

Seismic Hazard Assessment: Management of Uncertainty and Validation

*Stima della Pericolosità Sismica:
Trattamento dell'Incertezza e Validazione*

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Riassunto: La verosimiglianza dei diversi possibili scenari di scuotimento del suolo attesi in occasione di futuri eventi sismici (pericolosità sismica) viene valutata mediante l'applicazione di opportuni modelli probabilistici. In presenza di modelli di calcolo alternativi, risulta necessario fornire stime di pericolosità che combinino i risultati dei diversi modelli in modo da tenere conto del livello di verosimiglianza associato a ciascuno di questi. Utilizzando un approccio formale unitario viene descritta la procedura adottata per manipolare i diversi livelli di incertezza associati alle stime di pericolosità sismica, mettendo in evidenza come la procedura oggi più diffusa (albero logico basato su giudizi esperti “ex-ante”) presenti notevoli problemi di natura interpretativa che ne limitano l'effettiva affidabilità. Allo scopo di superare questo tipo di problemi viene proposta l'adozione di un approccio differente basato su procedure di validazione empirica dei risultati prodotti dai diversi modelli di calcolo.

Keywords: Seismic Hazard, Probabilistic Model, Logic Tree, Validation

1. Introduction

The seismic hazard is the ground shaking level g expected to occur at a site within a given future time interval (exposure time) as a consequence of earthquakes. In seismic countries, this information plays an important role in the planning of future emergencies, the assessment and application of building codes, allocating resources for retrofitting, etc.

In principle, physical modelling could allow the forecast of such occurrences given that a number of features (source geometry and location, recurrence of seismic events at the source, propagation pattern of seismic waves, etc.) are known. However, in the lack of precise information about these elements, several possible scenarios can be determined that are equally compatible with available data. For each scenario, a likelihood evaluation (expressed in terms of probability values) should be performed in order to provide a “robust” estimate of local hazard.

The management of such uncertainty (the so called “aleatory” uncertainty) induced the development of specific stochastic models devoted to the Probabilistic Seismic Hazard Assessment (PSHA), that constitute the current practice worldwide (McGuire, 1993). Since the seminal work of Cornell (1968), several PSHA models have been proposed each characterised by a varying role of deterministic elements (e.g., geometry of seismic sources, dynamic interaction between neighbouring sources, recurrence of events on the

same faults, etc.) with respect to probabilistic elements (Bommer, 2002; Abrahamson, 2006). The result of these models is a set of likelihood estimates (probabilities) associated to the possible ground shaking values expected during the exposure time. In particular, PSHA models result in a function “Seismic Hazard Function” $H(g)$ that represents the probability that the value g is exceeded during a fixed exposure interval time T . Thus, the probabilistic formalism is used to associate uncertainty relative to the underlying physical process (location and geometry of seismogenic sources, time series of seismic activations, energy propagation from the source to the site) to the uncertainty relative to the ground shaking expected at the site.

Each PSHA model requires the choice of a number of elements (recurrence model at the source, attenuation relationship to evaluate the ground shaking level at the site given that an amount of energy has been released at the source, etc.) that have to be determined empirically or on the basis of reasonable assumptions. Being each of these choices debatable, the common situation is the presence of different plausible hazard estimates for the same site. In this context, for a correct estimate, this additional source of uncertainty (commonly addressed as “epistemic” uncertainty) has to be accounted for and included in the computations. To this purpose, the likelihood of each PSHA model has to be evaluated. This is commonly achieved by using a “logic tree” approach (e.g., Budnitz et al., 1997; Coppersmith and Youngs, 1998; Rabinowitz et al., 1998) by evaluating the reliability of each element used in the PSHA model and by combining them to estimate the overall likelihood of resulting hazard estimates. These reliability judgments are supplied by a number of experts in the frame of an “elicitation” process (SSHAC, 1997).

