EARTHQUAKE ENGINEERING PRACTICE

The Use and Misuse of Logic Trees in Probabilistic Seismic Hazard Analysis

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Logic trees have become a standard feature of probabilistic seismic hazard analyses (PSHA) for determining design ground motions. A logic tree's purpose is to capture and quantify the epistemic uncertainty associated with the inputs to PSHA and thus enable estimation of the resulting uncertainty in the hazard. There are many potential pitfalls in setting up a logic tree for PSHA, mainly related to the fact that in practice, it is questionable that the requirements that the logic-tree branches be both mutually exclusive and collectively exhaustive can actually be met. Careful consideration is also required for making use of the output; in particular, in view of how PSHA is employed in current engineering design practice, it may be more rational to determine the mean ground motion at the selected design return period rather than to find the ground motion at the mean value of this return period.
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INTRODUCTION

Logic trees were first introduced to seismic hazard analysis more than 20 years ago by Kulkarni et al. (1984) and have become an increasingly popular tool in seismic hazard analysis. They are often considered as the state-of-the-art tool to quantify and incorporate epistemic uncertainty, which is uncertainty related to the lack of knowledge (e.g., Reiter 1990, McGuire 2004). The use of the logic-tree framework has almost become standard practice in probabilistic seismic hazard analysis (PSHA) to the extent that it is very rare to see a published hazard study or a site-specific PSHA that does not include a logic tree. Although the inclusion of a logic tree in PSHA is now *de rigueur*, the authors are of the view one can sometimes be left with the impression that it is applied without appreciation of its purpose and meaning. This short paper attempts to step back a little and ask some fundamental questions regarding the application of this tool in PSHA.

The published literature on the application of logic trees is limited and papers on their prerequisites and meaning are even fewer. As with many easy-to-use tools, the popularity of logic trees carries a danger. The way logic trees are currently applied can frequently produce numerical results that do not meet the intended objectives (and this is often difficult, if not impossible, to judge from the results themselves), and there is often

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no obvious penalty for ignoring the prerequisites under which logic trees may be applied. Although these prerequisites are easy to formulate in theory, it can become rather difficult to test them in practical applications. As a consequence, examples of what might be inappropriate applications of logic trees can be found in the literature with increasing frequency. The purpose of this paper is to discuss examples of some potential pitfalls in some detail, in particular drawing attention to the fact that the emphasis is generally placed on applying weights to models rather than the output of the models in terms of earthquake scenarios and consequent ground motions. Thereby, it is hoped to raise awareness of the fact that the (seemingly trivial) conditions under which logic trees may be applied warrant careful consideration in order to avoid the risk of producing unexpected and potentially meaningless results. In addition, the paper discusses different options for expressing output from logic-tree analysis and their application in engineering design.

From the outset, it should be made very clear that the authors are not attacking logic trees but rather issuing a challenge to those employing them in PSHA, questioning both the assumptions implicit in their use and current practice in terms of their formulation and application. Many of the issues addressed would apply equally to other representations of epistemic uncertainties, such as probability distributions, but the focus herein is on logic trees because these are currently the most commonly used tool in seismic hazard analyses.

REPRESENTING UNCERTAINTIES BY LOGIC TREES

The basic components of a PSHA for ground motions in rock are a model for the seismicity (characterizing the location, magnitude and frequency of occurrence of earthquakes in the region) and a model for the prediction of the ground-motion parameter (the distribution of the parameter for a given combination of magnitude and distance). Both models are associated with large uncertainties, and the principal challenge of seismic hazard assessment is to identify, quantify and incorporate these uncertainties into the analysis.

Although the physical basis for the distinction is debated, it has become standard practice to classify uncertainties into two different types, to which the names aleatory variability and epistemic uncertainty are generally applied. The aleatory component of uncertainty is sometimes referred to as intrinsic variability or stochastic or irreducible uncertainty, and epistemic uncertainty is also known as subjective, state-of-knowledge or reducible uncertainty. The aleatory variability, such as the location and magnitude of future earthquakes and the scatter in the ground-motion prediction, is incorporated directly into hazard calculations and is reflected in the shape of the resulting hazard curve. It is worth noting that although the ground-motion variability is an intrinsic part of the hazard calculations, it is still not always included or at least not included correctly (Bommer and Abrahamson 2006). The epistemic uncertainty leads to different sets of calculations with alternative input parameters and consequently, to suites of hazard curves. There are several options for representing epistemic uncertainty (Helton and Oberkampf 2004), among which the most commonly used is the concept of probability.

