OPINION PAPER

Probabilities and Fallacies: Why Hazard Maps Cannot Be Validated by Individual Earthquakes*

Iunio Iervolino[a)]

In countries with an advanced seismic technical culture, where best-practice hazard studies (which are therefore necessarily probabilistic) are available, the occurrence of a damaging event often triggers a debate, which is as understandable as it is delicate, aimed toward the verification and/or validation of the ground motion intensity estimates provided by the official hazard maps. Evaluations such as these are typically based either on the comparison of elastic response spectra derived from records of the event in question with uniform hazard (design) spectra, or on superimposing ground motion intensity measures on available hazard curves to retrieve the return period to which they correspond. This short note, using the recent 2012 M_w 6.0 Emilia (Italy) earthquake, discusses a few arguments, according to which this type of exercise should take into account the implications inherent in the probabilistic nature of hazard analyses, in order to avoid the risk of drawing conclusions that may be misleading or that may be likely to cause misconceptions about rationality of the current approach to seismic hazard. [DOI: 10.1193/1.4000152]

INTRODUCTION

Due to their underlying predictive meaning and relatively recent introduction in many countries, probabilistic seismic hazard analysis (PSHA; e.g., Cornell 1968, Reiter 1990) studies are understandably, but not necessarily legitimately, debated and questioned every time damaging earthquakes occur (e.g., Hanks et al. 2012, Kossobokov and Nekrasova 2012, Malagnini et al. 2012, Stein et al. 2011 and 2012, Stirling 2012). The L'Aquila 2009 (M_w 6.3) and Emilia 2012 (M_w 6.0) sequences, in central and northern Italy, respectively, are no exceptions in this sense. These sparked an extended discussion on the consistency and adequacy of the national hazard map (Stucchi et al. 2011), which serves as a basis for the definition of seismic actions for structural design according to the current building code (CS.LL.PP. 2008). The main arguments presented in support of such an assessment are based on comparing the observed ground motion with some representative values derived from seismic hazard analysis—for example, comparing response spectra of signals recorded

---

* Adapted from a note that appeared in Italian in the 2/2012 issue of *Progettazione Sismica* (IUSS Press, Pavia, Italy).

[a)] Dipartimento di Ingegneria Strutturale, Università degli Studi di Napoli Federico II, via Claudio 21, 80125, Naples, Italy.

Earthquake Spectra, Volume 29, No. 3, pages 1125–1136, August 2013; © 2013, Earthquake Engineering Research Institute

at one or more sites of interest with the uniform hazard spectra (UHS) from probabilistic estimates. However, it often seems that the implications of the probabilistic nature of hazard analyses and the consequences of the underlying assumptions are not explicitly accounted for during those attempts. The consequent risk is that of being led to fallacious—or at least misleading—conclusions, questioning a well-founded approach, supported by a wide scientific consensus, to the rational estimation of seismic hazard.

The modest aims of this Opinion Paper are to recall certain basic aspects of PSHA and derive some insights concerning what is legitimate and what is not when attempting to verify its results only by means of direct comparison with observed motion from a single earthquake. To this end, a brief review of the essentials of PSHA (in its classical form), is initially given. Then, the number of years of continuous observation required, in principle, to record events to validate ground motion hazard estimates, is derived analytically with reference to confidence intervals. Subsequently, the study addresses the reason why site-specific hazard analyses tend to produce—by their nature—results that cannot be compared only with epicentral records. Consequently, differences between site-specific and regional hazard are discussed. Finally, some issues about input data and models involved in PSHA are recalled, highlighting the points allowing evaluation of compatibility—more appropriately than validation—between hazard and individual seismic events.

