Have Recent Earthquakes Exposed Flaws in or Misunderstandings of Probabilistic Seismic Hazard Analysis?

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In a recent *Opinion* piece in these pages, Stein *et al.* (2011) offer a remarkable indictment of the methods, models, and results of probabilistic seismic hazard analysis (PSHA). The principal object of their concern is the PSHA map for Japan released by the Japan Headquarters for Earthquake Research Promotion (HERP), which is reproduced by Stein *et al.* (2011) as their Figure 1 and also here as our Figure 1. It shows the probability of exceedance (also referred to as the "hazard") of the Japan Meteorological Agency (JMA) intensity 6–lower (JMA 6−) in Japan for the 30-year period beginning in January 2010. JMA 6− is an earthquake-damage intensity measure that is associated with fairly strong ground motion that can be damaging to well-built structures and is potentially destructive to poor construction (HERP, 2005, appendix 5). Reiterating Geller (2011, p. 408), Stein *et al.* (2011, p. 623) have this to say about Figure 1:

> The regions assessed as most dangerous are the zones of three hypothetical "scenario earthquakes" (Tokai, Tonankai, and Nankai; see map). However, since 1979, earthquakes that caused 10 or more fatalities in Japan actually occurred in places assigned a relatively low probability. This discrepancy—the latest in a string of negative results for the characteristic model and its cousin the seismic-gap model—strongly suggest that the hazard map and the methods used to produce it are flawed and should be discarded.

Given the central role that PSHA now plays in seismic risk analysis, performance-based engineering, and design-basis ground motions, discarding PSHA would have important consequences. We are not persuaded by the arguments of Geller (2011) and Stein *et al.* (2011) for doing so because important misunderstandings about PSHA seem to have conditioned them. In the quotation above, for example, they have confused important differences between earthquake-occurrence observations and ground-motion hazard calculations.

PSHA has two essential ingredients: seismic-source characterization (SSC) and ground-motion characterization (GMC). SSC deals with the earthquakes that might affect some site or area of interest and specifies the locations, sizes, and rates of occurrence for them. GMC is concerned with the excitation of ground motion from all of these earthquakes and its propagation to the site(s) of interest. Even for very specific choices of magnitude M and distance R, however, there is considerable variability of the resulting ground motion, and modern PSHA projects devote considerable time and effort to quantifying these uncertainties. For any site of interest, SSC and GMC are combined in the hazard integral (e.g., Reiter, 1990; McGuire, 2004), which integrates over all magnitudes M and distances R to determine the exceedance rate of a chosen ground-motion measure. This results in the hazard curve, with ground-motion values on the abscissa and their rates of exceedance on the ordinate; when these rates of exceedance are small numbers, they are the same as probabilities of exceedance.

The hazard curves for many sites may be synthesized into a map showing hazard values for a fixed ground-motion/damage-intensity level (a vertical line in hazard space; Fig. 1) or ground-motion values for a fixed hazard level (a horizontal line in hazard space; Fig. 2). Most readers of *Seismological Research Letters* will find Figure 1 to be a very different presentation of hazard from what they are used to seeing. More familiar is the portrayal in Figure 2 (Petersen *et al.*, 2008) that shows the peak ground acceleration (PGA) in California and Nevada for a fixed probability of exceedance of 4×10^{-4}/yr (the 2,500-year PGA), also known as the "2% in 50 years" PGA because it represents the ground motion with a 2% exceedance probability in a 50-year interval. In this format, ground motions tend to become large close to high-slip-rate faults (the San Andreas, e.g., and its principal branches), where many large earthquakes are expected to occur in 2,500 years. We can illustrate this with a highly simplified example in which a single-size event occurs every 250 years along the same fault segment. In this case, we need to choose the 1-in-10 PGA to reach the hazard level of 4×10^{-4}/year ($1/250 \times 1/10$). This will be a factor of 2–3 times larger than the median PGA value for a single earthquake and leads to the very large PGA values along the high-slip-rate sections of the San Andreas fault system in Figure 2.