There is an ongoing debate related to the interpretation of the branch weights in logic trees and whether they are probabilities or simply subjective indications of relative merit (Abrahamson and Bommer 2005, McGuire et al. 2005, Musson 2005). However, in their current application—as envisioned, for example, in the Senior Seismic Hazard Analysis Committee (SSHAC) framework (Budnitz et al. 1997)—logic trees are an implementation of a probability model of uncertainties. This means that the weights associated with a particular branch of a logic tree, which express the degree-of-belief of the hazard analyst(s) in the corresponding model, are subsequently treated as (subjective) probabilities to calculate a distribution of hazard curves. A single hazard curve, corresponding to an individual branch of the logic tree, quantifies all aleatory aspects of the corresponding model, while the spread of hazard curves for different values of the ground-motion parameter of interest is determined by epistemic uncertainty. Therefore, the distribution corresponding to the full suite of hazard curves captures both aleatory and epistemic uncertainties.

It is worth noting that in general, weights are applied to models rather than to the physical consequences of those models, which means that the analyst may not have a full appreciation of the implications of the choices made. With regard to ground-motion prediction, the weights are generally applied to equations rather than to actual estimates of ground-motion amplitudes, whereas the latter perspective may be more useful (e.g., Scherbaum et al. 2005).

In the opinion of the authors, part of the popularity of logic trees is related to the fact that they are technically easy to implement. They are a powerful tool to organize one's thinking in situations where alternative models, in which the analyst has different degrees of confidence, might apply. However, the use of the probability model—in other words, the use of logic-tree branch weights as probabilities—requires the Kolmogorov axioms for probabilities to be met. This implies that the different models are mutually exclusive and collectively exhaustive (MECE criterion). This firstly requires that the model on one of the branches is applicable but not a combination of models (mutual exclusivity), and secondly that one of the models in the model set considered fully applies (collective exhaustiveness); these concepts are illustrated in Figure 1. In practice, these seemingly trivial conditions can generate considerable problems, as discussed below.

SETTING UP A LOGIC TREE

Creating a logic tree for PSHA involves selecting alternative models or model parameters for various inputs and then assigning weights to the different branches at each node to reflect the relative confidence of the analyst in the options. Although seemingly straightforward, there are both conceptual and practical problems associated with these steps.

Within the PSHA framework, the ground-motion parameter of interest is treated as a random variable for which it is attempted to determine the probability distribution, usually expressed as an exceedance frequency (i.e., a hazard curve). Conceptually, as noted earlier, this model has two constituents: the joint magnitude-distance distribution and the

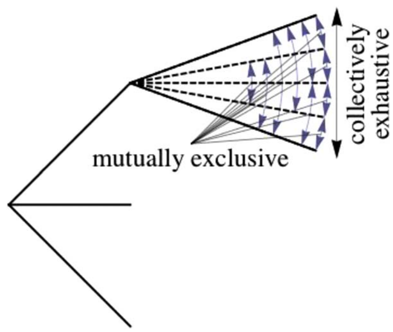

Figure 1. Schematic illustration of part of a logic-tree, showing where, in theory, the principles of mutual exclusivity and collective exhaustiveness apply to branches.

ground-motion exceedance probability (conditional on magnitude and distance). Each of these constituents carries epistemic uncertainty but this uncertainty cannot be easily expressed directly on the magnitude-distance or ground-motion distributions, whence an indirect approach is chosen. For example, instead of putting different models for the joint magnitude-distance distribution of different branches of a logic-tree section, the logic-tree sections are often set up for the constituents of the seismicity model (*a*- and *b*-values, M_{max}, etc). The same holds for the ground-motion model section; sometimes, as in the PEGASOS project (Abrahamson et al. 2002), separate logic trees are even set up for median ground-motions and their associated sigma values. To quantify the epistemic uncertainty directly on hazard curves would simply be impracticable since no tool is currently available to make such an assessment, although a quantitative approach has been put forward to do this for the ground-motion section (Scherbaum et al. 2005). Therefore the analyst expresses his or her degree-of-belief in a model, with the consequence that before seeing the results of a full hazard disaggregation he or she does not really know what this corresponds to in terms of magnitude-distance distribution or ground motion. Consequently, without a formal sensitivity analysis, which, in the experience of the authors as reviewers, is rarely done in small-scale hazard studies, the analyst is not able to judge the relevance of individual judgments.

