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Communicating with Uncertainty: A Critical Issue with Probabilistic Seismic Hazard Analysis

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Probabilistic seismic hazard analysis (PSHA) is a widely used method for seismic hazard assessment. PSHA predicts a relationship, called the seismic hazard curve, between the maximum ground motion or response spectra and the annual frequency of exceedance (return period). Generally, the smaller the annual frequency of exceedance, meaning the longer the return period, the larger the ground motion—seismic hazard—PSHA will predict, and vice versa. PSHA is the most widely used method for assessing seismic hazards 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 et al.*, 1996, 2002]. These maps are the basis for national seismic safety regulations and design standards, such as the National Earthquake Hazards Research Program (NEHRP) Recommended Provisions for Seismic Regulations for New Buildings and Other Structures [*BSSC*, 1998], the 2000 International Building Code, and the 2000 International Residential Code (IRC).

Adoption and implementation of these regulations and design standards have significant impacts on many communities in which estimated hazards are high, such as the New Madrid area in the central United States. For example, the Structural Engineers Association of Kentucky found that if IRC-2000 were adopted in Kentucky, it would be impossible to construct residential structures in westernmost Kentucky without enlisting a design professional. It also would not be feasible for the U.S. Department of Energy to obtain a permit from federal and state regulators to construct a landfill at a facility near Paducah, Kentucky.

It is well understood that there is uncertainty in PSHA because of the uncertainties inherent in input parameters that are used in the hazard analysis, especially for the central United States. In the central United States, the question is not whether there is any seismic hazard, but how high the hazard is. Scientists and engineers, including *Frankel* [2003] and *Stein et al.* [2003a, b], have long discussed this issue and will continue to do so. Although the products of PSHA are widely used and accepted, our experience is that few practitioners, let alone users, have an in-depth understanding of the limits of applicability of PSHA or their sensitivity to assumptions in the underlying parameters. Because PSHA influences policy decisions on issues ranging from building codes to science funding, an appreciation for the uncertainties and assumptions underlying it is valuable for the user and decision makers.

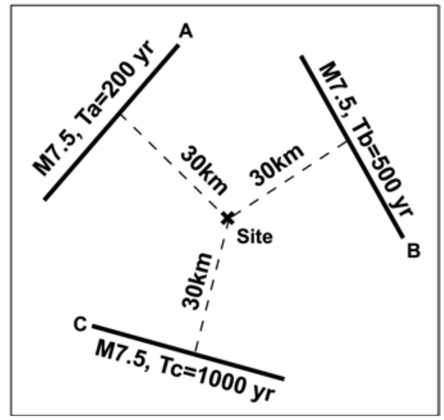

*Fig. 1. A hypothetical region with three seismic sources (**A**, **B**, and **C** faults) and a site of interest within 30 km of the faults.*

Functions of PSHA

Since its introduction in 1968, PSHA has been widely used in seismic hazard assessment [*Algermissen and Perkins*, 1976; *Frankel et al.*, 1996, 2002]. PSHA incorporates ground motions and occurrence frequencies for all earthquakes in a region through a mathematical model (triple integration). As an example, Figure 1 shows a hypothetical region in which there are three seismic sources (**A**, **B**, and **C** faults) and a site of interest. It is assumed that only characteristic earthquakes will repeat along the faults in certain time periods (recurrence times). This simple example was used to