The high-slip-rate faults in Japan are the subduction interfaces, with the Philippine Sea plate subducting beneath the Tokai–Tonankai–Nankai coast (at ~30 mm/year beneath Tokyo increasing to ~50 mm/year beneath the Nankai coast) and the Pacific plate subducting beneath the northern coast of Japan at ~80 mm/year. Both of these slip rates are somewhat significantly higher than that for the San Andreas fault, but only

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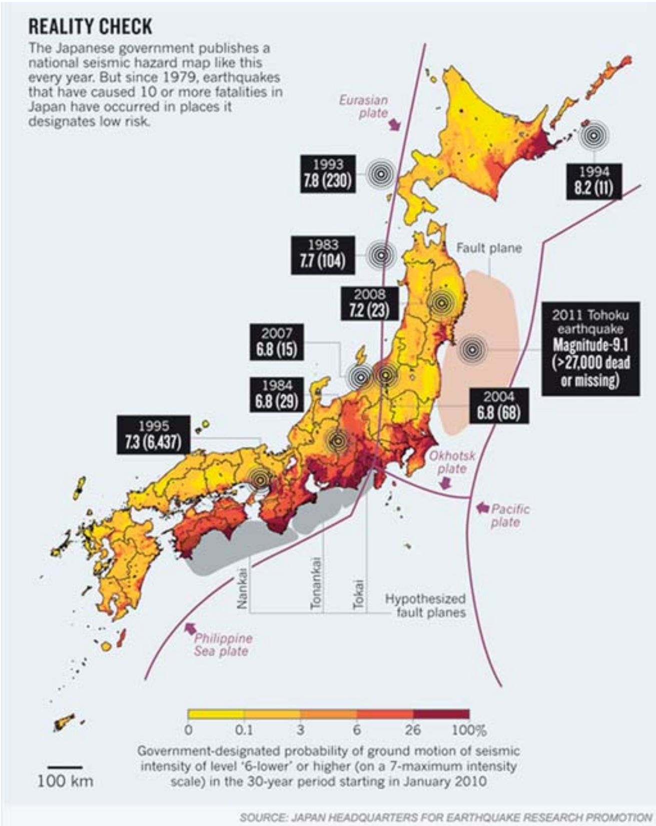
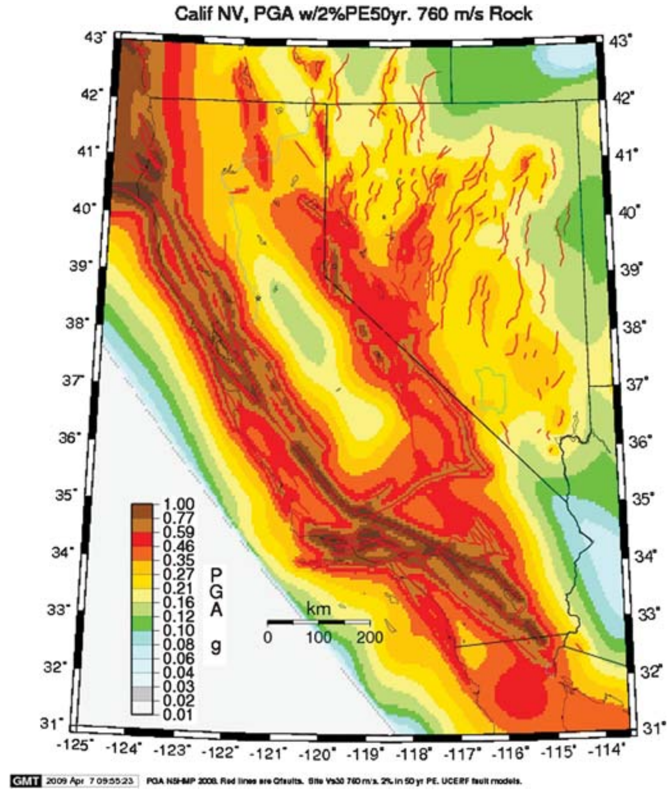


▲ **Figure 1.** Probability-of-exceedance for JMA 6– in Japan for the 30-year period starting January 2010. This is an update of the 2005 maps prepared by Japan HERP (2005).



