

A Short Note on Probabilistic Seismic Hazard Analysis

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Prepared for
United States Department of Energy Portsmouth/Paducah Project Office
Acknowledgment: This material is based upon work supported by the Department of Energy under
Award Number DE-FG05-03OR23032.



2007

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Abstract

Although probabilistic seismic hazard analysis (PSHA) is the most widely used method to assess seismic hazard and risk for various aspects of public and financial policy, it contains a mathematical error in the formulations. This mathematical error results in difficulties in understanding and application of PSHA. A new approach is presented in this paper. Seismic hazards derived from the new approach are consistent with the inputs in temporal and spatial characteristics. The hazard curve derived from the new approach is similar to those derived from flood and wind hazard analyses and can be used in risk analysis in a similar way.

Introduction

Probabilistic seismic hazard analysis (PSHA) has become the most widely used method to assess seismic hazard and risk for various aspects of public and financial policy since it was introduced by Cornell (1968) more than three decades ago. For example, the U.S. Geological Survey used PSHA to develop the national seismic hazard maps (Algermissen and Perkins, 1976; 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), the 2000 International Building Code (ICC, 2000), and the 2000 International Residential Code (ICC, 2000). The seismic design parameters for nuclear facilities, such as nuclear power plants, are also determined from PSHA (NRC, 1997).

The use of PSHA has caused difficulty in selecting a hazard level (ground motion) or risk level (ground motion with a probability of exceedance in a period) for engineering designs and other policy applications, however. For example, the 2000 International Residential Code (IRC-2000), based on the 1996 USGS maps with 2 percent probability of exceedance (PE) in 50 years, gives a design peak ground acceleration (PGA) of about 0.6g for Paducah, Ky., higher than the design PGA for San Francisco (Wang and others, 2003; Malhotra, 2005). An extremely high ground motion (5.0g PGA or greater) would have to be considered for engineering design of the nuclear waste repository in Yucca Mountain, Nev., if PSHA is applied (Stepp and others, 2001; Bommer and others, 2004). The use of PSHA also has the results that “the seismic risk to life and property from code-designed buildings is very different in different parts of the country” (Malhotra, 2005).

The difficulty in using PSHA for engineering designs and policy applications is not only caused by lack of understanding and lack of data on earthquakes, but also by the technical deficiencies of PSHA. It is well known that different practitioners could derive greatly different PSHA results (SSHAC, 1997). SSHAC (1997) concluded “that differences in PSHA results are due to procedural rather than technical differences.” In other words, “many of the major potential pitfalls in executing a PSHA are procedural rather than technical in character” (SSHAC, 1997). Technical problems may still be one of the main reasons for the large differences, however (Wang, 2005). They have resulted in: (1) unclear physical basis; (2) obscure uncertainty; and (3) difficulty in determining a correct choice (Wang and Ormsbee, 2005; Scherbaum and others, 2005; Wang, 2005, in press (a), (b)).

PSHA clearly inherits some technical deficiencies (Wang and others, 2003, 2005; Scherbaum and others, 2005; Wang and Ormsbee, 2005; Wang, 2005, in press (a), (b)). In this short note, the formulations of current PSHA will be reviewed and the probable causes of those technical deficiencies will be discussed. A new approach will also be presented and discussed.

PSHA

PSHA was originally developed to derive a theoretical hazard curve (i.e., ground motion vs. return period) for engineering risk analysis in consideration of the uncertainty in the number, sizes, and locations of future earthquakes (Cornell, 1968). Later, Cornell (1971) extended his method to incorporate the possibility that ground motion at a site could be different (i.e., ground-motion uncertainty) for different earthquakes of the same magnitude at the same distance, because of differences in site conditions or source parameters. Cornell’s (1971) was coded into a FORTRAN algorithm by McGuire (1976) and became a standard PSHA (Frankel and others, 1996, 2002). Following McGuire’s (1995) formulation, annual probability of exceedance (γ) of a ground-motion amplitude y^* can be expressed as a triple integration over earthquake magnitude, epicentral distance, and ground-motion uncertainty as

$$\gamma(y) = \sum_j v_j \iiint f_M(m) f_R(r) f_\varepsilon(\varepsilon) P[Y \geq y^* | m, r, \varepsilon] dm dr d\varepsilon, \quad (1)$$