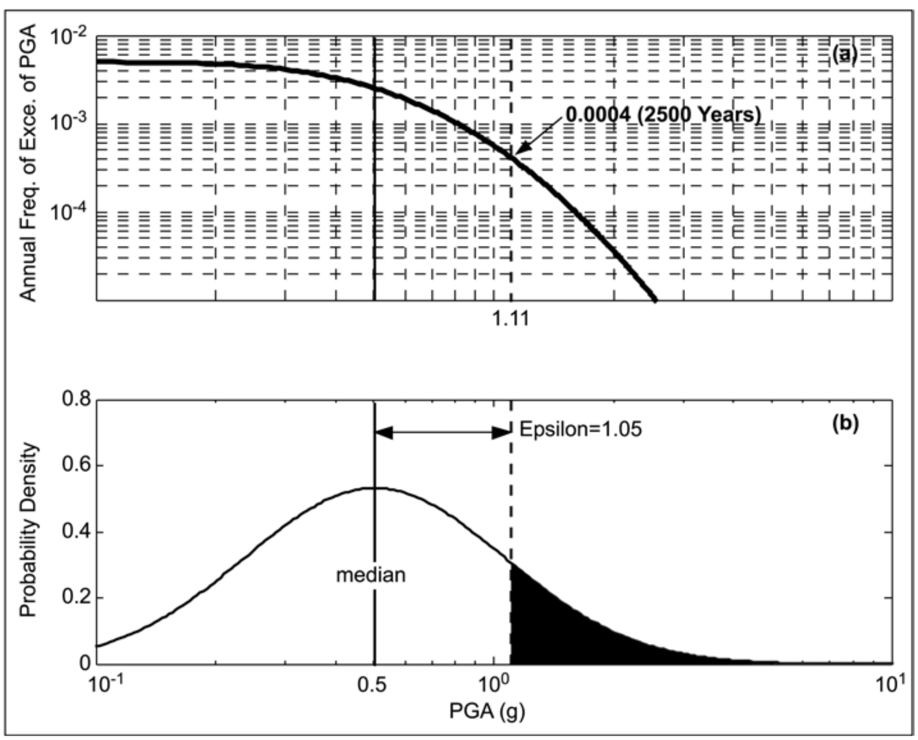

*Fig. 2. Steps for calculating the annual frequency of exceedance for the peak ground acceleration of 1.11g from fault **A**. (a) The annual frequency of exceedance (0.0004) is shown for the peak ground acceleration of 1.11g from fault **A**, and (b) probability (0.08) that the peak ground motion will exceed 1.11g (shaded area under ground-motion density function) is shown. The median ground motion (μ) is 0.5g, and the standard deviation (σ_{ln}) is 0.75. Epsilon=(ln y -ln μ)/σ_{ln}.*

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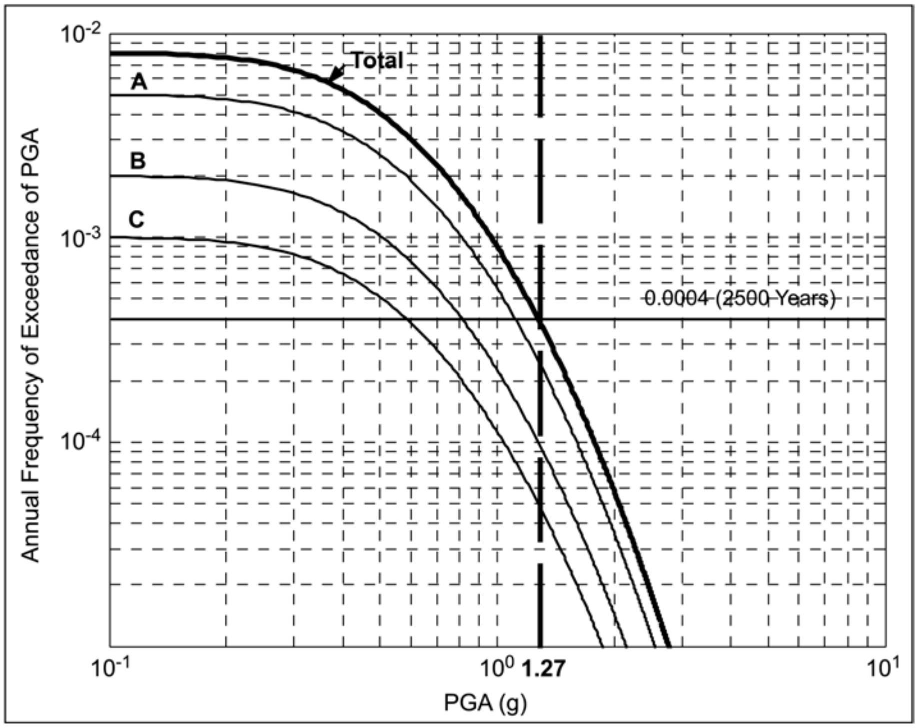

