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Comparison Between Probabilistic Seismic Hazard Analysis and Flood Frequency Analysis

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Probabilistic seismic hazard analysis (PSHA) was originally developed from the analogous flood or wind problem and was used for risk analysis in a similar way. PSHA was extended later to directly incorporate the uncertainty of ground motion. Such direct incorporation of uncertainty has no clear physical basis and makes it difficult to understand, explain, and use PSHA.

These difficulties may result in overly conservative seismic design for safeguarding structures such as buildings, bridges, and nuclear power plants against seismic risk. For example, ground motions with a risk level of 2% probability of exceedance (PE) in 50 years, developed from PSHA [*Frankel et al.*, 1996, 2002], are the basis for national seismic safety regulations and design standards such as the 2000 International Building Code (IBC-2000).

These regulations and standards require a similar or even higher seismic design for buildings in many communities in the central United States, such as Memphis, Tennessee, and Paducah, Kentucky, than for Los Angeles and San Francisco, California [*Stein et al.*, 2003; *Wang et al.*, 2003]. PSHA would also result in designing the proposed nuclear waste repository at Yucca Mountain, Nevada, for a peak ground acceleration (PGA) of 20*g* [*Reiter*, 2004].

It is, therefore, instructive to review the basics of PSHA, compare it with flood frequency analysis, and demonstrate how they are being used in risk analyses.

Risk Analysis

Risk analysis considers the probability p_t of a structure being overflowed or damaged one or more times (at least once) in t years by a flood or an earthquake having an annual probability of exceeding a given size P or, equivalently, a return period, $T = 1/P$. This probability can be estimated using a Poisson probability distribution [*Cornell*, 1968; *Gupta*, 1989]:

$$p_t = 1 - e^{-Pt} \approx 1 - (1-P)^t = 1 - (1 - \frac{1}{T})^t. \quad (1)$$

Although equation (1) was developed for natural events (earthquakes and floods), it can also be applied to their consequences, such as ground motions generated by the earthquakes [*Cornell*, 1968] and peak discharges generated by the floods [*Gupta*, 1989], at a point or in a region of interest. In practice, the annual probability of exceedance (P) or return period (T) of equation (1) is estimated from hazard analyses (i.e., PSHA in seismology and flood frequency analysis in hydrology) of the consequences.

For example, 2% PE in 50 years and 1% PE in 1 year are the risk levels considered in the building design for earthquake and flood hazards, respectively [*International Code Council*, 2000]. For a p_t of 2% PE in 50 years, equation (1) results in a P of about 0.0004 or T of 2500 years, which means that the ground motion has an 0.0004 annual probability of exceedance or a 2500-year return period (recurrence interval).

Thus, if a 2% probability of a structure being damaged in 50 years is considered, the structure should be designed for ground motion with a 2500-year recurrence interval. Similarly, for a risk level of 1% PE in 1 year, a structure should be designed for peak discharge with a 100-year recurrence interval, known as the 100-year flood. A very low risk level, 1% PE in 1 million years, is sometimes considered in seismic design for critical facilities. This extremely low risk level is equivalent to the ground motion expected in 1 million years or longer.

Probabilistic Seismic Hazard Analysis

PSHA was originally developed from the analogous flood or wind problem by C. A. Cornell in 1968. It was extended later to incorporate the possibility that ground motion at a site could be different for different earthquakes of the same magnitude at the same distance, because of differences in site conditions or source parameters [*Cornell*, 1971].

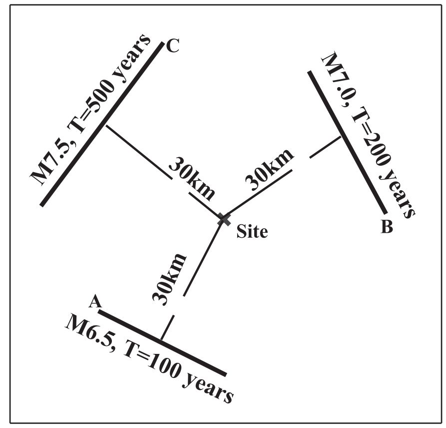

Fig. 1. Hypothetical region with three seismic sources (A, B, and C characteristic faults) and a site of interest within 30 km of the faults.