STANDARD PSHA ESSENTIALS

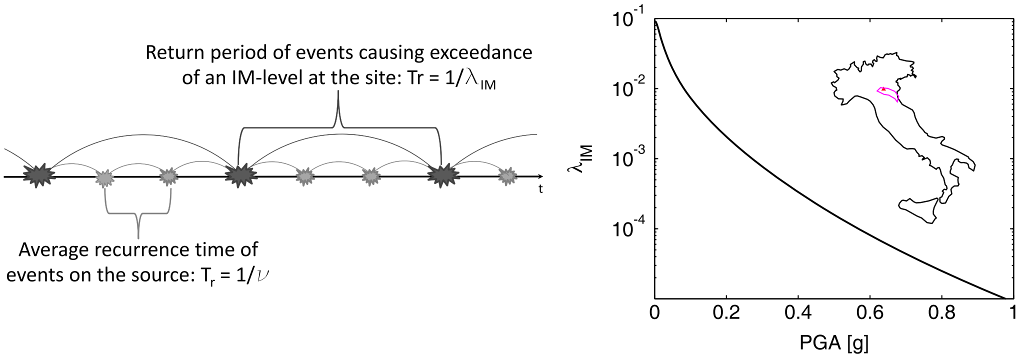
Before proceeding any further, it has to be recalled that, in its standard form, PSHA consists of the estimate of the mean rate (e.g., annual) of exceedance of a given value of a ground motion intensity measure (IM), for example, peak ground acceleration (PGA), at a site of interest (e.g., the location where a building under design is to be constructed). The computation of this rate, which can be represented as λ_{IM}, is often carried out considering the following: at first, the rate of earthquake occurrence at the source, v; then the conditional probability of IM exceedance given event magnitude (M) and source-to-site distance (R), $P[IM > im \mid m, r]$, as well as other parameters; and finally by averaging over all possible events, that is, *marginalizing* the probabilities across the conditioning random variables, as shown in Equation 1.[1] This articulation is only for convenience because the $P[IM > im \mid m, r]$ term is obtained from ground motion prediction equations (GMPEs), while v and $P[M = m \cap R = r]$, the latter being the joint probability of M and R, are provided based on seismicity—historical or instrumental—and geological information about the source.

$$\lambda_{IM} = v \cdot P[IM > im] = v \cdot \sum_{m,r} P[IM > im \mid m, r] \cdot P[M = m \cap R = r] \qquad (1)$$

In fact, it is possible to show that if the occurrence of earthquakes on the source follows a homogeneous Poisson processes (HPP) with rate v, then the process describing the occurrence of events determining exceedance of the IM at the site of interest also follows an HPP. Furthermore, the rate of the latter depends on that of the former, as in Equation 1.

---

[1] In order to maintain simplicity in this illustration, the probabilities are expressed for discrete random variables while, strictly speaking, these should be considered continuous. In fact, sums and probabilities should be replaced by integrals and probability density functions (or cumulative distribution functions) respectively.



(a) (b)

Figure 1. (a) Sketch of *filtering* HPP to pass from the earthquake occurrence at the source to the exceedance of a given intensity at the site; (b) example of hazard curve, which includes the considered site and the seismogenic zone it is enclosed in, according to the source model of Meletti et al. (2008).

It is a filtered process; the occurrence of earthquakes on the source is filtered by the probability that the resulting ground motion will cause the exceedance of the intensity level in question, *im*, at the site (Figure 1a). In other words, among all the earthquakes occurring on the fault, retaining only those causing the prescribed effect at the site, the occurrence of events belonging to this random selection is still described by a HPP.

If the site is subject to *n* earthquake sources, each of which generates earthquakes characterized by independent HHP occurrence, then the rate of exceedance of *im* at the site is simply the sum of the rates, as shown in Equation 2, where the meaning of symbols is obvious.

$$\begin{aligned}\lambda_{IM} &= \sum_{i=1}^{n} \lambda_{IM,i} = \sum_{i=1}^{n} \nu_i \cdot P[IM_i > im] \\ &= \sum_{i=1}^{n} \nu_i \cdot \sum_{m,r} P[IM_i > im \mid m, r] \cdot P[M_i = m \cap R_i = r] \qquad (2)\end{aligned}$$

If the analysis per Equation 2 is repeated for all IM values in a range of interest, a curve for λ_{IM}, as a function of *im*, is obtained. Such a diagram is termed *hazard curve*, and for each IM value provides the rate of the specific HPP regulating its exceedance at the site of interest. Indeed, different IM values feature different rates. For example, if the IM is the PGA, the larger the PGA value, the lower the rate of the HPP characterizing its exceedance. In other words, the larger is PGA, the rarer the event.

In Figure 1b, an example hazard curve is presented, which was calculated for the site of Mirandola (longitude 11.06, latitude 44.88; close to the epicenters of the May 2012 Emilia seismic sequence) taking into consideration, among the seismic zones considered in the Italian source model by Meletti et al. (2008), only that named 912, in which the site is enclosed. Parameters of earthquake occurrence for the zone were taken from Barani et al. (2009). The hazard was computed with software described in Convertito et al. (2009).