In our view, the way logic trees are routinely used in current PSHA practice could be likened to a chef who develops a recipe for a dish purely on the basis of selecting and mixing ingredients but without ever tasting what emerges from the oven. Moreover, in many cases the chef is selecting the ingredients on the basis of their brand names rather than quality and in some cases, purely on the basis of what is actually in his larder!

POTENTIAL CONCEPTUAL PROBLEMS

That the models occupying different branches of a section of a logic tree have to be mutually exclusive means that since they also have to be collectively exhaustive, one of the models is implicitly assumed to be the "true" model. The term "true model" (see Burnham and Anderson (2002) for a discussion of this term) is used here in the sense that it fully describes what it is supposed to model, without needing contributions from any of the other models. In practical terms, data generated from the true model should not be distinguishable (within a certain accepted imprecision) from the data generated by nature for the scope of the analysis. What if one believes, however, that each of the models captures only a partial aspect of the full complexity of reality and none can be considered fully true? In many situations in which logic trees are used nowadays, this may be an equally appealing perspective. One argument for this perspective could be that particular models have rarely been developed for exactly the same situation in which they are applied. Therefore, they can at best capture some aspect of the situation in a selected target region, but not all of it. In this case, the weights on a logic-tree branch lose their meaning as subjective probabilities, at least in the strict sense. Probability might still be a perfect representation of epistemic uncertainty in this case but we may have to accept the fact that we may not be able to determine the probabilities perfectly (O'Hagan and Oakley 2004).

Trying to meet the requirements of the MECE (mutually exclusive-collectively exhaustive) criterion easily leads to the temptation to include many branches following the reasoning that more branches (i.e., alternative models) increase the chance that the true model is among the options. On the other hand, more branches also increase the chances of model redundancy, a recognized problem in multi-model inference (Burnham and Anderson 2002), which will automatically violate the condition of mutual exclusivity. In addition to the temptation to include too many branches there is also a temptation to include too many sections (although it may satisfy both the analyst and the client to have a highly complicated logic tree). According to Dreyfus and Dreyfus (1986), however, to understand what is relevant is the main characteristic distinguishing an expert from a novice. Without a sensitivity analysis, it is also impossible to judge the relevance of a particular logic-tree section. Therefore, just as PSHA should always be done together with a disaggregation, our opinion is that setting up a logic tree should always be accompanied by a sensitivity study. Indeed, a clear exploration of the sensitivity to legitimate alternative models or parameters might be considered more valuable in some cases than a full logic-tree analysis constructed without clear objectives and criteria.

POTENTIAL PRACTICAL PROBLEMS

A fundamental principle in using logic trees is that they should be applied only to epistemic uncertainties and not to aleatory variability. An error in setting up logic trees that we have seen in papers in peer-reviewed journals and in site-specific studies is to include branches for the distribution of focal depths, with the weights assigned to reflect the observed distribution of this parameter in the earthquake catalog. The focal depth of future earthquakes is a random variability and not an epistemic uncertainty. Therefore, the hazard calculations should integrate over the distribution of depths in the same way as they integrate over the spatial distribution of epicenters across seismic source zones. Although the mean hazard curve obtained by including focal depth as logic-tree branches may be the same as that obtained by integration over the depth distribution, the inclusion of this parameter in the logic tree leads to individual hazard curves that are simply incorrect since they will correspond to all future seismicity being entirely concentrated at each of the specific depths (something the analyst will not be intending to postulate). Including focal depths in the logic tree violates its purpose and artificially widens the distribution of the resulting hazard curves. If there were different models for the depth distribution, perhaps reflecting the fact that the depth distribution of small-magnitude earthquakes might not automatically correspond to that for larger events, then these could legitimately be included as alternative branches in a logic tree, but the individual ranges of focal depths do not belong within the logic tree.

