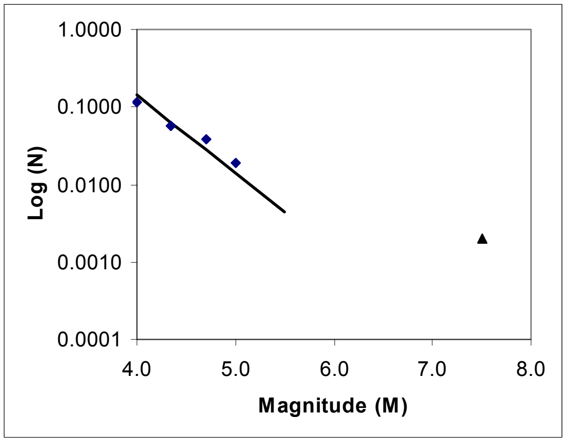

Figure 1. Gutenberg-Richter relationship for the New Madrid Seismic Zone. Diamonds ─ historical rates, triangle ─ geological rate.

As shown in Fig. 1, there is no data for earthquakes with magnitude between M5.5 and M7.0 in the New Madrid Seismic Zone. The earthquakes with magnitude between M5.5 and M7.0 are of safety concerns, however. It is difficult how to fill the data gap and how to determine whether the large earthquakes are characteristic. These require further study. In this paper, we assume that: the *a* and *b* values could be applied to earthquakes with magnitudes up to M5.5, and the large earthquake (~M7.5) is characteristic. Under these assumptions, we have:

$$\begin{cases} \tau = e^{-7.254+2.303M} & \mathit{for}\, 4.0 \le M \le 5.5 \\ \tau = 500 & \mathit{for}\;\; M \approx 7.5 \end{cases} . \tag{13}$$

Campbell (2003) described a PGA attenuation relationship for the central and eastern United States for very hard rock (Vs of 2.8 km/sec):

$$\ln(PGA) = 0.0305 + 0.633M - 0.0427(8.5 - M)^2 - 1.591\ln R \quad , \qquad (14)$$
$$+ (-0.00428 + 0.000483M)r_{rup} + \varepsilon_a + \varepsilon_e$$

where $r_{rup} \leq 70$ km is the closest distance to fault rupture, ε_a is aleatory (randomness) uncertainty, and ε_e is epistemic uncertainty, and

$$R = \sqrt{r_{rup}^2 + [c_7 \exp(c_8 M)]^2} \, . \qquad (15)$$

The standard deviation (σ_{lnY}) of ε_a is magnitude dependent and equal to

$$\sigma_{\ln Y} = \left\langle \begin{matrix} c_{11}+c_{12}M & \text{for } M<7.16 \\ c_{13} & \text{for } M\geq 7.16 \end{matrix} \right. . \qquad (16)$$

Coefficients c_7, c_8, c_{11}, c_{12}, c_{13}, and the standard deviation of ε_e are listed in Campbell (2003).

From Eqs. 13, 14, and 15, we can derive a seismic hazard (PGA) curve for a site at a certain distance from the source. Fig. 2 shows the median (ε=0.0) PGA hazard at a site 30 km from the source. Also shown in Fig. 2 are the PGA hazard curves with 16 percent and 84 percent confidence levels (i.e., ±1.0σ). These hazard curves are similar to those derived in flood-frequency analysis (Gupta, 1989; Wang and Ormsbee, 2005) and wind-frequency analysis (Sacks, 1978). Points on the hazard curves have a similar meaning. For example, the median PGA of about 0.08g has an average recurrence rate of 0.007, or a recurrence interval of 143 years. On average, this PGA (0.08g) occurs at least once in a 143-year period because it is a consequence of an earthquake with a magnitude equal to 5.25 or greater (Fig. 1). The PGA's with confidence levels of 16 and 84 percent are about 0.034 and 0.19g at the recurrence interval of 143 years, respectively. As shown in Fig. 2, the characteristic earthquake (~M7.5) dominates the hazard in the New Madrid Seismic Zone; i.e., 0.44g median PGA, 0.22g and 0.86g PGA's with 16 and 84 percent confidence level.