▲ **Figure 2.** Peak ground accelerations in California and Nevada for a 4×10^{-4}/year hazard level (http://earthquake.usgs.gov/hazards/products/conterminous/2008/maps/ or Petersen *et al.*, 2008). The smoothly varying character of this map with respect to Figure 1 is because it was prepared for a single site response (in this case $V_{S30} = 760$ m/s), whereas Figure 1 includes the considerable variability of site response across Japan.

the Tokai–Tonankai–Nankai coastal zone is well expressed on the hazard map (Fig. 1), a curiosity to which we will return.

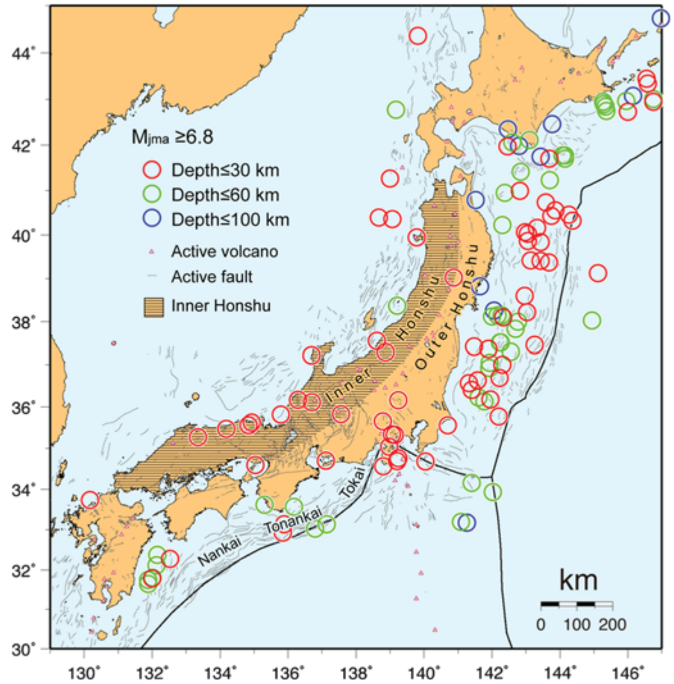
SEISMIC HAZARD IN INNER HONSHU

The earthquakes that "caused 10 or more fatalities in Japan actually occurred in places assigned a low probability" (Geller, 2011, p. 408; Stein *et al.*, 2011, p. 623), a region we refer to as Inner Honshu, the half of Honshu closest to the Sea of Japan. This low probability is not because earthquake rates here are small; since 1923, 14 crustal earthquakes of $M_{\mathrm{JMA}} \geq 6.8$ have occurred in Inner Honshu (Fig. 3) at an average rate of once every 6 years. So what makes the ground-motion hazard here so low? It is the large area of Inner Honshu, which we take here to be 1,500 km long and 100 km wide, relative to the area in which JMA 6– or greater occurs for these 14 earthquakes. There is considerable variability in what this area can be for M_{JMA} 6.8, ~400 km^2 according to Muramatsu (1969) and 1, 100 km^2 according to Kanda and Takemura (2011). To continue with our hazard calculation, the annualized ground-motion hazard for JMA 6– in Inner Honshu as a whole is simply the rate of $M_{\mathrm{JMA}} \geq 6.8$ earthquakes, 0.16 per year, times the area ratio $(400–1,100)/150,000$; this works out to be $(4–12) \times 10^{-4}$/year, and the corresponding 30-year hazard of JMA 6–, the format of Figure 1, is 1.3%–3.5%. To allow for the larger areas enclosed by JMA 6– of the few larger M_{JMA} earthquakes, we will take the last numbers to be 2%–5%.

The point of this arithmetic is to illustrate the essential simplicity of PSHA despite the many tedious details. It says that in the next 30 years ~2%–5% of the area of Inner Honshu, approximately 3, 000–7, 500 km^2, will experience JMA 6– or greater ground motions. At least in terms of the recent rate of $M_{\mathrm{JMA}} \geq 6.8$ earthquakes, this seems to be about right, the considerable variability in the real hazard map notwithstanding. It should be about right, of course, because we have used the same seismicity data that went into the hazard map in the first place. Important features of PSHA, then, are that it can only portray the future insofar as (1) the future will look like the past, at least probabilistically, and (2) the past is accurately known and accounted for. The second of these conditions is always a problem whenever and wherever the time scale of earthquake recurrence is long compared with the time scale of our observations.