This uncertainty of ground motion can be modeled using a lognormal distribution [*Campbell*, 1981, 2003]. To illustrate the process, the combined effect of three characteristic earthquake sources in Figure 1 were considered. The total annual probability of exceedance (λ) that the ground motion (U) at a site will exceed U_0 is the sum of the annual probabilities of exceedance from each individual source:

$$\lambda = \sum_i \frac{1}{T_i} P_i(U \geq U_0), \quad (2)$$

where T_i is the average recurrence interval of the characteristic earthquake, $P_i(U \geq U_0)$ is the probability that the ground motion (U) from source i will exceed U_0.

Figure 2 shows the steps in computing the total annual probability of exceedance (0.0004) at the site for a PGA of 0.97*g* from all sources. For PGA of 0.97*g*, the annual probability of exceedance from fault A (0.000086) equals the annual recurrence rate (0.01 or 1 in 100 years) times the probability (0.0086) that PGA will exceed 0.97*g* (Figure 2a). In other words, the meaning of 0.97*g* PGA with an annual probability of exceedance of 0.000086 is that there is an 0.0086 probability that PGA will exceed 0.97*g* if an earthquake of *M*6.5 occurs on fault A. Similarly, the meaning of 0.97*g* PGA with the annual probabilities of exceedance of 0.000147 and 0.000167 are that there are 0.0294 and 0.0835 probabilities that PGAs will exceed 0.97*g* if earthquakes of *M*7.0 and *M*7.5 occur on faults B and C, respectively.

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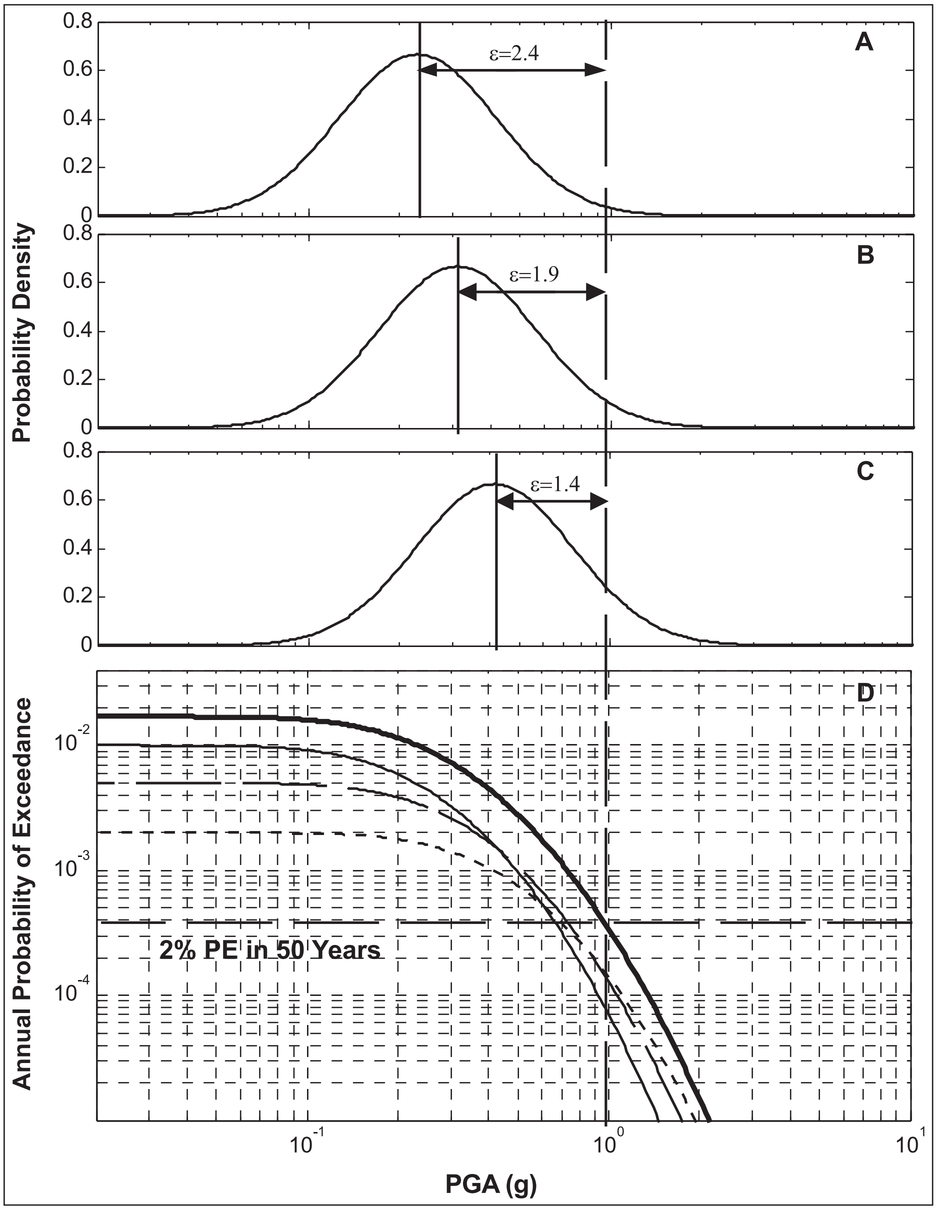