One important consequence of the HPP assumption for earthquake occurrence[2] is that the random time elapsed between two consecutive events (i.e., the interarrival time), is characterized by the exponential distribution. Therefore, the probability that the time between two events causing the exceedance of the IM value of interest at the site, $T(im)$, is lower than t is given by Equation 3. $T(im)$ can also be interpreted as the time until the next event, regardless of the epoch of evaluation, HHP being a memory-less process.

$$P[T(im) \le t] = 1 - e^{-\lambda_{IM} \cdot t} \tag{3}$$

It follows from Equation 3 that the design value of PGA, if the design criterion is that the structure must withstand an intensity having a 10% probability of being exceeded during its life equal to 50 years (e.g., CS.LL.PP. 2008), will that corresponding to $\lambda_{IM} = 0.002$ in the hazard curve of Figure 1b. Indeed, this is the rate for which $P[T(im) \le 50] = 0.1$.

By virtue of the properties of HHP, the result obtained from Equation 3, in terms of PGA and λ_{IM}, may also be interpreted by saying that the intensity of shaking from Figure 1b will be exceeded on average every $T_r = 1/\lambda_{IM} = 1/(2 \cdot 10^{-3}) = 475\ yr$. In fact, T_r is also termed the *return period* of the event causing exceedance of the specific PGA value.

OBSERVED OCCURRENCES AND RETURN PERIODS: HOW MANY YEARS DOES IT TAKE TO VALIDATE HAZARD AT A SITE?

Now, say one wants to validate the intensity measure having an annual rate of exceedance $\lambda_{IM} = 0.002$ according to the hazard curve for the site of interest, that is, the PGA that has a 10% probability of being exceeded within an observation window of 50 years. In order to confirm or disprove the frequency associated with this value taken from hazard analysis, one must be able to observe with what frequency this value of PGA is effectively exceeded as a consequence of seismic shaking at the site (e.g., Stirling and Gerstenberger 2010).

This problem is similar to that of predicting the possible overcrowding of a public transport bus following a certain schedule with respect to a given stop along its route. It is necessary to wait for an adequate number of hours to observe enough occurrences to estimate the frequency of buses in which crowding exceeds, say 80% of its capacity.

Thus, in the case of PGA, assuming that ten observed occurrences of the event with a mean return period equal to about 500 years would be sufficient (to follow), one would require 5,000 years of measurements for the site in question (see also Beauval et al. 2008). Unfortunately, the first accelerometric record of a seismic event was obtained during the Long Beach earthquake (CA, USA) in 1933; thus there is no site for which such a direct comparison can be made, nor will there be for quite a long time to come.

It can be said that the frequency of occurrence of intensity corresponding to ground motion with return period T_r requires—should we acquiesce to ten observations as being sufficient—$10 \cdot T_r$ years of recordings before it can be compared to its hazard-computed counterpart. In other words, if 50 years of continuous recordings are available for a particular

---

[2] In this work, considerations regarding the choice, however frequent, of the HPP to model earthquake occurrence are omitted, as well as any discussion of possible alternatives.

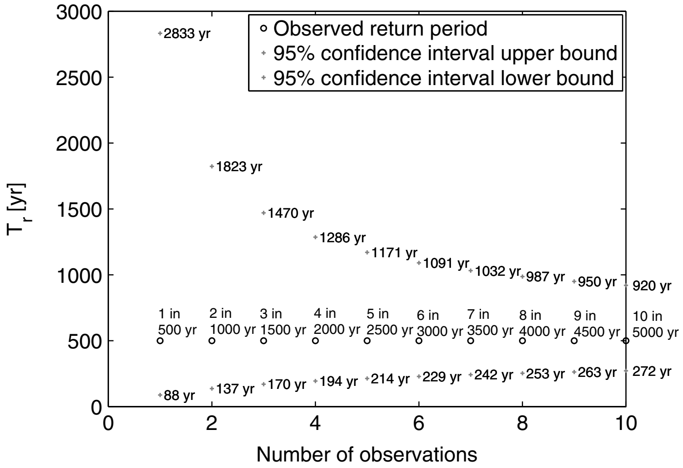


Figure 2. Confidence intervals for the return period as a function of the number of observation. It is assumed the frequency for which the CIs are built is always the reciprocal of 500 (the return period in years); therefore, the number of observations and the time-span vary accordingly.

site, according to the criterion stated above, one should be able to validate the PGA value with a return period (of exceedance) of no more than 5 years.