SEISMIC HAZARD IN OUTER HONSHU

The size and location of the Tohoku earthquake (11 March 2011; **M** 9.0) surprised many earthquake scientists in Japan,



▲ **Figure 3.** $M_{JMA} \geq 6.8$ earthquakes in Japan, 1923–2011. Note that the sizes of circles denoting earthquakes are somewhat larger than the areas enclosed by JMA 6– that they generate.

but not all of them. Minoura *et al.* (2001) found tsunami deposits from three events during the last 3,000 years on the Sendai plain. Sawai *et al.* (2007) found clear evidence for deposits from the 869 Jogan tsunami as far as 4 km inland. They also noted that the tsunami from the 1611 Keicho earthquake disrupted agricultural activity there, although that activity disturbed the sedimentary evidence for the tsunami. The estimates of magnitude of the Jogan earthquake are uncertain, but Minoura *et al.* (2001) estimated that $\mathbf{M} \geq 8.3$ is required to explain the tsunami. Sawai *et al.* (2007) estimated return times of 600–1,300 years for such events, whereas Minoura *et al.* (2001) found 800–1,100 years and went on to state (p. 87) the following:

> More than 1,100 years have passed since the Jogan tsunami, and given the recurrence interval, the possibility of a large tsunami striking the Sendai plain is high.

This knowledge of past, large tsunamigenic earthquakes could have been used to account for the possibility of larger earthquakes contributing to the PSHA of Figure 1, but apparently was not. Given the ground accelerations and velocities recorded by the NIED K-Net and KiK-Net for the Tohoku earthquake (Kunugi *et al.*, 2012), it would seem that much of Outer Honshu (Fig. 3) experienced JMA 6– or greater during this event. Assuming a 1,000-year repeat time for such large earthquakes, we estimate a 3% hazard for JMA 6– in the next 30 years. This hazard level is greater than most of the hazard values for Outer Honshu shown in Figure 1, so we can be confident that such earthquakes and ground motions were not included in Figure 1. But what of the many $M_{JMA} \sim 7$ to 8 earthquakes known in the historical/instrumental record?

These recent $M_{JMA} \sim 7$ to 8 events are included in the PSHA of Figure 1 but are either too deep or too far offshore to generate JMA 6– in Outer Honshu. Otherwise, the JMA 6– hazard would be much higher, given the frequency of such earthquakes beneath and offshore of Outer Honshu. Neither the offshore 1978 Miyagi earthquake (12 June, **M** 7.7, M_{JMA} 7.4, depth = 44 km) nor the model repeat of it used in the PSHA generated JMA 6– along the Outer Honshu coast (HERP, 2005). Where the Pacific plate first passes beneath the coastline, the interface earthquakes are at depths ≥ 50 km (Hasegawa *et al.*, 1994). Except for the very largest earthquakes, then, this high-slip zone is invisible in Figure 1 because it is too deep to excite JMA 6–.

These several interesting features of the seismic hazard in Outer Honshu notwithstanding, it is important to remember that the greater agent of damage and destruction in this area was the exceptionally large and extensive tsunami excited by the Tohoku earthquake, not the ground motion. Neither does it seem that earthquake ground motion was much responsible for the happenings at Fukushima. In this region (and perhaps elsewhere in coastal Japan as well), the tsunami hazard matters more than the seismic hazard, the positive results of the rigorous earthquake-resistant design, and the construction practice in Japan.

SEISMIC HAZARD IN THE NANKAI–TONANKAI–TOKAI REGION

This portion of the PSHA map in Figure 1 says that the probability of exceedance of JMA 6– during the next 30 years is very high. Time-dependent probabilities for the subduction-zone earthquakes here are calculated on the basis of their recurrence intervals and elapsed times since the most recent events, but these assumptions alone do not give rise to the high hazard in this region. Indeed, time-dependent probabilities are calculated for any crustal fault or subducting region in Japan for which usable recurrence intervals and elapsed times are available (HERP, 2005).

