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On the Use of Logic Trees for Ground-Motion Prediction Equations in Seismic-Hazard Analysis

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Abstract Logic trees are widely used in probabilistic seismic hazard analysis as a tool to capture the epistemic uncertainty associated with the seismogenic sources and the ground-motion prediction models used in estimating the hazard. Combining two or more ground-motion relations within a logic tree will generally require several conversions to be made, because there are several definitions available for both the predicted ground-motion parameters and the explanatory parameters within the predictive ground-motion relations. Procedures for making conversions for each of these factors are presented, using a suite of predictive equations in current use for illustration. The sensitivity of the resulting ground-motion models to these conversions is shown to be pronounced for some of the parameters, especially the measure of source-to-site distance, highlighting the need to take into account any incompatibilities among the selected equations. Procedures are also presented for assigning weights to the branches in the ground-motion section of the logic tree in a transparent fashion, considering both intrinsic merits of the individual equations and their degree of applicability to the particular application.

Introduction

Logic trees were first introduced into probabilistic seismic hazard analysis (PSHA) by Kulkarni *et al.* (1984) as a tool to capture and quantify the uncertainties associated with the inputs required to perform such an analysis, and they have since become a standard feature of PSHA (Coppersmith and Youngs, 1986; Reiter, 1990). Despite the widespread use of the methodology, guidelines on setting up logic trees and assigning weights to the branches are lacking in the current literature. The purpose of this article is to discuss the basic issues involved in using a logic-tree framework for PSHA and to provide guidance for avoiding fundamental errors and for optimizing the use of this tool.

Although the use of logic trees is generally associated with PSHA, the approach can equally be applied to deterministic seismic hazard analysis (DSHA). The issues addressed in this article are therefore applicable to both approaches to seismic hazard analysis (SHA).

The focus in this article is exclusively on logic trees for ground-motion models, because of the particular problems that arise from combining such equations, and also because the uncertainty associated with the selection of the ground-motion model tends to exert a greater influence on the results of hazard calculations than other sources of uncertainty related to the underlying seismicity model. Some of the ideas presented in later sections regarding the assigning of relative weights, however, could be equally applied to other parts of a SHA.

This article begins with an overview of the logic-tree methodology and then addresses the important issue of compatibility among ground-motion prediction equations combined in a logic-tree framework. A major part of this article is devoted to procedures that can be applied to adjust ground-motion prediction equations to achieve compatibility. This article then goes on to discuss the process of assigning weights to the different branches before closing with a brief discussion of the implications of the issues discussed in terms of practical application in routine SHA.

In a review of the state-of-the-practice in SHA, Abrahamson (2000) asserted that there are "widespread misunderstandings of the basic methodologies used in seismic hazard evaluations" and identified one of the causes as being "the lack of well written, easy to understand papers or textbooks on the topic of seismic hazard analysis" (p. 684). Several publications have appeared in recent years (e.g., Hanks and Cornell, unpublished manuscript, 1999; Thenhaus and Campbell, 2003; McGuire, 2004) that represent important contributions toward developing an improved state of the practice, but none of these publications has dealt with the mechanics of the logic-tree methodology in detail, and this article aims to fill that gap. We make no claim to be presenting a study of entirely new work; the article builds on our earlier work, as well as the work of others, combining this with new analyses of the effects of ignoring incompatibilities and the consequences of making appropriate conversions. By bringing these elements together into a single article, the aim is to provide clear guidelines for the use of logic trees in SHA and possibly guide future research in this topic.

The Logic-Tree Methodology and Its Pitfalls

Handling uncertainties is a key element of SHA. Distinction is made between two types of uncertainty in seismic hazard assessment, and these are given the adjectives aleatory and epistemic (e.g., Budnitz *et al.*, 1997), terms used to replace and distinguish between the terms randomness and uncertainty, whose use has become ambiguous (Bommer, 2003).