where v_j is the activity rate for seismic source j ; $f_M(m)$, $f_R(r)$, and $f_\varepsilon(\varepsilon)$ are earthquake magnitude, source-to-site distance, and ground-motion density functions, respectively; ε is ground motion uncertainty expressed in a standard deviation (logarithmic); and $P[Y \geq y^* | m, r, \varepsilon]$ is the conditional probability that Y exceeds y^* for a given m , r , and ε . Equation (1) is very complex and only computed through numerical approaches. Equation (1) is further complicated by the nonunique interpretations of seismological parameters, which are commonly treated by a logic-tree in PSHA (SSHAC, 1997; Stepp and others, 2001; Scherbaum and others, 2005).

In order to better understand the basics of PSHA, a special case in which all the sources are characteristic will be discussed here. For the characteristic sources, we have

$$f_M(m) = \begin{cases} 1, & \text{if } m=M_c \\ 0, & \text{if } m \neq M_c \end{cases}, \quad (2)$$

$$f_R(r) = \begin{cases} 1, & \text{if } r=R_c \\ 0, & \text{if } r \neq R_c \end{cases}, \quad (3)$$

and

$$f_\varepsilon(\varepsilon) = \begin{cases} 1, & \text{if } \varepsilon=\varepsilon_c \\ 0, & \text{if } \varepsilon \neq \varepsilon_c \end{cases}, \quad (4)$$

where M_C is magnitude of the characteristic earthquake, R_C is the shortest distance between the site and source, and ε_C is the ground-motion uncertainty for M_C at the distance R_C . Therefore, for characteristic sources, equation (1) becomes

$$\gamma(y) = \sum_j \frac{1}{T_j} P_j[Y \geq y^* | M_C, R_C, \varepsilon_C], \quad (5)$$

where T_j is the average recurrence interval of the characteristic earthquake for source j . In current practice, the inverse of the annual probability of exceedance ($1/\gamma$), called return period (T_P), is more often used and interpreted, as the ground motion (y^*) that will occur at least once in that return period (Frankel and others, 1996, 2002; Frankel, 2004). From equation (5), T_P is equal to

$$T_P(y) = \frac{1}{\sum_j \frac{1}{T_j} P_j[Y \geq y^* | M_C, R_C, \varepsilon_C]}. \quad (6)$$

For a single characteristic source, we have

$$T_P(y) = \frac{T}{P[Y \geq y^* | M_C, R_C, \varepsilon_C]}. \quad (7)$$

As demonstrated above, the return period (T_P) or annual probabilities of exceedance ($1/\gamma$) of a ground motion (y^*) is determined by the recurrence intervals of earthquakes and the conditional exceeding probabilities $P[Y \geq y^* | m, r, \varepsilon]$, particularly in the case of characteristic sources. In the current PSHA, $P[Y \geq y^* | m, r, \varepsilon]$ is assumed to be a log-normal distribution and equal to

$$P[Y \geq y^* | m, r, \varepsilon] = 1 - F_{Y,mr}(y^*) = 1 - \int_{-\infty}^{y^*} \frac{1}{\sqrt{2\pi}\sigma_{mr}} \exp\left(-\frac{(y - y_{mr})^2}{2\sigma_{mr}^2}\right) dy, \quad (8)$$

where y_{mr} and σ_{mr} are median ground motion and associated standard deviation and dependence of earthquake magnitude (m) and epicentral distance (r) (Campbell, 1981,

2003). $F_{Y,mr}(y^*)$ is the cumulative distribution function of ground motion y^* . As shown in equation (8), $F_{Y,mr}(y^*)$ is equal to the cumulative distribution function of a log-normal distribution.

According to Campbell (1981, 2003), y^* is equal to

$$\ln(y^*) = f(m, r) + \varepsilon \text{ or } y_{mr} = e^{f(m,r)+\varepsilon} . \quad (9)$$

For peak ground acceleration (PGA) in the central and eastern United States, for example, Campbell (2003) had

$$\begin{aligned} \ln(y^*) = & 0.0305 + 0.633m - 0.0427(8.5 - m)^2 - 0.7955 \ln(r^2) \\ & + [0.683 \exp(0.416m)]^2 + (-0.00428 + 0.000483m)r + \varepsilon \end{aligned} , \quad (10)$$

for $r \leq 70$ km. As shown in equations (9) and (10), y^* is a very complicated function of earthquake magnitude (m) and epicentral distance (r). As shown in Cornell (1968) and later in this paper, the cumulative distribution function for ground motion y^* , which is also a function of m and r , is not equal to the cumulative distribution function of a log-normal distribution, $F_{Y,mr}(y^*)$. This implies that equation (8) is mathematically incorrect.