*Fig. 2. Steps for calculating the total annual probability of exceedance for a PGA of 0.97*g *from all three faults. (a) Annual probability of exceedance (0.000086) for PGA of 0.97*g *from the earthquake on fault* A *is equal to the annual rate (0.01) times the probability (0.0086, solid area) that PGA would exceed 0.97*g. *(b) Annual probability of exceedance (0.000147) for PGA of 0.97*g *from the earthquake on fault* B *is equal to the annual rate (0.005) times the probability (0.0294, solid area) that PGA would exceed 0.97*g. *(c) Annual probability of exceedance (0.000167) for PGA of 0.97*g *from the earthquake on fault* C *is equal to the annual rate (0.002) times the probability (0.0835, solid area) that PGA would exceed 0.97*g. *The median PGAs are 0.23, 0.31, and 0.42*g *for sources* A, B, *and* C, *respectively, and the standard deviation is 0.6 [*Campbell*, 2003].*

Because it is impossible for the three earthquakes to occur at exactly the same time (1.5×10^{-19} probability at the same hour), the predicted PGA corresponding to the total annual probability of exceedance is a statistical measure and does not have a clear physical meaning. This was recognized by a U.S. National Research Council committee chaired by K. Aki, which noted "the aggregated results of PSHA are not always easily related to the inputs" [*National Research Council*, 1988].

As shown in Figure 2, the predicted PGA on the total hazard curve (aggregated results) is not related to any of the three characteristic earthquakes (inputs), and could reach infinity because of the unbounded "tail" of the lognormal distribution.

The annual probabilities of exceedance derived from PSHA have been used for risk analysis [*Cornell*, 1971; *Frankel*, 2004]. For example, a risk level of 2% PE in 50 years is equivalent to the annual probability of exceedance of 0.0004 or a return period of 2500 years. Figure 2 shows that PGA with 2% PE in 50 years is 0.97*g*. This PGA (0.97*g*) does not mean that it could occur in 2500 years; but rather that there are 0.0835, 0.0294, and 0.00086 probabilities that PGA will exceed 0.97*g* if each of the three earthquakes occurs.

Because of the "tail" of the lognormal distribution (Figure 2), PGA of 5*g* or even higher can be obtained for a risk level of 1% PE in 1 million years or less. This PGA (5*g*) does not mean that it could occur in 1 million years, but rather that there is an extremely low probability (several standard deviations above the median) of being exceeded. Hence, the annual probability of exceedance defined in PSHA does not have the same meaning as that defined in risk analysis.

Flood Frequency Analysis

In hydrology, flood frequency analysis is used to construct flood hazard curves, which are a relationship between physical measurements such as flow rate and the annual probability of exceedance (P_f) of the flood. Figure 3 illustrates an empirical method [*Gupta*, 1989] of flood frequency analysis for the Kentucky River at Lock 4 near Frankfort, Kentucky. The annual probability of exceedance P_f is computed from

$$P_f = \frac{m}{l+1}, \quad (3)$$

where m is total (cumulative) number of annual peak discharges exceeding a specific value, and l is the total number of years.