As stated above, one of the requirements of logic-tree branches is that they are mutually exclusive. Abrahamson (2000) points out pitfalls of setting up branches in a way that violates this principle, giving the example of having branches for non-segmented fault rupture and different segmentation models emerging from a single node, whereas the branches should simply be for segmented and non-segmented rupture since either branch should cover the entire fault length in order to provide the full contribution from the fault to earthquake recurrence. If there is a branch for rupture only on one segment, it would effectively be an incomplete model and hazard calculations including that branch would be neglecting the contributions from earthquakes occurring on the other segments of the same fault.

For other sections of the logic tree, however, the practical achievement of mutual exclusivity is far more complicated because of the subtle nature of the interdependence of models. The clearest case in point is the ground-motion prediction equations since the models applied to a PSHA in a particular region will almost always be derived from datasets that have appreciable overlap in terms of the strong-motion recordings employed. While the use of alternative equations may capture some epistemic uncertainty in representing the population from which the sample of observations was drawn, the fact that the sample is the same for two models means that the models cannot be completely mutually exclusive. Therefore, there must be some model redundancy.

In this respect, an alternative approach to populating the logic-tree branches with published prediction equations would be to use the equations and available data to define a standard model and some alternatives (G.M. Atkinson 2008, personal communication). One benefit of such approach is that the consequences of weights on models in terms of weights on resulting ground motions would be more easily inferred.

Another example of the misuse of logic trees that we have seen on a number of occasions is in the treatment of seismicity models; it is not uncommon to encounter logic trees in which there are separate and sequential branches for the three parameters of the Gutenberg-Richter recurrence relationship (*a*- and *b*-values, and M_{max},). This ignores the fact that first two parameters, at least, are correlated, and the consequence of having separate branches for the three parameters, rather than branches for alternative recurrence models, is that the possible combinations will probably cover an extremely wide range of implied moment release rates and thus present a range of uncertainty in the regional seismicity much wider than the analyst actually believes to be the case. If sequential branches are defined for the recurrence parameters, then each *a*-value branch could have different branches for *b*-values in order to avoid this problem.

Additionally, care must be taken in setting up the order of execution of the sections of the logic tree. For example, it may be necessary to apply adjustments to achieve compatibility among the ground-motion models in terms of magnitude scale (Bommer et al. 2005) and distance metric (Scherbaum et al. 2004); because the distance adjustment is magnitude dependent, it is necessary to apply the magnitude correction first.

When setting up a logic-tree section, the condition of collective exhaustiveness requires that the models corresponding to the set of branches also capture the highly unlikely but physically still possible part of nature. This requires quantification of the expert's knowledge while respecting his or her ignorance. In the terminology of the SSHAC framework, this is expressed in the aim to elicit estimates that "represent the center, the body, and the range of technical interpretations" (Budnitz et al. 1997). Again, this is easier said than done in practice. Although an analyst may be rather confident in specifying his or her degree-of-belief in what seem likely scenarios, it requires considerably more effort to specify what seems to him or her less likely but still possible. If one accepts that the goal of collective exhaustiveness is not being met, then weights summing to unity are simply a matter of convenience and can be misleading since they could be interpreted to imply that the suite of models or parameters emerging from a single node represents the full range of possibilities.

In examples of logic-tree implementations, it is very common to find uniform weights on the branches (i.e., an equi-probability distribution). This raises the question of whether these models are really considered equi-probable by the analyst, or if this is supposed to express lack of knowledge (which may actually be lack of imagination), since the expert does not feel that he or she knows enough to prefer one model over the other, or if this is actually due to an insufficient adjustment from an anchoring effect. One must also acknowledge that in seeking to build consensus, equal weighting may simply be the path of greatest political prudence. van Schie and van der Pligt (1994) describe several examples for the anchoring effect which suggests that when subjects are presented with a set of models, they initially distribute their confidence equally. As a consequence, a model is rated more relevant when the number of alternatives is small, which is referred to as pruning bias (O'Hagan et al. 2006). If the analyst has chosen uniform weights to express complete indifference, this creates another problem. Uniform weights on, say, a set of ground-motion models does not transform into uniform weights on all the ground-motion values within the range covered by the models, which may have actually been the intention of the analyst.