The mathematical error has led to that the ground-motion uncertainty is treated as a variable and intergraded in the determination of hazard curve (equation [1]) or using the ground-motion uncertainty to extrapolate the return period (T_P) or annual probability of exceedance (γ) from the earthquake recurrence intervals (equations [6] and [7]). The ground-motion uncertainty is a spatial statistical characteristic of ground-motion measurements, whereas the recurrence interval of earthquake is a temporal characteristic of earthquake occurrence. In other words, the current PSHA uses the spatial statistical characteristics of ground motion to extrapolate the temporal characteristics of ground motion occurrence from the temporal characteristics of earthquake occurrence because of the mathematical error. This is problematic and cause difficulties in understanding of PSHA.

For example, although there are only few thousand years of instrumental, historical, and geological records on earthquakes ($T_i < 10^4$ years), PSHA could be used to derive the ground motions with return periods for up to 10^8 years (Stepp and others, 2001; Bommer and others, 2004; Abrahamson and Bommer, 2005; McGuire and others, 2005; Musson, 2005). This can also be clearly shown in the case of a single characteristic source in the New Madrid Seismic Zone (Frankel, 2004; Wang and others, 2005). Paleoseismic interpretations suggest an average recurrence interval of about 500 years for large earthquakes (M7.0–8.0), similar to the 1811–1812 New Madrid events (Tuttle and others, 2002), in the New Madrid Seismic Zone. These large earthquakes are of safety concern and can be treated as a single characteristic source in PSHA for the New Madrid area (Frankel and others, 1996, 2002; Frankel, 2004). PSHA could derive a range of return periods from 500 years to infinity for a single characteristic earthquake (Wang and others, 2003, 2005; Frankel, 2004). In other words, PSHA could create infinite ground-

motion “events” with return periods ranging from 500 years to infinity for a single input earthquake.

New Approach

The main purpose of conducting seismic hazard analyses, PSHA in particular, is to estimate seismic risk. Seismic hazard and risk are two fundamentally different concepts (Wang, in press (b)). Seismic hazard is a phenomenon generated by earthquakes, such as surface rupture, ground motion, ground-motion amplification, liquefaction, and induced landslides that have potential to cause harm. Seismic risk, on the other hand, is the probability (likelihood) of experiencing a level of seismic hazard or damage caused by the hazard in a given exposure (time). The relationship between seismic hazard and risk is complicated and must be treated very cautiously. Seismic hazards are natural occurrences and can be evaluated from instrumental, historical, and geological records (or observations). Seismic risk depends not only on seismic hazard and exposure, however, but also on the models (i.e., time-independent [Poisson] and time-dependent ones) that could be used to describe the occurrences of earthquakes. 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 necessary to review the definitions of seismic hazard and risk.

Seismic risk was originally defined in earthquake engineering 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 risk (Cornell, 1968; Milne and Davenport, 1969). Poisson distribution is a common model for describing occurrences of these natural events (i.e., winds, floods, and earthquakes) (Cornell, 1968; Milne and Davenport, 1969; Gupta, 1989; Liu, 1991). Although the Poisson model may not be the best model for describing 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 Wyssession, 2003), it is the most used model for seismic risk analysis. According to the Poisson model (Cornell, 1968; Stein and Wyssession, 2003), the probability of n earthquakes of interest occurring in an area or along a fault during an exposure time (t) in years is

$$p(n, t, \tau) = \frac{e^{-t/\tau} (t/\tau)^n}{n!}, \quad (11)$$

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

$$p(0, t, \tau) = e^{-t/\tau}. \quad (12)$$

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

$$p(n \geq 1, t, \tau) = 1 - p(0, t, \tau) = 1 - e^{-t/\tau}. \quad (13)$$

Equation (10) is used to calculate seismic risk for earthquakes in terms of magnitude (M) with a percent PE in t years. In other words, the level of hazard is expressed in terms of earthquake magnitude (M) and its average recurrence interval (τ) or average recurrence rate ($1/\tau$). For engineering purposes, the level of hazard in terms of ground motion (peak ground acceleration [PGA] and response accelerations) is desired, however. In other words, engineers need to know the ground motions (consequences) of earthquakes at a given point. This is identical 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 at a specific site (Sacks, 1978; Gupta, 1989; Liu, 1991).