Uncertainties that are related to an apparent randomness in nature, such as the scatter associated with empirical relationships, are referred to as aleatory variability. If the aleatory variability can be measured, usually by fitting observations to an assumed probability distribution, it is then straightforward to incorporate this variability directly into the hazard calculations. The most important aleatory variability in SHA is that associated with ground-motion prediction equations, which is generally represented by the standard deviation of the logarithmic residuals of the predicted parameter. Standard practice in PSHA is now to integrate across this aleatory variability within the hazard calculations. At the risk of stating the obvious—but acknowledging what is not infrequently done in practice—performing the hazard calculations using the 84-percentile level of motion as a deterministic prediction is not an adequate way of handling this component of the uncertainty. In DSHA, the aleatory variability in the ground-motion model is either effectively ignored (by considering only median values of the predicted parameter) or, as is becoming a more common practice, the 84th percentile of ground motion is considered (Krinitzsky, 2002).

Uncertainties reflecting the incomplete knowledge of, say, seismicity, rupture characteristics, and seismic energy excitation, are referred to as epistemic. There are many epistemic uncertainties in any seismic hazard assessment, including the characteristics of the seismic source zones (be these area zones or specific faults), the model for the recurrence relationship, and the maximum earthquake magnitude. In PSHA, the established procedure is to incorporate the epistemic uncertainty into the calculations through the use of logic trees. The logic tree is set up so that for each of the steps in which there is epistemic uncertainty, separate branches are added for each of the choices that the analyst considers feasible. To each of these a normalized weight is assigned that reflects that analyst's confidence that this is the most correct model, and the weights are generally, but not necessarily, centered on a best estimate. The hazard calculations are then performed following all the possible branches through the logic tree, each analysis producing a single hazard curve showing ground motion against annual frequency of exceedance. The weighting of each hazard curve is determined by multiplying the weights along all the component branches. The results allow the definition of a mean and a median hazard curve, as well as similar curves for different confidence intervals. For every branch added to a logic tree, a penalty is paid in terms of additional calculations; if there are multiple branches for each component of the hazard analysis, the total number of hazard calculations can rapidly become very large. For this reason it is advisable to avoid using branches with very small differences between the options that they carry, in cases when these options result in very similar nodes.

Notwithstanding the views expressed by some proponents of the deterministic approach to seismic hazard analysis (e.g., Krinitzsky, 1995), logic trees can be used equally effectively in DSHA. Part of the resistance to using logic trees on the part of proponents of DSHA may arise from the presentation of the weights on logic-tree branches as probabilities. We believe that the models distributed over different branches are not outcomes of experiments of chance and, therefore, the weights are simply ratings to reflect the relative confidence of the analyst that the most appropriate model has been selected (Abrahamson and Bommer, 2005). As such, a logic tree applied in a deterministic hazard assessment will simply yield confidence assignments associated with the design ground motions obtained by using different input options.

The separation and balance between aleatory variability and epistemic uncertainty is not always simple, however. The physical processes modeled in SHA are essentially deterministic, but often have to be modeled as random processes in the lack of specific knowledge. Over time one should therefore expect that some of the uncertainties may slowly migrate from aleatory to epistemic, in parallel with increased understanding and knowledge of the physics of earthquakes. A frequently encountered example of aleatory variability and epistemic uncertainty being mixed is the inclusion of branches for different focal depths, with weights assigned according to the distribution of observed hypocentral depths in the earthquake catalog. This practice is not consistent with the purpose of a logic tree, because the distribution of focal depths of earthquakes within a source zone represents an aleatory variability, whose distribution can be determined from the earthquake catalog, and which strictly should be included in the hazard integrations.