In fact, one may even question whether ten occurrences are sufficient to get a *good* estimate of the return frequency. In Figure 2, the 95% confidence intervals (CI) are obtained for the $T_r = 500\ yr$ event as a function of the number of observation. The CIs are built from those for the rate of the Poisson distribution as in Equation 4, where $\overline{\lambda}_{IM}$ is the sample mean, and $u_{\alpha/2} = 1.96$. It can be seen that even if ten observations are available over a 5000 yr observation period (n), the CI for T_r is still quite large.[3]

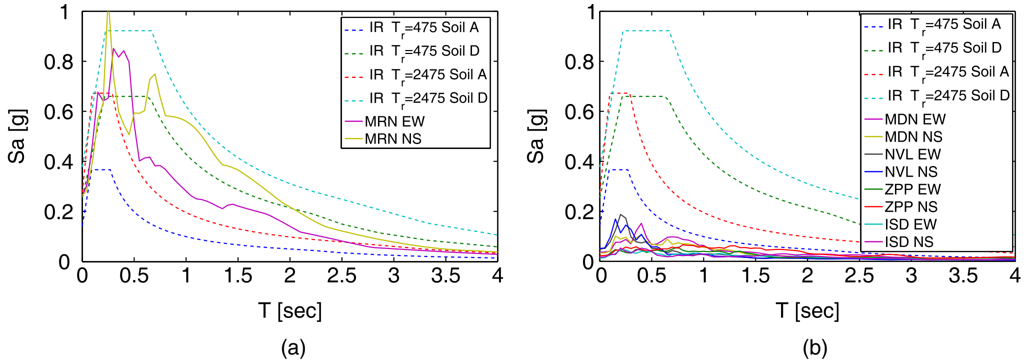
$$\begin{cases} P\left[-u_{\alpha/2} < \dfrac{\overline{\lambda}_{IM} - \lambda_{IM}}{\sqrt{\lambda_{IM}/n}} < u_{\alpha/2}\right] = 1 - \alpha \\ \alpha = 0.05 \end{cases} \tag{4}$$

WHY DO PSHA RESULTS ALWAYS SEEM TO HAVE BEEN EXCEEDED?

When hazard estimates are compared to earthquake records, the latter are usually selected among the largest observed, that is, they are often as close as possible to the source. As an example, design spectral accelerations, Sa, according to the Italian building code (Italian regulation, or IR hereafter) are presented in Figure 3 for return periods of 475 years and 2,475 years for the site of Mirandola (MRN) and various site soil classes, along with those of horizontal records from the 20 May 2012 earthquake, which had an epicenter

---

[3] The equation avails of the Gaussian approximation, providing largest errors for low number of observations. In fact, the exact CI with only one observation would be much larger than that of Figure 2, yet Equation 4 was chosen so as the reader can easily make similar calculations.



(a)
(b)

Figure 3. (a) Spectra recorded near the epicenter of the 20 May 2012 Emilia earthquake, compared with design spectra for the same site for two return periods, and (b) other spectra recorded within 47 km from the epicenter compared with the same design spectra. (For sites in the right panel, IR spectra for each of those should be considered; however, those of the left panel are used instead. This is for simplicity, as design spectra for neighboring Italian sites are similar in amplitude and shape.)

close to MRN recording station (for details, see Iervolino et al. 2012). On the right-hand panel of the figure, the same design spectra are compared with those from recording stations, still close but further away from the epicenter (at most, 47 km off).

One preliminary observation is that the hazard estimates (the IR design spectra practically coincide with the UHS derived by the analysis described in Stucchi et al. 2011) are only comparable in amplitude to the records near the epicenter. One should consider that, per Equation 1, PSHA averages all possible epicentral locations within the seismic zone(s) of interest around the site. In other words, because the location of the earthquake, which will cause the exceedance of the estimated IM value, is uncertain, the estimated rate corresponding to a given return period is, actually, an average accounting for ground motions from all possible locations. Given M, the weights are the probabilities that the site and epicenter will be separated by a given distance. For this reason, the probabilistic estimate is bounded between upper and lower limits. Due to the nature of common GMPEs, the upper bound will coincide with the value calculated, assuming that the site of interest is the epicenter, for any fixed magnitude. Therefore, in case one would like to actually compute the hazard considering the epicenter certainly located at the site of interest (i.e., conditional on said fact), then the calculated rate for *im* would certainly not be lower than in the case where the possible epicentral location is spread on the source, per Equation 5, which is written in the hypothesis that M and R are independent variables:

$$\lambda_{IM|R=0} = \nu \cdot \sum_{m} P[IM > im \mid m, 0] \cdot P[M = m] \geq \lambda_{IM} \tag{5}$$

An example for the Mirandola site is presented in Table 1, where hazard is expressed in terms of PGA, corresponding to some return periods (i.e., Figure 1b). In the table, the same calculation, conditional on the epicenter located in Mirandola, is also presented. The increased hazard is apparent. One might then raise the question of whether it would be

Table 1. PGA [g] hazard for Mirandola, considering potential epicenters uniformly distributed in the seismogenic zone containing the site, and conditional on the epicenter located at the site.