As has been mentioned earlier, in setting up a logic tree efficiently and effectively, it is essential to identify what really matters, which ultimately can only be identified through sensitivity analyses. It can be said, however, that in general, the uncertainty in the ground-motion model exerts greater influence on the hazard results than uncertainty in the seismicity model (Scherbaum et al. 2006). Because logic trees often require the combination of ground-motion models employing different parameter definitions, adjustments need to be made, such as for the magnitude scale or distance metric, as mentioned previously, or for the definition of the horizontal component of motion (Beyer and Bommer 2006, 2007). A very large penalty can be paid for applying such conversions in terms of increased variability, with sigma values potentially becoming so large as to be unusable for practical purposes (Scherbaum et al. 2006).

A great deal of attention is often given to the weights assigned to the logic-tree branches, but once there are more than a few branches the hazard results are found to be relatively insensitive to the assigned weights (e.g., Sabetta et al. 2005, Scherbaum et al. 2005). Populating the branches of a logic tree is where the real art of seismic hazard analysis lies, with the objective being to identify the smallest feasible set of alternative models or parameters that captures the range of possibilities (e.g., Cotton et al. 2006). As mentioned previously, unnecessary over-branching is to be avoided because of the computational costs and the risk of model redundancy. High uncertainty does not necessarily imply many branches, only "widely spaced" branches (i.e., alternative models or parameter values that are appreciably different from one another).

HARVESTING LOGIC TREES

A PSHA conducted in a logic-tree framework produces a suite of seismic hazard curves, and the engineer has a number of options for how to extract from these curves the ground-motion values to be employed in design. Before considering how to harvest the fruits of a logic-tree analysis, it may be useful to briefly consider how a single hazard curve is used in engineering design practice.

Any seismic hazard analysis is based on considering the effects at a site of specified earthquake scenarios, defined by the magnitude, M, and location of the event, with the latter determining the source-to-site distance, R. The scenario must also include the ground-motion exceedance level, usually defined in terms of the number of logarithmic standard deviations, ε, away from the logarithmic mean. Deterministic seismic hazard analysis (DSHA) is generally based on just a few scenarios and possibly even a single scenario, in which the three parameters are selected on a more or less arbitrary basis. If the earthquake source is a well-defined active fault, then R may be unambiguously known (assuming that the closest portion to the site will rupture) and if the fault is modeled as producing characteristic earthquakes, then M may also be rationally selected. However, other than employing a probabilistic criterion, such as selecting the motion with a 1-in-10 chance of exceedance (e.g., Strasser et al. 2008), DSHA can only make arbitrary selections of the ε level. PSHA was introduced to allow for the fact that there is uncertainty associated with the appropriate values of all three parameters (M, R, and ε) and instead of considering a single M-R-ε scenario it considers all possible combinations and calculates the rate at which different levels of ground motion are exceeded at the site. To then make use of the output, which is a hazard curve showing a given ground-motion parameter against its associated annual frequency of exceedance, decisions need to be made regarding the appropriate annual frequency of exceedance. In engineering design practice, single values of the ground-motion parameter are employed (either a single value or a series of values attached to different performance levels), and each of these is anchored to a pre-selected annual exceedance frequency, often expressed by its reciprocal, which is a return period. Until recently, the majority of seismic design codes around the world presented ground motions anchored to a return period of 475 years, a number whose origins lie in some very arbitrarily-made decisions (Bommer and Pinho 2006, Bommer 2006). Ultimately, the selection of the return period should be based on risk considerations, relating to the acceptable frequency of exceedance of given levels of loss rather than ground motion (i.e., a decision based on risk not on hazard). An