An important principle to follow in setting up a logic tree, but not always taken into account, is that the options represented by the branches extending from a single node should encompass the complete range of physical possibilities that particular parameter could be expected to take. This is consistent with the objective of the logic tree in capturing epistemic uncertainty, which arises from lack of knowledge. The branches should be set up so that, as knowledge improves, mainly through the gathering of more and better data, revised estimates for the parameters should fall within the bounds expressed by the logic-tree branches. This should not be interpreted as a license to include physically unrealizable scenarios, however. The use of a logic tree does not relieve the analyst from the responsibility of judging if the specified value of a particular parameter could actually be expected to occur in nature; simply assigning very low weights to extreme (and unphysical) branches should not be used as way of "covering one's back." Impossible scenarios should be assigned weights of zero (and therefore should not be included as branches).

Compatibility of Dependent and Independent Variables

In the few regions of the world with abundant strong-motion data (i.e., coastal California and Japan), the analyst generally has a number of region-specific ground-motion prediction equations to choose from for use in SHA. The median values of motion predicted by these equations will often differ as the result of differences in many aspects of deriving the relationships, such as choice of functional form, regression techniques, data selection, and definitions of variables. The differences in the median predictions (other than those due to differences in parameter definitions) reflect—but do not necessarily capture—the epistemic uncertainty in the ground-motion model, and although the differences may seem to be relatively small, the influence on the hazard can be significant (e.g., Sabetta, Lucantoni, Bungum, and Bommer, 2005). As a result, it is rightly considered important to capture this uncertainty in the hazard calculations. For example, in the derivation of the new U.S. Geological Survey (USGS) national hazard maps (Frankel *et al.*, 2002), four equations were used for crustal earthquakes in the western United States (Abrahamson and Silva, 1997; Boore *et al.*, 1997; Sadigh *et al.*, 1997; Campbell and Bozorgnia, 2003), and for extensional zones these four equations were combined with those of Spudich *et al.* (1999).

The predictive equations available for any particular region will rarely be uniform in terms of the definition of the predicted ground-motion parameter and all the explanatory variables, because a wide variety of definitions are used (e.g., Campbell, 2003a,b; Douglas, 2003). As a result, conversions will generally need to be made to achieve compatibility among the predictions from the equations. Failure to make such conversions will result in distortion of the epistemic uncertainty, in general widening the confidence limits of the hazard estimates artificially. The outcome of the PEER NGA (Pacific Earthquake Engineering Research Center, Next Generation of Attenuation of Ground Motion) project (PEER, 2004) may improve the compatibility among the equations derived for western North America (WNA) in the near future, but for current applications conversions for different parameter are still unavoidable. However, when the analyst is faced with carrying out a seismic hazard assessment outside WNA, the situation immediately becomes more complex. There will often be no indigenous strong-motion data and hence no region-specific equations, or perhaps just one or two equations derived for use in that area. In such situations, a SHA will have to incorporate equations from other regions of the world. In addition to the problem of different parameter definitions, the need may exist to make conversions for parameters, such as style-of-faulting, which are included in some models but not in others.

To illustrate the nature of the conversions and their effects on ground-motion predictions, this article considers a suite of empirical equations that are in current use for crustal earthquakes in active tectonic regions. The ground-motion parameter considered is spectral acceleration for 5% of critical damping. The selected candidate equations, and their main characteristics, are listed in Table 1. This selection does not necessarily imply that this particular collection of predictive equations might be applicable to a logic-tree analysis in any given region but rather is made purely for illustrative purposes. Outside of the WNA there are, however, many seismically active areas for which it is conceivable that a number of these equations could be combined in a logic-tree formulation for a SHA. Criteria and procedures for selecting suites of equations for application in regions with few or no indigenous equations are discussed elsewhere (Cotton, Scherbaum, Bommer, and Bungum, unpublished manuscript, 2004). In addition to the conversions for incompatible parameters, which *must* be made, the analyst may also consider it necessary to make additional conversions for fundamental differences among the host regions from which the candidate equations are adopted, and between these and the target region where the hazard is to be assessed (Cotton, Scherbaum, Bommer, and Bungum, unpublished manuscript, 2004).