	T_r [yr] (λ_{IM} [events/yr])			
	50 (0.02)	475 (0.002)	975 (0.001)	2475 (0.0004)
Epicenter uniformly distributed within zone 912	0.046	0.172	0.222	0.288
Epicenter fixed in Mirandola	0.251	0.442	0.509	0.597

appropriate to always make this assumption about the epicenter when calculating hazard maps, since it appears to lead to systematically conservative results. As a matter of fact, it would not reflect the effective state of knowledge on the phenomenon of epicenters of future earthquakes being known with uncertainty. During hazard calculations, each location should have an importance (i.e., a weight in hazard computation) proportional to the belief it will be the epicenter of the event of interest (i.e., its probability).

To summarize, it may be said that to question a probabilistic hazard map, the bulk of sites for which PSHA has been carried out in the same assessment should be considered. If, in multiple earthquakes, it will be found that in a fraction of them—statistically corresponding to λ_{IM}—the IM value is exceeded, this is expected by the probabilistic model. In fact, if such a fraction derives from observations in the long run, it is a confirmation that the hazard reconciles with actual rates of occurrence (see also McGuire and Barnhard 1981 and Ward 1995).

INDIVIDUAL (LOCAL) RISK VERSUS SOCIAL (REGIONAL) RISK

It is therefore a fact that whenever a strong (i.e., above-average) earthquake strikes a region, the design threshold can be exceeded at sites near the epicenter, while due to intervening attenuation with distance, other sites may be substantially under-shaken. Actually, in densely populated zones, it is likely that one of the residential areas will be the epicentral location.

This problem is similar to that of a lottery. On each drawing of lots, a single ticket is extracted, which translates to single winner at most and many non-winners. The probability that any individual wins (individual risk) is very low, but the probability that there is at least one winner (aggregate or social risk) is much higher, depending on the number of tickets sold out of the total in the draw. If one is not interested in the probability of any single winner, but in the probability of the winner belonging to a specific party (e.g., a person from a specific city), a suitable criterion for the calculation is needed.

In the case of seismic hazard, one probabilistic method of accounting for this phenomenon could be that of calculating the ground-motion intensity, which has a specific annual rate of exceedance in at least one of several sites of interest. To better clarify this concept, let us consider two sites $\{1, 2\}$ within the region in question and subject to the same seismic source (Figure 4a). Let the objective of regional probabilistic seismic hazard analysis (e.g., Malhotra 2008, Esposito and Iervolino 2011) be to compute the annual rate of the event that

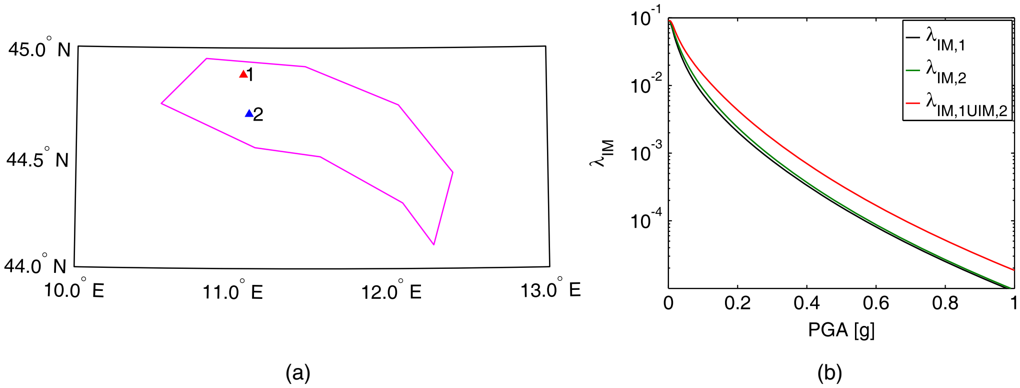


Figure 4. (a) Sites 1 and 2 taken within seismogenic zone 912 and (b) regional hazard curve of the two sites compared with site-specific hazards.

causes the exceedance of a certain IM value in at least one of the two sites. Such a calculation could be carried out by implementing Equation 6, which will yield values not lower than those corresponding to hazard in each individual site[4] (Figure 4b). Note that the greater the number of sites considered (i.e., the larger the region is), the greater the discrepancy will be between regional hazard and the hazard for the individual sites.[5]

$$\begin{aligned}\lambda_{IM_1 \cup IM_2} &= \nu \cdot \left\{1 - \sum_{m,r_1,r_2} P[IM_1 \leq im \cap IM_2 \leq im \mid m, r_1, r_2] \cdot P[M = m \cap R_1 = r_1 \cap R_2 = r_2]\right\} \\ &\geq \max(\lambda_{IM_1}, \lambda_{IM_2}) \end{aligned} \tag{6}$$