Ground motions and their recurrence intervals or recurrence rates can be determined through seismic hazard analysis (Cornell, 1968; Milne and Davenport, 1969). Milne and Davenport (1969) developed an empirical method which derives a relationship between ground motions and their recurrence intervals from instrumental and historical records. A similar method was recently used in seismic hazard and risk assessment in the Tokyo, Japan, area (Stein and others, 2005). As pointed out by Milne and Davenport (1969), this method may not be applicable in areas where historical data are insufficient. An alternative method was proposed by Wang (in press (a), (b)) and is briefly described here.

Similar to flood occurrences (Gupta, 1989) and wind storm occurrences (Liu, 1991), earthquake occurrences follow the well-known Gutenberg-Richter magnitude-frequency relationship:

$$\text{Log}(N) = a - bM \text{ or } N = 10^{a-bM}, \quad (14)$$

where N is the cumulative number of earthquakes with magnitude equal to or greater than M occurring yearly, and a and b are constants. Equation (11) can be rewritten as

$$N = e^{2.303a-2.303bM} \text{ or } N = e^{\alpha-\beta M}, \quad (15)$$

where $\alpha=2.303a$ and $\beta=2.303b$. The Gutenberg-Richter relationship describes the relationship between the average recurrence rate (N) or recurrence interval ($1/N$) and earthquakes exceeding a specific magnitude (M). Therefore,

$$N = \frac{1}{\tau} = e^{\alpha-\beta M}. \quad (16)$$

Figure 1 shows a Gutenberg-Richter curve with $a=3.15$ and $b=1.0$ for earthquakes with magnitude between M5.0 and M8.0. According to equation (13), the average recurrence intervals (τ) are 709 and 7,091 years for earthquakes of magnitude equal to or greater

than 6.0 and 7.0, respectively. These calculations result in 6.8 and 0.7 percent probabilities of exceedance for earthquakes of magnitude 6.0 and 7.0 in 50 years, respectively.

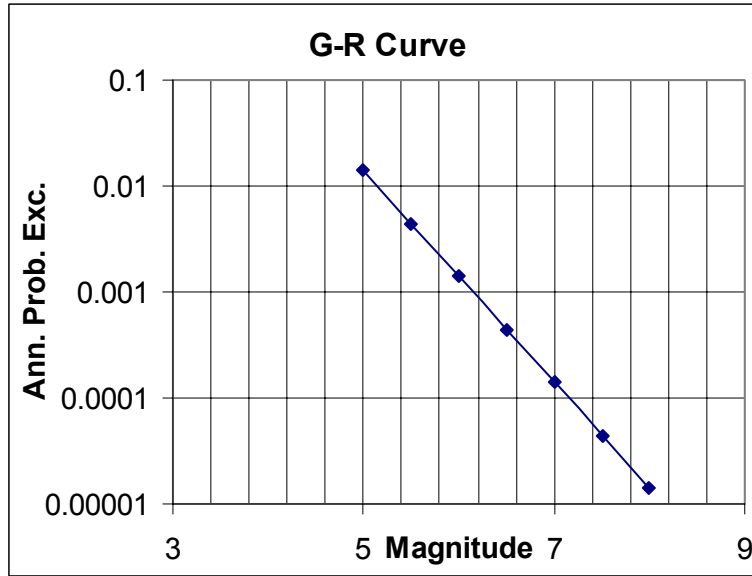


Figure 1. Gutenberg-Richter curve.