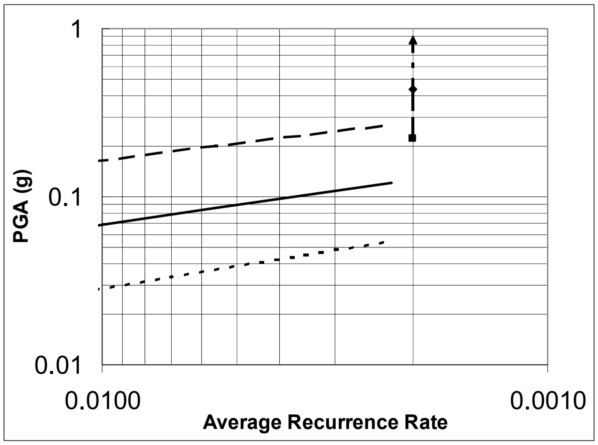

Figure 2. PGA hazard curves at a site 30 km from the New Madrid faults. Solid line─median PGA, short-dashed line─16 percent confidence, long dashed line─84 percent confidence. Diamond─median (mean) PGA, square─PGA with 16 percent confidence, and triangle─PGA with 84 percent confidence for the characteristic earthquake of M7.5.

The hazard curve (Fig. 2) can be used to calculate risk in terms of ground motion (PGA) with X percent PE in *t* years. For example, for the recurrence interval of 143 years, Eq. 3 gives about 30 percent PE in 50 years for median, 16 and 84 percent confident PGA's of 0.08, 0.034 and 0.19g, respectively, at the site. Similarly, the median, 16 and 84 percent confident PGA's with 10 percent PE in 50 years are 0.44, 0.22 and 0.86g, respectively, at the site. If an exposure time (*t*) of 30 years is considered, PE's are 19 and 6 percents for the recurrence intervals of 143 and 500 years, respectively.

Discussion

Seismic hazard and risk assessments not only depend on the definitions of hazard and risk, but also on the methodologies used. Seismic hazard is the intrinsic natural occurrence of earthquakes or the resultant ground motion and other effects and their frequencies, whereas seismic risk is the probability (danger) of hazard (earthquakes or their effects) to life and property during a certain time period. Because many different definitions of hazard and risk have been used, the resultant estimates differ dramatically.

The risk posed by earthquakes with magnitude of about M7.5 is about 10 percent PE in 50 years in the New Madrid Seismic Zone. If SHA is used, the risk posed by ground motion at a given site generated by such earthquakes is also about 10 percent PE in 50 years, consistent with physics and intuition. However, PSHA has predicted 5 percent PE in 50 years for ground motion generated by these earthquakes (Frankel, 2004; Wang and others, 2005). As a matter of fact, by equating the so-called return period to the actual average recurrence interval of earthquakes, PSHA could derive ground motion with a range of PE, from 10% to an infinitely small number, in 50 years for the same earthquakes in the New Madrid Seismic Zone (Frankel, 2004; Wang and others, 2005).

Although it is the most widely used method for seismic hazard and risk analyses, PSHA has several intrinsic drawbacks: (1) unclear physical basis, (2) obscure uncertainty, and (3) ambiguous selections of design ground motion (Wang and other, 2003; Wang and Ormsbee, 2005; Wang, 2005a, b; Wang, 2006). These drawbacks may result in either unsafe or overly conservative engineering design. For example, the ground motion with 10 percent PE in 50 years (risk) or, equivalently, with 500-year return period (hazard) given by the USGS (Frankel and others, 1996, 2002) may not be adequate for building seismic design in the New Madrid area because it does not include any contribution from the characteristic earthquakes in the New Madrid Seismic Zone (Frankel, 2004, 2005; Wang and others, 2005). The characteristic earthquakes are of safety concern in the New Madrid area. On the other hand, PSHA could derive astronomical ground motion values (10g PGA or greater) with a return period of 10^6 to 10^8 years at the proposed nuclear waste repository at Yucca Mountain, Nev. (Stepp and others, 2001); these ground motions are physically unrealistic and would be too conservative for engineering design.

SHA, developed in this paper for estimating seismic hazards (ground motions) at a point of interest, is similar to the procedure described by Cornell (1968), but there is one significant difference: Cornell (1968) treated the uncertain epicentral distance as an independent term with a probability density function and incorporated the uncertainty directly into hazard analysis with the median ground-motion attenuation relationship ($\varepsilon =$

0) only. In SHA, the epicentral distance uncertainty is implicitly included in the ground-motion attenuation relationship with a total uncertainty ($\varepsilon \neq 0$). As shown in the ground-motion attenuation relationships (EPRI, 2003; Klügel, 2005), the total uncertainty (ε) is not only a function of the epicentral distance, but also of other earthquake source parameters, such as stress drop. Therefore, it is more appropriate to directly use the ground-motion attenuation relationship and its uncertainty to estimate the hazards (ground motions) 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.

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