Fig. 3. Total and individual hazards (annual probabilities of exceedance) at the site are plotted.

demonstrate how PSHA works. The magnitude (M7.5) and recurrence times (*Ta*, *Tb*, and *Tc*) for the characteristic faults are shown in Figure 1, and the ground motion attenuation relationship of *Frankel et al.* [1996] was used. For each characteristic fault, the annual frequency of exceedance at the site is equal to the annual recurrence rate (1/T) times the probability that the ground motion will be exceeded.

Figure 2 demonstrates the steps to infer the annual frequency of exceedance (return period) corresponding to the peak ground acceleration of 1.11g from the characteristic fault A. For the given ground motion density function and peak ground acceleration of 1.11g, the probability (0.08) that the peak ground motion will exceed 1.11g is obtained (shaded area under ground-motion density function shown in Figure 2b). The annual frequency of exceedance of 0.0004 (return period of 2,500 years) (Figure 2a) is equal to the annual recurrence rate (1/200) times the probability of 0.08 (that the peak ground acceleration of 1.11g will be exceeded). The total hazard (total annual frequency of exceedance) at the site is the sum of the individual hazards (annual frequency of exceedance) (Figure 3). In Figure 3, the total annual frequency of exceedance of 0.0004 (return period of 2500 years) is the sum of the individual annual frequencies of exceedance of 0.00025, 0.0001, and 0.00005 from faults A, B, and C, respectively.

The ground motion uncertainty is inherently a part of PSHA. This can be seen in Figure 2: the annual frequency of exceedance from fault A (Figure 2a) is determined by the probability that the peak ground acceleration will be exceeded, the shaded area in the ground motion density function (Figure 2b). Other uncertainties in PSHA are treated with logic trees, by which different weights are assigned manually to a set of expert estimates for each input parameter [*Frankel*, 2003]. For example, the weights 0.15, 0.2, 0.5, and 0.15 were assigned to M7.3, M7.5, M7.7, and M8.0 for the characteristic earthquake of the New Madrid seismic source in the 2002 U.S. Geological Survey (USGS) national seismic hazard maps [*Frankel et al.*, 2002]. Generally, PSHA involves many seismic sources, ground motion attenuation relationships, recurrence times, and multiple logic trees. The USGS national seismic hazard mapping [*Frankel et al.*, 1996, 2002] is a typical example. No matter how complicated the parameters and logic trees are, however, the end results from PSHA are simple, total hazard curves, which give a range of annual frequencies of exceedance versus a range of ground-motion values.

Limitations

The example given above is a simple demonstration of PSHA incorporating the uncertainties through a mathematical model (triple integration over ground motion, recurrence rate, and earthquake source). One of the advantages of PSHA is that it could be readily incorporated into risk assessment. PSHA also has some limitations, however. These limitations have significant implications for how public and financial policies are being made. It was found that policy decisions based on PSHA [*BSSC*, 1998] do not provide the intended uniform protection against seismic risk; risk assessment is either over-conservative in some areas or not conservative enough in other areas [*Wang*, 2003].