Also, in seismology, observed ground motion (y_ϵ) with an uncertainty ($\epsilon=0$ [median], $\pm\sigma$, $\pm 2\sigma$), at a site from an earthquake of magnitude M with an epicentral distance R can be described by a ground-motion attenuation relationship (Campbell, 1981, 2003), such as equation (9). From equation (9), M can be expressed in terms of R and y_ϵ as

$$M = M(R, y_\epsilon), \quad (17)$$

As shown in equation (10), the relationships between M , R , and y_ϵ are quite complicated, and the function, $M(R, y_\epsilon)$, can only be solved numerically. Combining equations (16) and (17) results in

$$\frac{1}{\tau} = e^{\alpha - \beta M(R, y_\epsilon)}. \quad (18)$$

Equation (18) describes a relationship between the earthquake recurrence interval (τ) and the ground motion (y_ϵ) with an uncertainty (ϵ) and distance (R). For a given R , equation (18) describes a relationship between ground motion with an uncertainty and its recurrence interval: a hazard curve. Using the PGA attenuation relationship for the central and eastern United States, equation (10), and σ which is dependent of earthquake magnitude and in the range of 0.6 to 0.9 (Campbell, 2003), a PGA hazard curve can be derived at a point of interest from a known source.

Figure 2 shows PGA hazard curves for a site 40 km from a point source in which earthquake occurrences follow the Gutenberg-Richter relationship shown in Figure 1. From Figure 2, the median PGA's with the average recurrence intervals of 709 and 7,091 years are 0.09 and 0.2g, respectively. In terms of median PGA, these calculations result in 6.8 and 0.7 percent probabilities of exceedance for 0.09 and 0.2g in 50 years, respectively. Similarly, in terms of median $\pm\sigma$ PGA, Figure 2 will result in 0.04 and 0.19g, and 0.10 and 0.39g, for 6.8 and 0.7 percent probabilities of exceedance in 50 years, respectively.

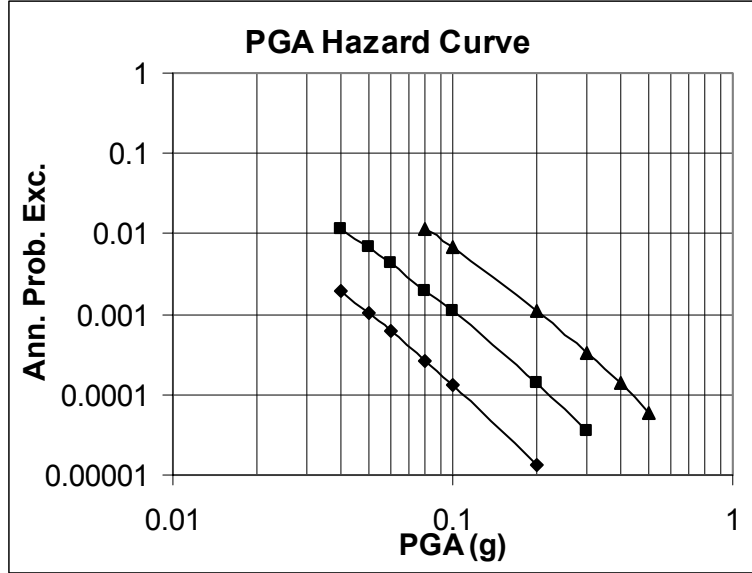


Figure 2. PGA hazard curves for a site 40 km from a point source. Square – median; Diamond – median- σ ; Triangle – median+ σ .

As shown above, the hazard curve in terms of ground motion can be derived directly from the Gutenberg-Richter and ground-motion attenuation relationship. This derivation [equation (18)] is only valid for a single point source or a source with constant distance, however. In general, the size and location of a future earthquake are uncertain. Uncertainties in the size and location of a future earthquake along a line source can be considered by using probability theory. For a given $R=r$, the conditional probability that ground motion Y at a site exceeds y_ϵ is

$$P[Y \geq y_\epsilon | R = r] = P[e^{f(M,R)+\epsilon} \geq y_\epsilon | R = r] . \quad (19)$$

From equations (9) and (17), we have

$$P[e^{f(M,R)+\epsilon} \geq y_\epsilon] = P[M \geq M(r, y_\epsilon)] . \quad (20)$$

For the Gutenberg-Richter distribution, the cumulative distribution function of magnitude, $F_M(m)$, is

$$P[M \geq M(r, y_\varepsilon)] = 1 - F_M[M(r, y_\varepsilon)] = e^{-\beta[M(r, y_\varepsilon) - m_0]}, \quad (21)$$

where m_0 is the lower bound magnitude. Hence, we have

$$P[Y \geq y_\varepsilon | R = r] = e^{-\beta[M(r, y_\varepsilon) - m_0]}. \quad (22)$$