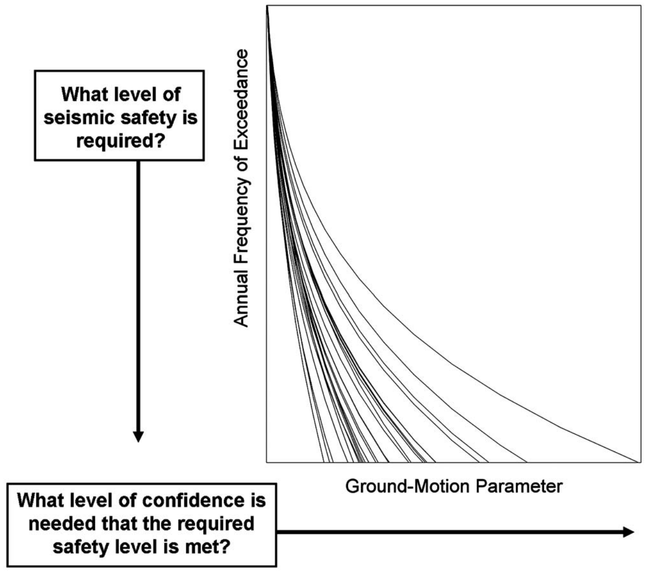

Figure 2. Schematic illustration of the process of determining design ground motions from the output of a PSHA performed within a logic-tree framework, in terms of selecting the target return period and the appropriate hazard curve.

expression encountered frequently in site-specific hazard studies and earthquake engineering reports is "conservatism": in DSHA, supposedly conservative decisions are made at some stages of the analysis, which it is sometimes claimed provides a mechanism for circumventing the issue of uncertainty by identifying worst-case scenarios (even though the scenarios are generally a long way short of warranting this onerous description). In PSHA, there is only one place for conservatism, and that is at the end of the process in the selection of the design return period. This should prevent the analyst from making "conservative" decisions regarding population of the logic-tree branches, which should be constructed simply to capture the range of uncertainties.

When PSHA is performed within a logic-tree framework, there are two decisions to be made in order to obtain values of ground-motion parameters for design: which return period should be adopted, and from which hazard curve should the ground-motion value be read? The first question is the same as that discussed above with regards to using a single hazard curve, and it is in effect the question of what level of seismic safety is required. This determines the y-coordinate of the design ground-motion selection (Figure 2). The selection of the appropriate hazard curve, which then fixes the x-coordinate, is the response to a second question, which could be stated as what is the desired level of confidence that the target level of safety is being achieved? In current practice, the standard approach is to use the mean hazard curve, in which case the question is effectively obviated. If instead one opts to use the hazard curve corresponding to a particular fractile (which may be the median or some higher level), then the second question can

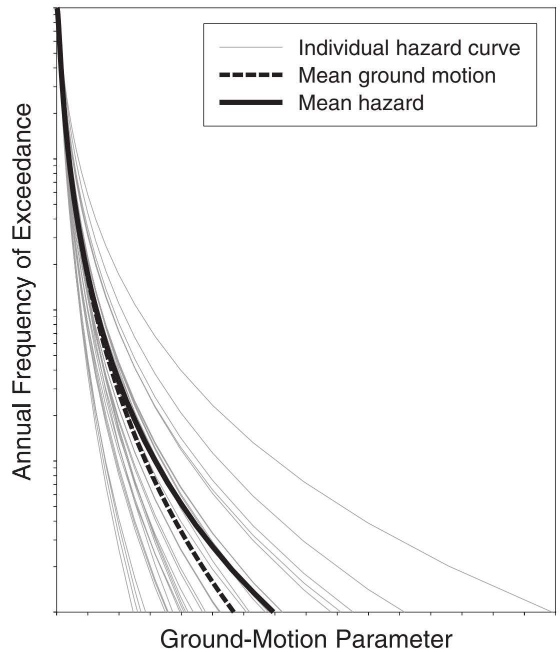

Figure 3. Suite of hazard curves from a logic-tree with equally weighted branches in all sections, showing the difference in the curves obtained by calculating the mean hazard (exceedance frequency) associated with each ground-motion level, and by calculating the mean ground motion associated with each annual exceedance frequency.

be answered explicitly. The use of the mean hazard curve has been debated (Abrahamson and Bommer 2005) and defended (McGuire et al. 2005, Musson 2005), and it is not the intention of this paper to raise this question again; the reader may review the published discussions on the matter and reach their own conclusion. The objective here is only to prompt consideration of how PSHA output is used; however, even if the mean is agreed to be the preferred option, then there is still another interesting question to be addressed.