The whole procedure has been most cases applied without a through discussion of the underlying principles and interpretations. On the other hand, a coherent interpretation of is mandatory for its correct application. In fact “Although this seems to be a philosophical issue at first glance, its consequence are not, since the issue is intimately linked to the question of which hazard curve ... should be used.” (Scherbaum et al., 2005; Abrahamson and Bommer, 2005). This situation has recently resulted in a sharp dispute that have involved a number of researchers (see Klügel, 2005; Budnitz et al., 2005 and references therein).

In the following all these aspects will be discussed in the frame of a coherent formalism based on the “epistemic” interpretation of probability. This allows to clarify what I think to be the major drawbacks of the “logic tree” approach.

2. Probabilistic Seismic Hazard Assessment (PSHA)

2.1 The management of “aleatory” uncertainty

To compute the “Seismic Hazard Function” $H(g)$, the total probability theorem is used to combine probability distributions associated to the physical parameters and features that characterize the relevant seismogenic process (see, e.g., Kramer, 1996). Thus, one has

$$H_T(g) = \text{prob}(\geq g|T, \theta) \quad (1)$$

where θ represents the set of parameters that characterise the relevant probability distributions. In the following, to simplify the notation, the subscript T will be considered as implicit. For engineering purposes, a specific reference value for g (g_{max}) is computed from H as the maximum expected shaking level characterized by an exceedence probability lower than a fixed threshold.

$$g_{max} : H(g_{max}) = w \quad (2)$$

Thus, g_{max} , is one of the possible outputs of PSHA and corresponds to a precise choice of w and T depending on the “conservatism” level fixed in local regulations (Reiter, 1990). As an example, in the Italian seismic code, these parameters are fixed to 0.1 e 50 years respectively.

In the simple case that the time series of events able to induce at the site seismic ground motions $>g$ can be modelled as simple stationary Poissonian point process, one has

$$H(g) = 1 - e^{-\lambda(g)T} \quad (3)$$

where the parameter λ is the average occurrence rate earthquakes responsible for seismic shaking at the site not less than g (i.e., the inverse of the average return period of these events). An example of the function $H(g)$ is shown in figure 1.

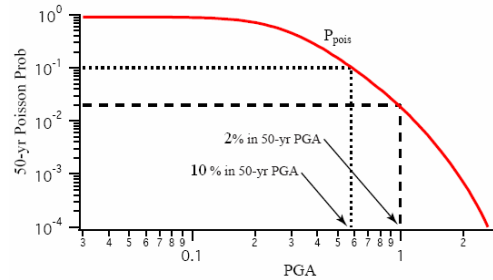


Figure 1: Aspect of the function $H(g)$ relative to the exceedence probabilities a given value of the Peak Ground Acceleration (PGA) at a site for an exposure interval equal to 50 years. The curve has been deduced in the assumption that seismic events are a stationary Poisson process. Two percentiles (2% and 10%) are also indicated

In the frequent case that $1 \gg \lambda$, equation (3) can be approximated in the form

$$H(g_0) \approx \lambda(g)T \quad (4)$$

It should be noted that this relationship only holds “numerically” and no formal equivalence is determined between H and λ . Actually, the former one is a probability (and should be coherently manipulated) while the latter is a frequency that, in principle, can also assume values greater than 1.

From equation (4) it results the common use to consider as the result of PSHA the function $\lambda(g)$ instead of $H(g)$ (see, e.g., Scherbaum et al., 2005). In the case that equation (3) holds, $g_{\max}$ can be easily obtained as