According to the *total probability theorem*, the probability that ground motion Y at the site exceeds a given y_ε from a line source is

$$P[Y \geq y_\varepsilon] = \int e^{-\beta[M(r, y_\varepsilon) - m_0]} f_R(r) dr, \quad (23)$$

where $f_R(r)$ is the probability density function of R and has

$$\int f_R(r) dr = 1.0. \quad (24)$$

The average annual probability that ground motion Y at the site exceeds a given y_ε from a line source is equal to

$$\lambda(y_\varepsilon) = \nu P[Y \geq y_\varepsilon] = \nu \int e^{-\beta[M(r, y_\varepsilon) - m_0]} f_R(r) dr, \quad (25)$$

where ν is the activity rate (Cornell, 1968; McGuire, 1995) and equal to

$$\nu = e^{\alpha - \beta m_0}. \quad (26)$$

For all line sources, the total average annual probability that ground motion Y at the site exceeds a given y_ε is equal to

$$\lambda_T(y_\varepsilon) = \sum_j \nu_j P_j[Y \geq y_\varepsilon] = \sum_j \nu_j \int e^{-\beta_j[M(r, y_\varepsilon) - m_0]} f_{R_j}(r) dr. \quad (27)$$

If all sources are characteristic, equation (27) will become

$$\lambda_T(y_\varepsilon) = \sum_j \nu_j e^{-\beta_j[M(R_{C_j}, y_\varepsilon) - m_0]} = \sum_j e^{\alpha_j - \beta_j M(R_{C_j}, y_\varepsilon)}. \quad (28)$$

For a single characteristic source, equation (28) becomes

$$\lambda_T(y_\varepsilon) = e^{\alpha - \beta M_C} = \frac{1}{T}. \quad (29)$$

Figure 3 shows a hypothetical site 40 km (minimum) from a line source. It is assumed that earthquake occurrences along the line source follow the Gutenberg-Richter relationship shown in Figure 1. Equation (27) can be applied to derive a PGA hazard

curve from the line source (Fig. 3). Figure 4 shows the hazard curves for the median and median $\pm\sigma$ PGA at 40 km from the line source (Fig. 3). From Figure 4, the median PGA's with the average recurrence intervals of 709 and 7,091 years are 0.07 and 0.15g, respectively. In terms of median PGA, these calculations result in 6.8 and 0.7 percent probabilities of exceedance for 0.07 and 0.15g in 50 years, respectively. Similarly, in terms of median $\pm\sigma$ PGA, Figure 4 will result in 0.03 and 0.14g, 0.08 and 0.3g for 6.8 and 0.7 percent probabilities of exceedance in 50 years, respectively.

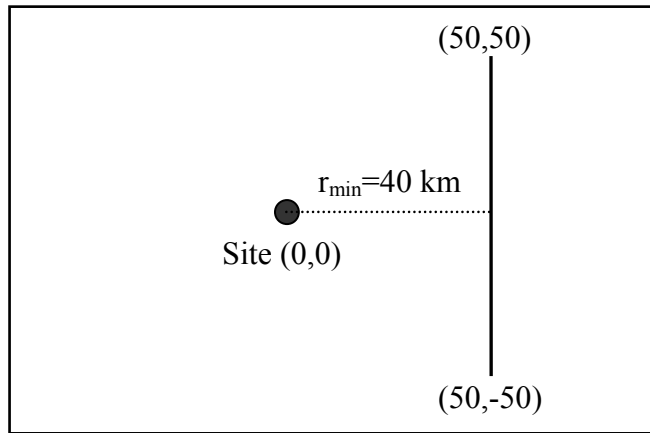


Figure 3. A hypothetical site 40 km from a line source.