One should note that regional hazard could be useful from the point of view of controlling social risk, in the case when a collapse in at least one of these sites has consequences felt over the entire region. Consider, for instance, a seismic zone where various nuclear plants are located; the consequences of potential collapse of any of those installations would affect the entire region regardless of the exact location of failure. It would therefore make sense to calculate hazard as the probability of exceeding the critical acceleration in at least one of these sites, which entails their joint consideration in the hazard calculation (Crowley and Bommer 2006, discuss similar issues). On the other hand, it should be kept in mind that the results of regional hazard analysis cannot be used to assess the risk of single buildings located in only one of the sites in the region. In fact, such design situations aim at controlling seismic risk in site-specific projects and require individual (local) hazard assessment, per modern construction codes.

---

[4] The need for the joint probability, $P[IM_1 \leq im \cap IM_2 \leq im \mid m, r_1, r_2]$, in Equation 6 recalls that GMPEs always imply stochastic dependency of IMs at different sites. This is an effect of both the mean and, virtually, standard deviation of the ground motion model (e.g., Esposito and Iervolino 2011).

[5] Regional criteria, which are able to rely on observations from multiple sites, would be easier to validate. Indeed, some attempts exist (Albarello and D'Amico 2008).

SOME OTHER DO'S AND DON'TS IN COMPARING EARTHQUAKE OBSERVATIONS TO HAZARD ANALYSIS

Despite the arguments just developed, it should be taken into account that some evaluations concerning the compatibility of the input parameters of the models used in hazard estimation are nonetheless possible (e.g., Appendix B in U.S. Nuclear Regulatory Commission 2012). For example, it may be verified upon earthquake occurrence whether the event magnitude and the source location are among the range of those considered plausible during the hazard analysis, and whether they are related to the characteristics of the sources taken into consideration by the seismic source model adopted. Moreover, it may be verified whether the observed ground motion intensities are found to be not significantly different (statistically speaking) with the distributions of IM, conditional to M and R, provided by the GMPEs considered. This will at least guarantee that the earthquake that occurred was not atypical, that is, not properly accounted for by the tools employed in hazard analysis (e.g., Crowley et al. 2008 and Iervolino et al. 2012).

On the other hand, comparisons (as in Figure 3) of observed response spectra with UHS, which are plots of spectral accelerations from PSHA having the same exceedance probability at all oscillation periods, should be carried out with caution. In fact, according to the rationale presented above, even the basis for the choice of which UHS (with respect to return period) to select for said comparison is put into question. Furthermore, UHS are, by definition, combinations of spectra derived from substantially different earthquakes. For example, it is known that high frequencies may be mostly influenced by moderate magnitude events from sources near the site while low frequencies may be predominantly influenced by larger magnitudes at greater distances (e.g., Reiter 1990).

As an illustration, in Figure 5, the disaggregation of seismic hazard for Mirandola is given for PGA and Sa(1 sec) belonging to the same UHS referring to 10% exceedance probability in 50 years. Disaggregation results in a distribution that, given exceedance of the considered

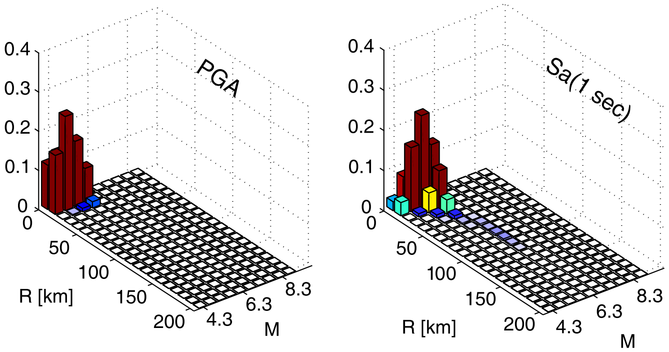


Figure 5. 10% in 50 years hazard disaggregation for PGA and Sa(1 sec) in Mirandola. Vertical axis is always the probability of the M-R pair being causative given the exceedance of the considered *im*.

IM-level, provides the probability of each *M*-*R* pair being the causative event. Figure 5 shows that multiple *M*-*R* pairs have comparable probability. Moreover, disaggregation changes with the spectral ordinate considered (even if variation across the spectrum at this site are smoother with respect to other Italian sites; see Iervolino et al. 2011 for details).

Along these lines, it can be said that UHS do not represent any specific earthquake, and comparisons with records from any single specific event may have little meaning.