The full suite of hazard curves resulting from a PSHA performed within a logic-tree framework (or the corresponding joint distribution for ground motion and exceedance probability for ground-motion levels of interest) is usually condensed into a single curve before subsequent processing, such as in engineering design. For the sake of the following argument, as stated above, it is assumed that this is the mean curve. There are two different perspectives in which this can be achieved, however, which can lead to rather different results. One can either ask for the mean value (or any other summary statistic) for fixed values of ground motion or for fixed values of exceedance probability. The first approach is the proper choice if one is interested in the expected exceedance probability for a fixed value of ground motion while the second one is the option to be taken if, for a selected exceedance probability, one wants to determine the expected value of ground motion. The two approaches can yield very different design values of motion (Figure 3).

In risk analysis, which can use the full suite of hazard curves, convolution of the mean hazard curve with the mean vulnerability yields the mean risk. However, in current engineering design practice the procedure is to adopt the ground-motion level at a preselected exceedance frequency (or return period), so it could be argued that the natural choice would be to use the expected ground motion at this hazard level.

DISCUSSION AND CONCLUSIONS

Logic trees are now part of the *de facto* state-of-the-art in PSHA. While they can be powerful tools aiding the analysis, their use is not a guarantee for the usefulness of the results, and they are also not ends in themselves. If not used with consideration for their theoretical framework, they can actually represent enormous effort for little benefit. Although seemingly simple, to meet the conditions of mutual exclusiveness and collective exhaustiveness for its branches in practice is a real challenge, especially for the ground-motion part of the analysis. The fact that the MECE criterion is not usually satisfied may not be of great practical importance but the authors believe that the users of logic trees should be aware of the issue. This does not necessarily mean that the underlying probabilistic framework becomes invalid but that the weights of logic tree branches can at best be treated as approximate probabilities (O'Hagan and Oakley 2004). Although alternative representations of epistemic uncertainties are being explored (Helton et al. 2004), there is still strong disagreement within the scientific community regarding if, and possibly how, the probability framework can be or should be replaced by any other approach (Helton and Oberkampf 2004).

The purpose of the present paper is to raise awareness of the objectives and implications of using a logic tree in PSHA, and additionally to warn against ignoring the prerequisites for setting up the branches. The authors strongly believe that a logic-tree formulation should always be accompanied by a sensitivity analysis in addition to the disaggregation that should always accompany a PSHA. Only in this way can the seismic hazard analyst see whether certain branches are actually exerting an appreciable influence on the hazard results. More importantly, the sensitivity analysis will enable the analyst to obtain a sense of the impact of the branch populations and weights on the actual hazard.

The intention of the authors is not to discourage the use of logic trees in PSHA, and many of the issues discussed apply equally to other representations of epistemic uncertainty. Logic trees are a useful tool and while in the future they may be replaced by other approaches for incorporating epistemic uncertainty in seismic hazard analysis, the challenge now is to ensure that they are used correctly, with awareness of the underlying implicit assumptions in their formulation, and with critical consideration of how they are ultimately used in engineering design decisions.

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REFERENCES

Abrahamson, N. A., 2000. State of the practice of seismic hazard assessment, in *Proceedings, GeoEng 2000*, vol. 1, 659–685, Melbourne, Australia.

Abrahamson, N. A., Birkhauser, P., Koller, M., Mayer-Rosa, D., Smit, P., Sprecher, C., Tinic, S., and Graf, R., 2002. PEGASOS: A comprehensive probabilistic seismic hazard assessment for nuclear power plants in Switzerland, in *Proceedings, Twelfth European Conference on Earthquake Engineering*, paper 633, London.

Abrahamson, N. A., and Bommer, J. J., 2005. Probability and uncertainty in seismic hazard analysis, *Earthquake Spectra* **21**, 603–607.

Beyer, K., and Bommer, J. J., 2006. Relationships between median values and aleatory variabilities for different definitions of the horizontal component of motion, *Bull. Seismol. Soc. Am.* **94**, 1512–1522.

——, 2007. Erratum, *Bull. Seismol. Soc. Am.* **97**, 1769.

Bommer, J. J., 2006. Rethinking seismic hazard mapping and design return periods, in *Proceedings, First European Conference on Earthquake Engineering*, Paper no. 1304, Geneva.

Bommer, J. J., and Abrahamson, N. A., 2006. Why do modern probabilistic seismic hazard analyses lead to increased hazard estimates? *Bull. Seismol. Soc. Am.* **96**, 1967–1977.