First, there is no consensus on exactly how to select seismological parameters and assign weights in PSHA. The variation in selecting the parameters and assigning weights is so large that two groups of scientists and engineers could often give significantly different results for the same area. Two landmark studies from the late 1980s, known as the Lawrence Livermore (LLNL) study and the Electric Power Research Institute (EPRI) study, differed significantly. These disparate studies triggered a thorough review of PSHA by a senior seismic hazard analysis committee [*SSHAC*, 1997]. The committee concluded that "there is not likely to be 'consensus' (as the word is commonly understood) among the various experts" and that "no single interpretation concerning a complex Earth-science issue is the 'correct' one" [*SSHAC*, 1997]. Any group of scientists and engineers, including USGS, has made concerted efforts to build consensus when selecting parameters and assigning weights, but the results are not consensus products.

Second, the ground motion derived from PSHA does not have a clear physical meaning and should not be compared to ground motion from any individual earthquake. *Frankel* [2003] pointed out that "it is not correct to compare the intensity observations from 1811–1812 with the probabilistic hazard maps that also include the hazard from earthquakes closer to St. Louis." PSHA addresses the chance of a frequency of occurrence being exceeded at a level of ground motion from all possible earthquakes. The reverse interpretation may not be appropriate: the ground motion (total hazard) at an annual frequency of exceedance does not physically associate with any individual earthquake, but with many earthquakes.

For example, the PGA of 1.27g on the total hazard curve (Figure 3) at the annual frequency of exceedance of 0.0004 does not physically associate with any individual earthquake, but with three earthquakes. On the 1996 USGS national seismic hazard maps, the total hazard in Chicago, Illinois, was contributed by a series of earthquakes with magnitudes ranging from M5.0 to M8.0 at distances from 0 to 500 km [*Harmsen et al.*, 1999]. It is hard to imagine the actual physical model—that is, a real earthquake—with a ground motion that is composed of so many earthquakes.

Third, PSHA cannot define the worst-case ground-motion scenario. The worst-case scenario depends on a reference ground motion. The results of PSHA are the total seismic hazard curves, which provide a range of ground-motion values versus a range of annual frequencies of exceedance (Figure 3). Numerically, the ground motion could reach infinity, because the ground-motion density is a log-normal distribution. There is no reference point on the total hazard curves that is a minimum or maximum.

Fourth, PSHA provides not one, two, or three, but infinite choices for the users and decision makers. The product from PSHA is a series of seismic hazard curves. The hazard curves provide a large range of ground-motion values versus a large range of annual frequencies of exceedance. For example, the hazard curves 0from the 1996 USGS national seismic hazard mapping gave a range of ground-motion values from 0.01 to 10.0g, with corresponding annual frequencies of exceedance from 0.1 to

0.00001 [*Frankel et al.*, 2000]. Only three sets of hazard maps, with 10%, 5%, and 2% PE in 50 years, were published, however. The three maps represent only three specific points on the hazard curves. All other points on the curves would also be equally valid choices. Having so many choices from PSHA makes it difficult for users and policy-makers to scientifically choose one.

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Satellite Data Help Predict Terrestrial Carbon Sinks

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Accurate estimates of how much CO_2 ecosystems can absorb will be fundamental to successful systems of international carbon accounting. NASA's Terra satellite platform, with the moderate resolution imaging spectroradiometer (MODIS) instrument on board, provides a new era of observations for carbon cycle assessments. Direct input of satellite vegetation index "greenness" data from the MODIS sensor into ecosystem simulation models can be used to estimate spatial variability in monthly net primary production (NPP), biomass accumulation, and litter fall inputs to soil carbon pools. Global NPP of vegetation can be predicted using the relationship between leaf reflectance properties and the fraction of absorption of photosynthetically active radiation (FPAR) [*Knyazikhin et al.*, 1999].