The hazard here is absolutely high because great earthquakes have visited these areas several times a century for the past several centuries, but this is also true of Outer Honshu. In fact, the region deemed to have the greatest probability (99% for the next 30 years) of a future large earthquake in the area of Figure 1 is the Miyagi-oki region in Outer Honshu (HERP, 2010). The anticipated magnitude was thought to be ≤ 8, and it contributed little to the hazard numbers because it was expected offshore and too deep to excite JMA 6– at the coast. The hazard is higher along the Nankai–Tonankai–Tokai coast than along the Outer Honshu coast because historical earthquake ruptures of the subduction zone have been closer to shore and the subducting slab is at shallower depth as it passes beneath the shoreline. Interface earthquakes beneath the coastlines of the Nankai–Tonankai–Tokai region are only

$\sim$30 km deep as the Philippine Sea plate subducts beneath southwest Japan and Shikoku (Miyoshi and Ishibashi, 2004), compared with the $\sim$50-km depths along the Outer Honshu coast.

REGIONS OF LOW SEISMIC HAZARD

In addition to the recent earthquakes in Inner Honshu, Stein *et al.* (2011, p. 623) were concerned about the occurrence of earthquakes in other low-hazard areas around the world:

> Similar discrepancies have occurred around the world. The 2008 Wenchuan earthquake (**M** 7.9) in China occurred on a fault system assessed, based on the lack of recent seismicity and slow slip rates, to have low hazard. Another example is the convergent boundary between Africa and Eurasia in North Africa. The 1999 Global Seismic Hazard Map (Shedlock *et al.*, 2000), which shows peak ground acceleration expected at 10% probability in 50 years, features a prominent hazard "bull's-eye" at the site of the 1980 **M** 7.3 El Asnam earthquake. The largest subsequent earthquakes to date, the 2003 **M** 6.8 Algeria and 2004 **M** 6.4 Morocco events, did not occur in the bull's-eye or regions designated as having high hazard levels. The 2010 **M** 7.1 Haiti earthquake similarly occurred on a fault mapped in 2001 as having low hazard, and it produced ground motion far greater than the map predicted.

To the list mentioned, we can add the Darfield (3 September 2010; **M** 7.1) and Christchurch (21 February 2011; **M** 6.2) New Zealand earthquakes. Are earthquakes breaking out all over in low-hazard areas to make PSHA maps and methodologies look foolish? We doubt it, thinking rather that there are so many low-hazard zones around the world that it is just inevitable that such events will occur somewhere every several years or so.

There are $\sim 1.5 \times 10^8$ km^2 of subarial land area on Earth, most of which is aseismic in the sense that it is not considered to be an active tectonic terrain. Again for illustrative purposes, we assume that two-thirds of this land area, or 10^8 km^2, can be considered as 1,000 low-hazard regions, each having an area of $100{,}000$ km^2 ($\sim 300 \times \sim 300$ km; the area of the United States east of the Rockies is $\sim 5 \times 10^6$ km^2 or about 50 of these low-hazard regions). If each one of these has $\sim 1{,}000$-year recurrence intervals for significant earthquakes, we can expect about one of them a year to occur in some low-hazard area somewhere on Earth, on average. If enough of these regions have much longer recurrence intervals, the average rate of such earthquakes might drop to one every several years. The real Earth, of course, is not so simple as this end-member (low-hazard/high-hazard) idea, but it includes a whole spectrum of entries between high hazard and low hazard.

With few exceptions, very little is known about these low-hazard regions, especially how often potentially damaging or destructive earthquakes might occur. Even so, it is not much of a surprise that such earthquakes do occur, Stein *et al.* (2011) notwithstanding. Indeed, the explanation of the seeming paradox as to why so many **M** ≥ 6 earthquakes in southern California do not occur on the high-slip-rate strands of the San Andreas fault system is simply that there are so many more low-slip-rate strands, with a much greater cumulative length of faulting.