CONCLUDING REMARKS

When damaging earthquakes occur in countries for which public seismic hazard assessment is available, its consistency with observed ground motions typically becomes a subject of debate. In the case where hazard is probabilistically evaluated, several points have to be made clear before carrying out such an exercise. This brief Opinion Paper attempts to shed some light on a few of the critical issues following from the nature of classical PSHA and the Poissonian assumption of the earthquake occurrence process, which underlie current best-practice hazard studies. More specifically, the following should be kept in mind:

1. In order to validate the frequency associated with a certain ground-motion intensity derived from hazard analysis at a site, a time-span of many years is necessary. To actually estimate the frequency of intensity with a return period of exceedance at a given site of T_r years, one would need on average $10 \cdot T_r$ years of continuous observation, provided one acquiesces to ten occurrences for the estimate. In fact, this sample size may still imply significant uncertainty.
2. Intensity levels referring to design, calculated by means of hazard studies, often appear to be exceeded during particularly strong earthquakes. More often than not, such conclusions derive from only comparing records obtained near the epicenter with the hazard for that site. However, one has to consider that PSHA accounts for ground motion from all *probable* epicenters, while if the earthquake originates at the site, the hazard to compare it to should be that conditional to the fact that the site is located on the epicenter. All other parameters being equal, the latter cannot be lower if the GMPE provides the largest effect at the smallest distance.
3. It follows from point 2 that in all likelihood, a strong earthquake will be critical for the epicentral site, if urbanized. An alternative way to account for this is the regional hazard concept, which entails computing the probability that a certain level of ground motion intensity will be exceeded, for example, in at least one site in the region. However, it will lead to larger hazard estimates, which should not be used for the risk evaluation of engineering projects at specific sites, that being the objective of PSHA in its classical form.
4. Due to the fact that uniform hazard spectra do not represent any specific ground motion—but rather are combinations of spectra from all possible earthquakes accounted for during hazard analysis—straightforward comparisons with their observed counterparts may have little meaning, if any.

Finally, in light of these arguments (as well as some not addressed here), it can be said that the validation of probabilistic seismic hazard with individual earthquakes can be a very difficult task. On the other hand, it is possible to investigate the compatibility (also in quantitative and statistical terms) between observations and the input parameters or the models considered in hazard studies.

Additionally, although it was supported that it is not the case to question the current approach to probabilistic assessment of seismic hazard, it should be said that this type of analysis can, and should always, be improved to incorporate the progress in scientific knowledge. Indeed, probabilistic analyses are always conditional on the state of knowledge on the phenomenon which is the object of study. For instance, it is already documented that in near-source areas, where earthquakes are typically most damaging due to issues related to the rupture mechanism and site-to-source geometry, effects of some peculiarity may become manifest (i.e., directivity), which have not yet been accounted for in current-practice hazard maps (e.g., Chioccarelli and Iervolino 2010 and 2013). This is mainly due to the fact that one would require information on existing faults at a level of detail that is seldom available; yet this issue may pose a limitation on hazard studies, especially those based on seismogenic zones.

ACKNOWLEDGEMENTS

The idea for this Opinion Paper was born of a debate with Professors Gian Michele Calvi, Gaetano Manfredi, Carlo Meletti, and Massimiliano Stucchi. Discussions with Professor Massimiliano Giorgio were essential. Professors Edoardo Cosenza and Polat Gülkan provided helpful comments on early drafts of the manuscript. Dr. Eugenio Chioccarelli has contributed to the examples presented. Mrs. Racquel K. Hagen has proofread the manuscript. Professor Julian J. Bommer, Dr. Thomas C. Hanks, an anonymous reviewer, and the Responsible Editor for *Earthquake Spectra*, who have all provided valuable reviews, are also gratefully acknowledged.

REFERENCES

Albarello, D., and D’Amico, V., 2008. Testing probabilistic seismic hazard estimates by comparison with observations: An example in Italy, *Geophys. J. Int.* **175**, 1088–1094.

Barani, S., Spallarossa, D., and Bazzurro, P., 2009. Disaggregation of probabilistic ground motion hazard in Italy, *B. Seismol. Soc. Am.* **99**, 2638–61.

Beauval, C., Bard, P.-Y., Hainzl, S., and Guéguen, P., 2008. Can strong-motion observations be used to constrain probabilistic seismic-hazard estimates?, *B. Seismol. Soc. Am.* **98**, 509–520.

Chioccarelli, E., and Iervolino, I., 2010. Near-source seismic demand and pulse-like records: a discussion for L’Aquila earthquake, *Earthq. Eng. Struct. D.* **39**, 1039–1062.