$$g_{\max} : \lambda(g_{\max}) = -\frac{\ln[1-w]}{T} \quad (5)$$

2.1 The management of “epistemic” uncertainty: Logic Trees

Alternative probabilistic parameterizations θ result in different PSHA models and different probability distributions $H(g)$. To each of these estimates can be associated a likelihood value p^i . The “logic tree” approach, (Budnitz et al., 1997) constitutes a quantitative procedure for the computation of p by the comparative evaluation of the several plausible choices of the elements θ considered for hazard evaluations. These choices constitute the branches of a “tree” that aims at representing all the possible alternative parameterizations (Fig.2). The nodes of the resulting net are the input parameters of model and the branches departing from each node represents the alternative parameterizations considered. Starting from the “root” of the logic tree and following a specific sequence of branches one can identify one of the possible PSHA models. In this way, the i -th PSHA model will be identified by peculiar path running along a sequence of N branches. The relevant likelihood p^i associated to each i -th PSHA model is computed as follows. At each j -th node M_j branches depart. To each m_j -th branch it is associated a likelihood q such that

$$\sum_{m_j=1}^{M_j} q_j^{m_j} = 1 \quad (6)$$

The overall likelihood associated to the i -th PSHA is thus computed as

$$p^i = \prod_{j=1}^{N^i} q_j^{m_j} \quad (7)$$

The marginal hazard $H(g)$ (i.e., the hazard resulting from the convolution of “aleatory” and “epistemic” uncertainties) relative to the shaking level g should be given by

$$H(g) = \sum_{i=1}^N p^i H^i(g|\theta^i) \quad (8)$$

Taking equation (4) into account one can also write

$$H(g) \approx T \sum_{i=1}^M p^i \lambda^i(g) \quad (9)$$

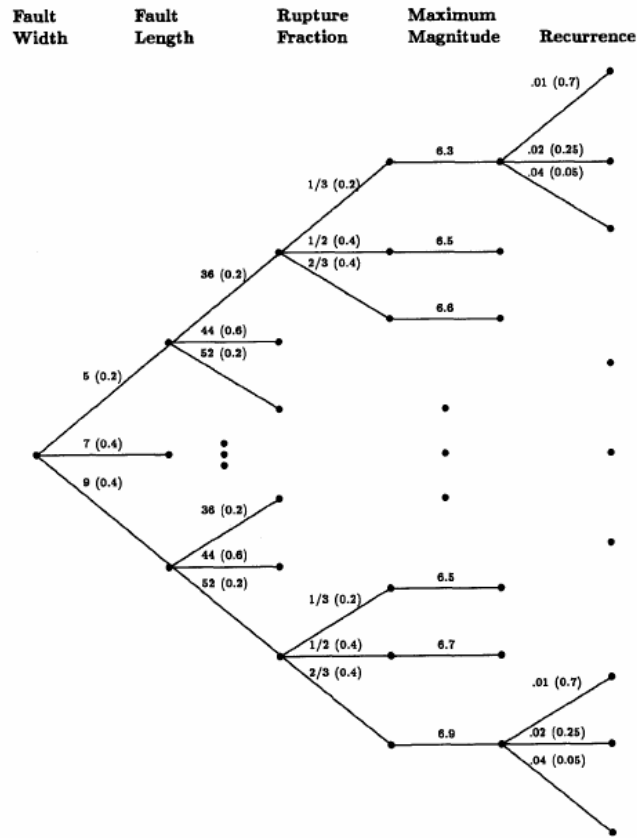


Figure 2. An example of the “logic tree” approach. Each node corresponds to a specific element for PSHA. Numbers indicate the possible values to be attributed to the relevant parameter. Figures in round parenthesis at each branch indicate the likelihoods associated to the each value of these parameters

3. Misapplications and Drawbacks in the “Logic-Tree” approach

The common use of g_{max} to express seismic hazard tends to mask the essential methodological differences between PSHA and deterministic approaches. In PSHA, attention is displaced from the estimate of the expected value g to the likelihood $H(g)$ of the different plausible scenarios. The deterministic estimate g can be affected by uncertainty and PSHA is devoted just to estimate such uncertainty in terms, e.g., of the function $H(g)$. The percentile g_{max} in this context “summarizes” the $H(g)$ distribution (i.e., uncertainty on g) and cannot be considered uncertain on itself. This basic aspect has been in many cases overlooked, producing several misunderstandings due to the use of probabilistic methodologies in the frame of a deterministic view. It is clear, in fact, that the association to g_{max} any kind of variance implies that the marginal probability H (on which the estimate of g_{max} ultimately relies on) is affected by uncertainty on itself. Some Authors explicitly take this position (e.g., Page and Carlson, 2006). However, this is reasonable if (and only if) one assumes that H intrinsic to the seismogenic process