The way to construct a flood hazard curve by this empirical method is almost identical to the way a Gutenburg-Richter curve is constructed in seismology. The statistical parameters for the annual peak discharges of the Kentucky River at Lock 4 are listed in Table 1. The annual peak discharges at the mean, 5%, and 95% confidence levels for the corresponding annual probabilities of exceedance were computed and plotted in Figure 3. From Figure 3, a mean annual peak discharge of 3143 m^3/s can be obtained for the 100-year flood ($P_f = 0.01$) or 1% PE in a 1-year risk level.

To account for the uncertainty in the discharge measurements, peak discharges with 5% and 95% confidence levels can also be estimated [*Gupta*, 1989]. For example, the peak discharges with 5% and 95% confidence levels are estimated to be 2857 and 3542 m^3/s, respectively, for the 100-year flood at Lock 4. This example shows that the peak discharge is a direct statistical inference from measured values, so the peak discharge of 3143 m^3/s for 1% PE in 1 year could occur at least once in 100 years.

A longer return period, 500 years, for example, sometime is desired. One way to obtain the discharge with a longer return period is to extrapolate from the shorter records. Such extrapolation should be done cautiously, however [*Gupta*, 1989]. Another way to estimate the discharge with a longer return period is to use the historical records; this is similar to the use of historical and geologic records to estimate recurrence intervals for large earthquakes in seismology.

Summary

This comparison illustrates crucial differences between PSHA and flood frequency analysis. Although they have been used in risk analyses in the same way, PSHA and flood frequency analysis have different meanings. The peak discharge with 1% PE in 1 year means that it

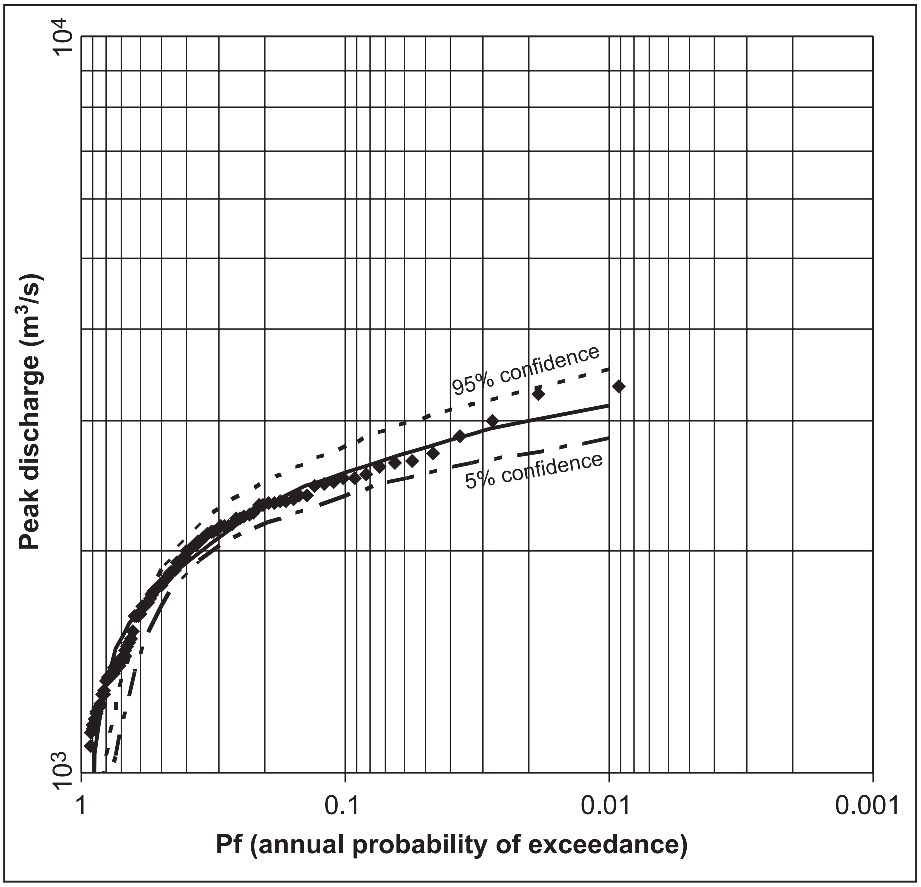

Fig. 3. Flood frequency curve of the Kentucky River at Lock 4. Diamonds indicate observed values; solid curve indicates mean peak discharge; dash-dotted curve indicates peak discharge with 5% confidence; dashed curve indicates peak discharge with 95% confidence.