Chioccarelli, E., and Iervolino, I., 2013. Near-source seismic hazard and design scenarios, *Earthq. Eng. Struct. D.*, **42**, 603–622.

Convertito, V., Iervolino, I., and Herrero, A., 2009. The importance of mapping the design earthquake: insights for southern Italy, *B. Seismol. Soc. Am.* **99**, 2979–2991.

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

Crowley, H., and Bommer, J. J., 2006. Modelling seismic hazard in earthquake loss models with spatially distributed exposure, *B. Earthq. Eng.* **4**, 249–275.

Crowley, H., Stafford, P. J., and Bommer, J. J., 2008. Can earthquake loss models be validated using field observations?, *J. Earthq. Eng.* 12, 1078–1104.

CS.LL.PP., 2008. *Decreto Ministeriale 14 gennaio 2008: Norme tecniche per le costruzioni*, Gazzetta Ufficiale della Repubblica Italiana, n. 29, 4 febbraio 2008, Suppl. Ordinario n. 30. Ist. Polig. e Zecca dello Stato S.p.a., Rome (in Italian).

Esposito, S., and Iervolino, I., 2011. PGA and PGV spatial correlation models based on European multi-event datasets, *B. Seismol. Soc. Am.* **101**, 2532–2541.

Hanks, T. C., Beroza, G. C., and Toda, S., 2012. Have recent earthquakes exposed flaws in or misunderstandings of probabilistic seismic hazard analysis?, *Seismol. Res. Lett.* **83**, 759–764.

Kossobokov, V. G., and Nekrasova, A. K., 2012. Global Seismic Hazard Assessment Program maps are erroneous, *Seismic Instruments* **48**, 162–170.

Iervolino, I., Chioccarelli, E., and Convertito, V., 2011. Design earthquakes from multimodal hazard disaggregation, *Soil Dyn. Earthq. Eng.* **31**, 1212–1231.

Iervolino, I., De Luca, F., and Chioccarelli, E., 2012. Engineering seismic demand in the 2012 Emilia sequence: preliminary analysis and model compatibility assessment, *Ann. Geophys.-Italy* **55**, 639–645.

Malagnini, L., Herrmann, R. B., Munafò, I., Buttinelli, M., Anselmi, M., Akinci, A., and Boschi, E., 2012. The 2012 Ferrara seismic sequence: Regional crustal structure, earthquake sources, and seismic hazard, *Geophys. Res. Lett.* **39**, L19302, doi: 10.1029/2012GL053214.

Malhotra, P., 2008. Seismic design loads from site-specific and aggregate hazard analyses, *Bull. Seism. Soc. Am.* **98**, 1849–1862.

McGuire, R. K., and Barnhard, T. P., 1981. Effects of temporal variations in seismicity on seismic hazard, *B. Seismol. Soc. Am.* **71**, 321–334.

Meletti, C., Galadini, F., Valensise, G., Stucchi, M., Basili, R., Barba, S., Vannucci, G., and Boschi, E., 2008. A seismic source zone model for the seismic hazard assessment of the Italian territory, *Tectonophysics* **450**, 85–108.

Reiter, R., 1990. *Earthquake Hazard Analysis: Issues and Insights*, Columbia University Press, New York, 254 pp.

Stein, S., Geller, R. G., and Liu, M., 2011. Bad assumptions or bad luck: why earthquake hazard maps need objective testing, *Seismol. Res. Lett.* **82**, 623–626.

Stein, S., Geller, R. G., and Liu, M., 2012. Why earthquake hazard maps often fail and what to do about it, *Tectonophysics* **562/563**, 1–25.

Stirling, M. W., 2012. Earthquake hazard maps and objective testing: the hazard mapper's point of view, *Seismol. Res. Lett.* **83**, 231–232.

Stirling, M. W., and Gerstenberger, M., 2010. Ground motion–based testing of seismic hazard models in New Zealand, *B. Seismol. Soc. Am.* **100**, 1407–1414.

Stucchi, M., Meletti, C., Montaldo, V., Crowley, H., Calvi, G. M., and Boschi, E., 2011. Seismic hazard assessment (2003–2009) for the Italian building code, *B. Seismol. Soc. Am.* **101**, 1885–1911.

U.S. Nuclear Regulatory Commission, 2012. *Practical implementation guidelines for SSHAC level 3 and 4 hazard studies*, NUREG-2117, Revision 1, Office of Nuclear Regulatory Research, Washington D.C. (http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr2117/)

Ward, S. N., 1995. Area-based tests of long-term seismic hazard predictions, *B. Seismol. Soc. Am.* **85**, 1285–1298.

(Received 16 September 2012; accepted 8 February 2013)