Bommer, J. J., and Pinho, R., 2006. Adapting earthquake actions in Eurocode 8 for performance-based seismic design, *Earthquake Eng. Struct. Dyn.* **35**, 39–55.

Bommer, J. J., Scherbaum, F., Bungum, H., Cotton, F., Sabetta, F., and Abrahamson, N. A., 2005. On the use of logic trees for ground-motion prediction equations in seismic-hazard analysis, *Bull. Seismol. Soc. Am.* **95**, 377–389.

Budnitz, R. J., Apostolakis, G., Boore, D. M., Cluff, L. S., Coppersmith, K. J., Cornell, C. A., and Morris, P. A., 1997. *Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts*, US Nuclear Regulatory Commission Report NUREG/CR-6372.

Burnham, K. P., and Anderson, D. R., 2002. *The Model Selection and Multimodel Inference: A practical information-theoretic approach*, 2nd edition, Springer, New York, NY, 488 pp.

Cotton, F., Scherbaum, F., Bommer, J. J., and Bungum, H., 2006. Criteria for selecting and adjusting ground-motion models for specific target applications: applications to Central Europe and rock sites, *J. Seismol.* **10**, 137–156.

Dreyfus, H. L., and Dreyfus, S. E., 1986. *Mind over Machine*. The Free Press, New York, 252 pp.

Helton, J. C., and Oberkampf, W. L., 2004. Alternative representations of epistemic uncertainty, *Reliab. Eng. Syst. Saf.* **85**, 1–10.

Helton, J. C., Johnson, J. D., and Oberkampf, W. L., 2004 An exploration of alternative approaches to the representation of uncertainty in model predictions, *Reliab. Eng. Syst. Saf.* **85**, 39–71.

Kulkarni, R. B., Youngs, R. R., and Coppersmith, K. J., 1984. Assessment of confidence intervals for results of seismic hazard analysis, in *Proceedings, Eighth World Conference on Earthquake Engineering*, vol. 1, San Francisco, pp. 263–270.

McGuire, R. K., 2004. *Seismic Hazard and Risk Analysis, EERI Monograph MNO-10*, Earthquake Engineering Research Institute, Oakland, California, 187 pp.

McGuire, R. K., Cornell, C. A., and Toro, G. R., 2005. The case for the mean hazard curve, *Earthquake Spectra* **21**, 879–886.

Musson, R. M. W., 2005. Against fractiles, *Earthquake Spectra* **21**, 887–891.

O'Hagan, A., and Oakley, J. E., 2004. Probability is perfect, but we can't elicit it perfectly, *Reliab. Eng. Syst. Saf.* **85**, 239–248.

O'Hagan, A., Buck, C. E., Daneshkhah, A., Eiser, J. R., Garthwaite, P. H., Jenkinson, D. J., Oakley, J. E., and Rakow, T., 2006. *Uncertain Judgements: Eliciting Experts' Probabilities*, John Wiley & Sons Ltd., Chichester, England, 321 pp.

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

Sabetta, F., Lucantoni, A., Bungum, H., and Bommer, J. J., 2005. Sensitivity of PSHA results to ground motion prediction relations and logic-tree weights, *Soil Dyn. Earthquake Eng.* **25**, 317–329.

Scherbaum, F., Schmedes, J., and Cotton, F., 2004. On the conversion of source-to-site distance measures for extended earthquake source models, *Bull. Seismol. Soc. Am.* **94**, 1053–1069.

Scherbaum, F., Bommer, J. J., Bungum, H., Cotton, F., and Abrahamson, N. A., 2005. Composite ground-motion models and logic-trees: methodology, *Bull. Seismol. Soc. Am.* **95**, 1575–1593.

Scherbaum, F., Bommer, J. J., Cotton, F., Bungum, H., and Sabetta, F., 2006. Ground-motion prediction in PSHA: A post-PEGASOS perspective, In *Proceedings, First European Conference on Earthquake Engineering*, Paper no. 1312, Geneva.

Strasser, F. O., Bommer, J. J., and Abrahamson, N. A., 2008. Truncation of the log-normal distribution of ground-motion residuals, *J. Seismol.* **12**, 79–105.

van Schie, E. C. M., and van der Pligt, J., 1994. Getting an anchor on availability in causal judgment, *Org. Behav. Hum. Decis. Process* **57**, 140–154.

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