Table 1. Statistical Parameters for the Annual Peak Discharge (m^3/s) at Lock 4.

Parameter	*Value*
Total number	107
Mean (log)	3.237
Standard deviation	0.144
Coefficient of skewness	–0.673

could occur at least once in 100 years. In contrast, the ground motion with 2% PE in 50 years does not mean that it could occur at least once in 2500 years; rather, it means that it has a certain probability of being exceeded if all the considered earthquakes occur at the corresponding recurrence intervals.

Although there are only a few hundred years of instrumental and historical records and a few thousand years of geologic records on earthquakes, PSHA could infer "earthquakes" or ground motions generated by the "earthquakes" that have much longer return periods.

For example, the geologic record indicates that the large earthquakes (~*M*7.7) occurred about every 500 years in the past 1200 years in the New Madrid Seismic Zone [*Tuttle et al.*, 2002]. PSHA could infer the ground motions having a 2500-year return period (2% PE in 50 years) in the New Madrid area. Similarly, PSHA could infer the ground motions having a 1-million-year return period (annual probability of exceedance of 10^{-6}) or longer at the proposed nuclear waste repository at Yucca Mountain, Nevada.

Hence using PSHA for risk analysis is not only confusing, but is also inappropriate.

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References

Campbell, K. W. (1981), Near-source attenuation of peak horizontal acceleration, *Bull. Seismol. Soc. Am., 71*, 2039–2070.

Campbell, K. W. (2003), Prediction of strong ground motion using the hybrid empirical method and its use in the development of ground-motion (attenuation) relations in eastern North America, *Bull. Seismol. Soc. Am., 93*, 1012–1033.

Cornell, C. A. (1968), Engineering seismic risk analysis, *Bull. Seismol. Soc. Am., 58*, 1583–1606.

Cornell, C. A. (1971), Probabilistic analysis of damage to structures under seismic loads, in *Dynamic Waves in Civil Engineering*, edited by D. A. Howells et al., 473– 493, Wiley-Interscience, Hoboken, N. J.

Frankel, A. (2004), How can seismic hazard around the New Madrid Seismic Zone be similar to that in California?, *Seismol. Res. Lett., 75*, 575–586.

Frankel, A., C. Mueller, T. Barnhard, D. Perkins, E. Leyendecker, N. Dickman, S. Hanson, and M. Hopper (1996), National Seismic Hazard Maps: Documentation June 1996, *U.S. Geol. Surv. Open File Rep., 96-532*, 110 pp.

Frankel, A., et al. (2002), Documentation for the 2002 update of the National Seismic Hazard Maps, *U.S. Geol. Surv. Open File Rep., 02-420*, 33 pp.

Gupta, R. S. (1989), *Hydrology and Hydraulic Systems*, Prentice Hall, Upper Saddle River, N. J.

International Code Council (2000), *International Building Code*, Falls Church, Va.

National Research Council (1988), Probabilistic seismic hazard analysis: Report of the Panel on Seismic Hazard Analysis, 97 pp., Nat. Acad. Press, Washington, D. C.

Reiter, L. (2004), When are ground motion estimates too high?, *Seismol. Res. Lett., 74*, 282.

Stein, S., J. Tomasello, and A. Newman (2003), Should Memphis build for California's earthquakes?, *Eos Trans. AGU, 84*, 177, 184–185.

Tuttle, M., E. Schweig, J. Sims, R. Lafferty, L. Wolf, and M. Haynes (2002), The earthquake potential of the New Madrid Seismic Zone, *Bull. Seismol. Soc. Am., 92*, 2080–2089.

Wang, Z., E. Woolery, B. Shi, and J. Kiefer (2003), Communicating with uncertainty: A critical issue with probabilistic seismic hazard analysis, *Eos Trans. AGU, 84*, 501, 506, 508.

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