(i.e., an true expression of the physical phenomenon) and not an expression of our knowledge about the phenomenon. However, this “realistic” interpretation contrasts with the “logic” tree approach that explicitly assumes an “epistemic” interpretation of the probability H (e.g. Budnitz et al., 2005). In particular, the whole “logic tree” approach to PSHA relies on the assumption that the values p^i are actually likelihoods expressed in terms of probabilities: any alternative view (e.g., Abrahamson and Bommer, 2005) simply undermines the rationale of whole procedure making it meaningless. Being the “epistemic” interpretation necessary, any probability distribution on H should represent the probability of a probability, i.e., the likelihood of a likelihood and I do not know what this means.

Thus, it is meaningless to interpret p^i as a probability distribution on g_{max} . In fact this position cannot be sustained by any coherent argumentation (neither theoretical nor heuristic) and is explicitly rebutted by the proponents of the “logic tree” approach (Budnitz et al., 1997).

Some Authors (e.g., Abrahamson and Bommer, 2005) suggest that the genuine hazard estimate is the annual rate of exceedence $\lambda(g)$. In this case, the p^i values are considered to represent a probability distribution on the set of the possible λ values. Since this parameter is not a probability, the problems discussed above are apparently overcome. In this position, the logic tree approach could result in a reference λ^c value (for each value of g) such that

$$\lambda^c(g): p^i(\geq \lambda) \approx c \quad (10)$$

and c is a fixed probability threshold (Fig.3). However, hazard estimates in terms of λ values only are useless for practical applications and have to be converted in H values to compute g_{max} . This can be done by computing

$$H(g) \approx T\lambda^c(g) \quad (11)$$

(from equation (4)). The problem of using (10) arises when one tries to interpret the resulting g_{max} value. As stated above (equation (2)) this should be the ground shaking value characterised by an exceedence probability w in T . However, in this case this will correspond to a value of the average annual exceedence rate λ associated, on its turn, to an exceedence probability less than c (!?). As one can see, the argument becomes increasingly fuzzy. To make evident the problem one should try to answer to the simple question: “*what is the exceedence probability of g_{max} when the value is computed in this way?*”. Is this equal to w , q or, as an example, to the product wq ?

Despite of possible incoherent applications of the logic-tree formalism, severe drawbacks exist anyway. First of all, to be formally correct, the values probabilities involved in the computation of the p^i should be mutually independent and exhaustive and this is considered unrealistic by several Authors (e.g., Abrahamson and Bommer, 2005). Furthermore, recent analyses (Page and Carlson, 2006) indicate that hazard estimates provided by the logic-tree approach are sensitive to the arbitrary order of branches and nodes present in the logic-tree. In general, it can be shown (Rabinowitz and Steinberg, 1991) that the importance of several input parameters depends critically

on the settings of other parameters. In this sense, each PSHA procedure should be considered (and checked) as a whole and not by merely combining reliability of single aspects or choices.

Logic tree approach is also problematic in practical applications since the full development of the relevant logic-tree results in an explosion of branches (of the order of hundreds) difficult to be manipulated and exhaustively explored.

Other arguments against an indiscriminate use of the logic-tree approach can be found in Krinitzky (1993, 1995).