Predicted net ecosystem production (NEP) flux for atmospheric CO_2 in 2001 was estimated as an annual net sink of +3.6 Pg (1 billion metric tons) of carbon. NEP is computed as NPP minus soil microbial CO_2 fluxes, excluding the effects of small-scale fires and other localized disturbances or vegetation regrowth patterns on carbon fluxes. Our NASA Carnegie-Ames-Stanford Approach (CASA) model results for NEP in 2001 reflect observed climate patterns between and among major continental areas of the terrestrial biosphere (Figure 1). For instance, above-average temperatures were strongly associated with positive NEP (net sink fluxes) across the high-latitude zones of eastern Canada and Eurasia. Positive NEP fluxes were also associated with the heavy rainfall reported in eastern Europe, Siberia, Australia, West Africa, and southern Africa. Negative NEP (net source fluxes) was associated with severe droughts reported in south Asia, eastern Africa, northern China, and northern and eastern coastal South America.

As documented in *Potter* [1999], predicted monthly NPP flux, defined as net fixation of CO_2 by vegetation, is computed in NASA-CASA on the basis of light-use efficiency. Monthly production of plant biomass is estimated as a product of time-varying surface solar irradiance, and FPAR from the MODIS sensor, plus a constant light utilization efficiency term (emax) that is modified by time-varying stress scalar terms for temperature and moisture effects. The NASA-CASA model is designed to couple monthly NPP patterns to soil nutrient mineralization and microbial respiration of CO_2 from soils worldwide. The NASA-CASA soil model uses a set of compartmentalized difference equations with a structure comparable to the CENTURY ecosystem model.

First-order decay equations simulate exchanges of decomposing plant residue (metabolic and structural fractions) at the soil surface.

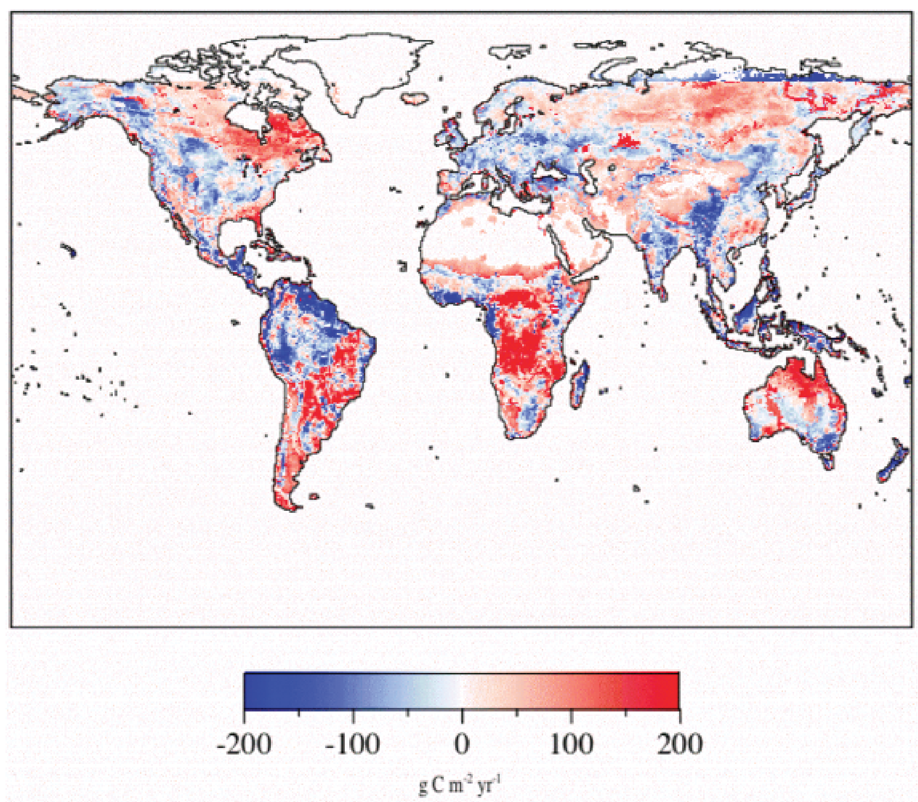

Fig. 1. Predicted global distribution of annual net ecosystem production fluxes in 2001. Net annual source areas are shown in blue, while net annual sink areas are shown in red.