For the purposes of illustration, it is assumed in this article that the hazard is to be evaluated for a rock site, or at least for rock conditions, for which the most appropriate site class is selected and the V_{s30} value of this site category is indicated in Table 1. It is also assumed that the hazard calculations are to be performed in terms of moment magnitude, M_w, and, again for illustration purposes, that the seismic sources affecting the site are all dominated by reverse faults, with dip angles of 50°.

Another assumption is that the seismogenic sources will be modeled in such a way that the most appropriate distance metric will be the shortest distance to the surface projection of the fault rupture, r_{jb} (called the "Joyner-Boore" distance). The final assumption is that the response spectral ordinates to be used are those defined by the geometric mean component, for compatibility with the fragility functions to be used in risk assessments.

Figure 1 compares the median spectral ordinates predicted by all the equations in Table 1, for "rock" sites located at 5 km from an earthquake of M_w 5 and at 15 km from an earthquake of M_w 7. The upper plots show the spectra obtained if all distances are simply entered to each equation as 5 or 15 km, and all magnitude scales are assumed equivalent; for the equations that include style-of-faulting as a predictor variable, the coefficients are set to reverse rupture. The lower plots show the spectral ordinates obtained after applying all the conversions described in the following subsections. If the hazard assessment is performed without the appropriate conversions (i.e., using the upper plots), the epistemic uncertainty would be significantly overestimated, thus under-

Table 1
Characteristics of Candidate Ground-Motion Prediction Equations

Equations	Comp*	Magnitude Scale	Distance Metric†	Region‡	Rock V_{s30}§
Abrahamson and Silva (1997)	Geom.	M_w	r_{rup}	Mainly WNA	> 600
Ambraseys and Douglas (2003)	L-env	M_s	r_{jb}	Mainly WNA	> 750
Ambraseys *et al.* (1996)	L-env	M_s	r_{jb}	Eur. ME	> 750
Berge-Thierry *et al.* (2003)	Both	M_s	r_{hyp}	Eur. ME-WNA	> 800
Boore *et al.* (1997)	Geom.	M_w	r_{jb}	WNA	~ 620
Lussou *et al.* (2001)	Both	M_{JMA}	r_{hyp}	Japan	> 800
Sabetta and Pugliese (1996)	L-PGA	M_s, M_L	r_{epi}, r_{jb}	Italy	> 800
Spudich *et al.* (1999)	Geom.	M_w	r_{jb}	Ext. Reg.	~ 620

*Geom., geometric mean; Both, both horizontal components as independent points; L-env, larger ordinate at each response period (envelope); L-PGA, ordinates of component with larger PGA.

†As defined by Abrahamson and Shedlock (1997).

‡WNA, western North America; Eur. ME, Europe and the Middle East; Ext. Reg., extensional tectonic regimes.

§Representative 30-m shear-wave velocities declared in the study as the definition of the rock or stiff site category.