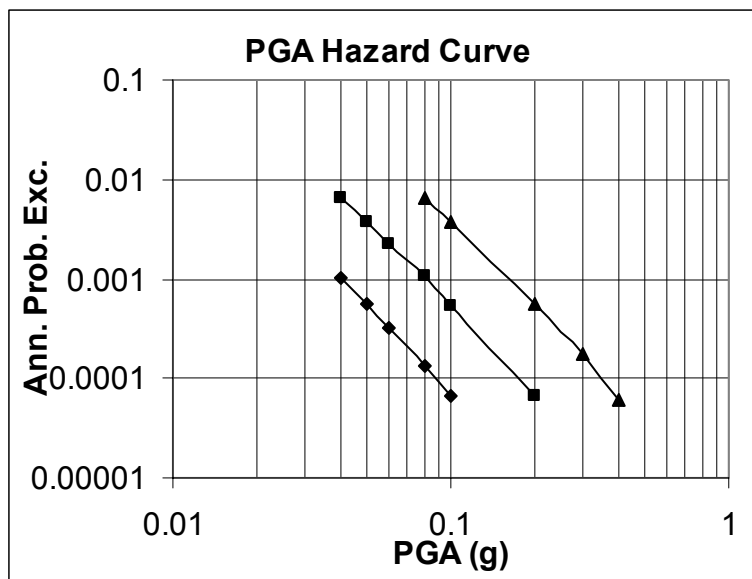


Figure 4. PGA hazard curves for a site 40 km from a line source. Square – median; Diamond – median- σ ; Triangle – median+ σ .

As shown in Figure 1, the recurrence intervals of earthquakes vary from about 100 years for earthquakes equal to or greater than 5.0, to 10,000 years for earthquakes equal to or

greater than 8.0. These intervals determine that the range of recurrence intervals of the ground motions should also be between 100 and 10,000 years, because the ground motions are the consequences of those earthquakes. The new approach derives the ground motions with the recurrence intervals between 100 and 10,000 years (Figs. 2, 4). Therefore, in terms of temporal characteristics, the outputs from the new approach are consistent with the inputs. Particularly in the case of a single characteristic source, the output recurrence interval is equal to the input [equation (29)].

Discussion

Ground motion is a consequence of earthquake. Occurrence of a ground motion at a site must be associated with occurrence of an earthquake. Hence, the temporal characteristics of ground motion occurrence must be consistent with that of earthquake occurrence. The current PSHA does not derive the temporal characteristics of ground motion occurrence that is consistent with that of earthquake occurrence because the treatment of the ground-motion uncertainty: using the spatial statistical characteristics of ground motion to extrapolate the temporal characteristics of ground motion from the temporal characteristics of earthquake occurrence, however. As discussed in this paper, this extrapolation is caused by a mathematical error in the formulations: the cumulative distribution function for ground motion attenuation relationship (function of magnitude and distance) is incorrectly equated to the cumulative distribution function for ground motion at a specific point (log-normal distribution). This mathematical error causes difficulties in understanding and applications of PSHA.

The new approach presented in this paper will derive ground motions that have the temporal characteristics consistent with that of earthquakes. Although being developed differently, the new approach is similar to the original PSHA by Cornell (1968). In fact, the new approach is identical to Cornell's (1968) if the ground-motion uncertainty is not considered ($\varepsilon=0.0$). For $\varepsilon=0.0$, according to Cornell (1968), the total probability that the MMI, I , at a site is equal to or greater than a given i from a line source is

$$P[I \geq i] = \int e^{-\beta[M(r,i)-m_0]} f_R(r) dr, \quad (30)$$

where $I(M,R)$ is the intensity attenuation relationship and equal to

$$i = d_1 + d_2 M - d_3 \ln R, \quad (31)$$

where d_1 , d_2 , and d_3 are constants. Therefore, we have

$$M(R,i) = \frac{i + c_3 \ln R - c_1}{c_2}. \quad (32)$$

Similarly for a ground motion y :

$$y = b_1 e^{b_2 M} R^{-b_3}, \quad (33)$$

where b_1 , b_2 , and b_3 are constants, and we have

$$M(R, y) = \frac{\ln(yR^{b_3} / b_1)}{b_2}. \quad (34)$$

Similarly, Cornell (1968) derived the MMI that had the temporal characteristics consistent with that of the input earthquakes: Figure 4 in Cornell's (1968).

The new approach should be easily expanded to consider the non-unique interpretations of seismological parameters, which are commonly characterized by a logic-tree in PSHA (SSHAC, 1997; Stepp and others, 2001; Scherbaum and others, 2005). The hazard curve derived from the new approach is similar to those derived from flood and wind hazard analyses (Gupta, 1989; Liu, 1991) and can be used in risk analysis in a similar way.

Acknowledgments

This research is in part supported by a grant from the U.S. Department of Energy, contract no. DE-FG05-03OR23032. I thank Kenneth W. Campbell for his thoughtful comments, and also Meg Smath of the Kentucky Geological Survey for editorial help.

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