TESTING PSHA

Testing PSHA is good advice at any time, and much has been written about this subject already (e.g., McGuire, 1979; Ward, 1995; Stirling and Petersen, 2006; Beauval *et al.*, 2008; Miyazawa and Mori, 2009; Musson, 2012). The recently released NUREG-2117 (Kammerer and Ake, 2012) has an extensive discussion of testing seismic hazard studies in its appendix B. The most meaningful tests will come from observations collected over long periods, where "long" means times some multiple of the reciprocal of the hazard levels of interest. A thousand years of earthquake locations, magnitudes, and ground motions in and near Japan should provide a serious test of the HERP (2005) PSHA; 30 years of such data does not (Fig. 1). Fortunately, one can also work backward in time, at least in regions with low erosion and deformation rates such as Yucca Mountain. Here, the extreme ground motions research program (Abrahamson and Hanks, 2008; Hanks and Abrahamson, 2008) utilized fragile geologic structures to determine unexceeded ground motions to test the 1998 Yucca Mountain PSHA (Stepp *et al.*, 2001) at hazard levels of 10^{-4}/year to 10^{-7}/year. Unexceeded ground motions can demonstrate that a PSHA is wrong, but they cannot prove that it is right. Quite generally, it will be difficult to prove that a PSHA study is right until long after the fact. Testing individual SSC and GMC components should also be part of the testing protocols; it is a straightforward matter, for example, to analyze models alternative to the "seismic gap/characteristic earthquake model" for the Nankai–Tonankai–Tokai region of such concern to Geller (2011) and Stein *et al.* (2011). Various consistency checks of the sort that we have utilized here, although hardly comprehensive tests, are nevertheless of value in determining whether a PSHA map makes sense. The metric that really matters, however, is whether PSHA, together with the design-and-construction practices based on it, increases public safety and reduces economic losses.

EARTHQUAKE PREDICTION, EARTHQUAKE FORECASTING, AND PSHA

Almost 80 years ago, Wood and Gutenberg (1935, p. 219) distinguished sharply between earthquake prediction and earthquake forecasting:

> To have any useful meaning the prediction of an earthquake must indicate accurately, *within narrow limits*, the region or district where and the time when it will occur—and, unless otherwise specified, it must refer to a shock of important size and strength....

> On the other hand, generalized forecasting of the occurrence of shocks in regions known to be seismically active is entirely possible, but this is not earthquake prediction in the proper sense. The exact, or even approximate, time, place and magnitude cannot be stated; only that shocks will occur and that some will be strong, so that proper safeguards should be set up to minimize the risk incurred from them.

This is just what PSHA does and has done for almost half a century (Cornell, 1968), combining the rate of earthquake occurrence with the ground motions excited by them in the form of probabilities of exceedance of some ground-motion measure and using them as a basis for design-and-construction decisions. These calculations are now the foundation for all manner of seismic risk analyses, performance-based engineering, and design-basis ground motions.

Although PSHA can express the future in terms of ground-motion exceedance probabilities for some place or area of interest, it can do so reliably only insofar as the past is accurately known and can faithfully represent the future. Because our understanding of earthquakes and their effects continues to increase and evolve, so will the input data and models for PSHA. Most PSHA applications are for time-independent (Poisson) probabilities. Time-dependent models and methodologies are now being developed and have been used by HERP (2010) for Figure 1, but their successful application will require more information and more detailed information than are customarily assembled for time-independent PSHA.

Low seismic hazard does not mean no seismic hazard. Even when the seismic hazard is very low, damaging and destructive earthquakes can still occur anywhere, at any time, with the Christchurch earthquake being the most painful, recent reminder of this truism. Damaging and destructive earthquakes occur less frequently in low-hazard areas than in high-hazard areas, and because earthquake-risk mitigation is generally not a high priority in low-hazard areas, their vulnerability and potential losses will generally be greater than for high-hazard areas. That unforeseen earthquakes occur in unexpected places is a simple fact of life, not a failure of PSHA, and we should not be surprised by them: they speak eloquently to what we do not yet know about the Earth and earthquakes. Neither are the devastating consequences that occasionally attend such earthquakes a failure of PSHA, reflecting instead social–political decisions concerning acceptable risk and allocation of resources.

Finally, we can find no basis to support the assertions of Geller (2011) and Stein *et al.* (2011) that the methods and results of PSHA, as shown in Figure 1 for example, should be discarded; rather, we believe that their assertions are based on misunderstandings of what PSHA is and what it can do, not fundamental flaws. Just as importantly, we do not see what would serve as a replacement. Forty years of earthquake prediction research offers scant promise for deterministic earthquake prediction (Geller, 1997); indeed, little seems to have changed on this front since 1935.

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