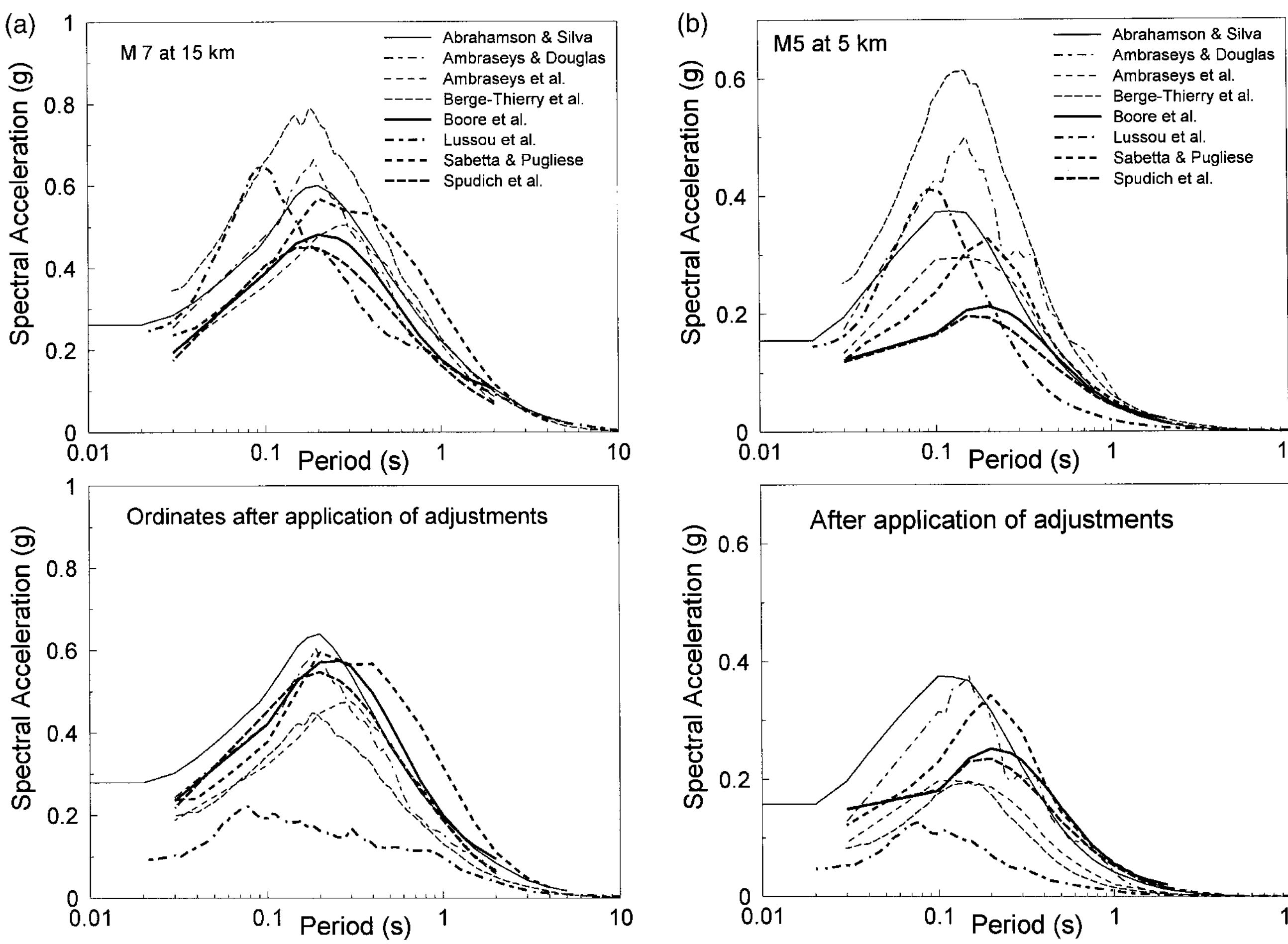

Figure 1. (a) Median acceleration spectra from the candidate equations for "rock" sites at 15 km from a M 7 earthquake. The upper panel shows the spectral ordinates obtained, assuming that all the equations use the same parameter definitions; the lower panel shows the spectral ordinates obtained after making conversions for the different definitions used in the equations. (b) Same as for (a) but for an earthquake of M_w 5 at 5 km.

mining the value and purpose of the logic-tree approach. This is clear particularly for the moderate-magnitude earthquake at short distance (M_w 5 at 5 km), where the differences in magnitude scales and distance measures are very large. This may seem like a rather trivial point, because it is clearly incorrect to use an equation with parameters defined differently from those for which the equation was derived. However, it is not at all uncommon to encounter seismic hazard studies in which incompatible ground-motion models are combined in logic trees without any appropriate conversions. Similarly, many examples exist of graphical comparisons of the predictions obtained from different ground-motion relations that do not make any suitable conversion for the fact that the equations use different definitions for one or more variable.