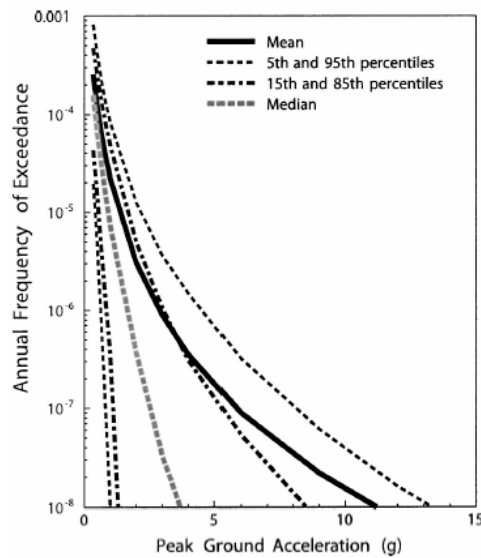


Figure 3. Result of a logic tree approach applied to the exceedance rates as function of the for ground shaking level (expressed in terms of Peak Ground Acceleration) at a site (Abrahamson and Bommer, 2005). Different curves corresponds to different percentiles of the likelihood distribution p^i (see text for details). The curve corresponding to the mean has been computed by using equation (8).

4. Discussion and Conclusions

Several seismic scenarios relative to the effects of future seismic events are possible on the basis of available knowledge. Some of them appear more plausible than the others and the probabilistic seismic hazard assessment aims at the estimate of the relevant likelihoods. The manipulation of uncertainty relative to the elements concurring in the formulation of these forecasts is thus of major concern. Such uncertainty is intrinsically “epistemic”, i.e., it concerns the present knowledge about future occurrences and not a physical property of the seismogenic process. In this regard, the current differentiation of “epistemic” and “aleatory” uncertainty is immaterial and only differentiate the rules adopted for their manipulation.

The “logic-tree” approach is used to manipulate uncertainty relative to the most reliable computational scheme. This approach is mainly constituted by a set of rules to combine expert judgments about the “ex-ante” reliability of the different elements involved in the

competing PSHA models. These rules can be justified only on the basis of the “internal” coherency of the adopted formalization. In particular, they require a coherent probabilistic interpretation of the terms involved in the combination rules. However, it has been shown that in many applications such internal coherency is at least debatable. Furthermore, a strong suspect exists that such coherency cannot be found at all.

As a result, the logic-tree procedure lacks of any sound justification. This, in my opinion, can be considered a useful tool to explore the sensitivity of PSHA models to the involved input parameters and models. This aspect is of great importance (e.g., Giner et al., 2002; Beauval and Scotti, 2004; Sherbaum et al., 2005; Bommer and Abrahamson, 2006; Beauval et al., 2006) but it only concerns the comparison and the optimal setting of different PSHA models and not their overall validity with respect to the domain of application, i.e., the forecast of future seismic events.

A different approach should be attempted. The basic idea is that to evaluate the reliability (likelihood) of the different PSHA models an empirical validation of the relevant models is mandatory. This validation should be performed “ex-post” by comparing the hazard estimates provided by each PSHA model to the seismicity occurred during a control period. The fact that forecasts provided by PSHA models are probabilistic in character does not prevent in any case the possibility of empirical validations (e.g., Lind, 1996; Winkler, 1996).

In general, this validation should not be considered as secondary due to the important economic impact of each hazard estimates in seismic countries. Despite of this, with respect to the mainstream of ongoing researches in PSHA, very few efforts have been devoted in this direction. Most of earlier attempts have been devoted to the empirical validation of some aspects of the current PSHA models (McGuire, 1979; McGuire and Barnhard, 1981; Grandori, 1993; Oreskes et al., 1994; Jackson, 1996; Grandori et al., 1998; Mucciarelli et al., 2000; Petersen et al., 2000; Kagan and Jackson, 2000; Musson, 2004) and some major efforts should be devoted to develop coherent approach for the validation of PSHA models as a whole (e.g., Albarello and D’Amico, 2000; Mucciarelli et al., 2006).

It is common experience data available data set increases quite slowly with respect to the growing sophistication of computational procedures. Thus, effective future developments in PSHA should be devoted much less to develop new sophisticated models and much more to make the best use of data actually available and to set up procedures for checking the actual reliability of hazard estimates provided by the different available approaches in relation with observed seismicity.

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