Uncertainties in Conversions

The conversions used to compensate for parameter incompatibilities are usually empirical and usually carry an associated aleatory variability because the two parameters, for example, M_s and M_w, are generally not perfectly correlated. This variability needs to be carried across into the aleatory variability in the ground-motion predictions, because, for a given value of the independent parameter definition used in the hazard calculations, the value of the converted parameter will differ from the median value given by the empirical relationship in accordance with the standard deviation. If the empirical correlations used to make the conversion for independent parameter X have an associated measure of aleatory variability, σ_X, then this should be carried across into the $\sigma[log(Y)]$ of the ground-motion prediction equations by using the expression:

$$\sigma_{\text{Total}} = \sqrt{\sigma^2 + \left(\frac{\partial \log(Y)}{\partial X}\right)^2 \sigma_x^2} \,. \qquad (1)$$

More than one empirical relationship will often exist that could be used to make the conversion and the differences between these relationships represent another component of epistemic uncertainty. In a strict sense, to fully capture the uncertainties, additional branches should be added for the alternative conversions. This will rarely be necessary in practice, however, because the differences between them will generally be small. In most cases, the propagation of the aleatory variability is much more important.

Horizontal Component Conversions and Missing Frequencies

The two horizontal components from an accelerogram can be treated in several ways when determining values of parameters to characterize the motion (Table 1). The average ratios of spectral accelerations are relatively stable and therefore can be easily and reliably determined from strong-motion data sets. Figure 2a shows the ratios between various pairs of definitions determined from a large global set of accelerograms. The assumption is made that the ratio is essentially independent of magnitude and distance. This assumption is supported by Boore *et al.* (1993) who derived equations for both the larger component and geometrical mean component from the same data set; comparison of the predicted median values from the equations reveals very small variations of their ratio with magnitude and distance.

An important observation from Figure 2a is that, as would be expected, the median values of spectral accelerations obtained using the random component, the geometric mean of the components, and both components, are almost identical. The ratios of the associated standard deviations of the residuals differ, however, as can be observed from Figure 2b, which shows ratios of residuals of spectral ordinates calculated with respect to the median values from the equations of Abrahamson and Silva (1997). The ratios are generally close to unity, although for some conversions the ratios reach values of 1.04. The conversions may still be worth making, however, because of the sensitivity of hazard results to the value of sigma.

Regarding the propagation of errors, note that the standard deviations associated with the trends illustrated in Figure 2 are very small, even when the magnitude and distance dependence of the ratios is ignored, and the application of equation (1) would make their impact practically null; hence, for this particular conversion it is possible to simply neglect the propagation of errors. Using different subsets of the global dataset used to derive the ratios in Figure 2 resulted in very small changes, from which it can be concluded that the epistemic uncertainty is small and branches are not required.

Another issue that arises in the combination of several equations is that coefficients are often given for different response frequencies in each study. The equations in Table 1 provide coefficients for common frequencies between 0.5 and 10 Hz, but some do not extend to lower frequencies and many of the equations are sparse in the high-frequency range, which requires an assumption to be made regarding at what frequency the spectral acceleration becomes equivalent to the zero-period response (i.e., peak ground acceleration [PGA]); estimates vary from 33 Hz to 50 Hz, with all studies presenting ordinates that are almost identical at 50 and 100 Hz. We recommend setting the coefficients for 50 Hz equal to those for PGA, if available, or otherwise use the coefficients for the highest available frequency. Linear interpolation can then be used after plotting the coefficients against logarithm of frequency. Some studies have assumed that spectral accelerations at 34 Hz are equivalent to PGA; for the equations of Berge-Thierry *et al.* (2003), for example, the spectral accelerations at this frequency vary with damping ratio, but by such small amounts (about 1% variation in ordinates between 5% and 10% damping) that the assumption may be assumed to be reasonably valid. This result does indicate, however, that the frequency that can really be considered equivalent to PGA is probably a little higher, perhaps

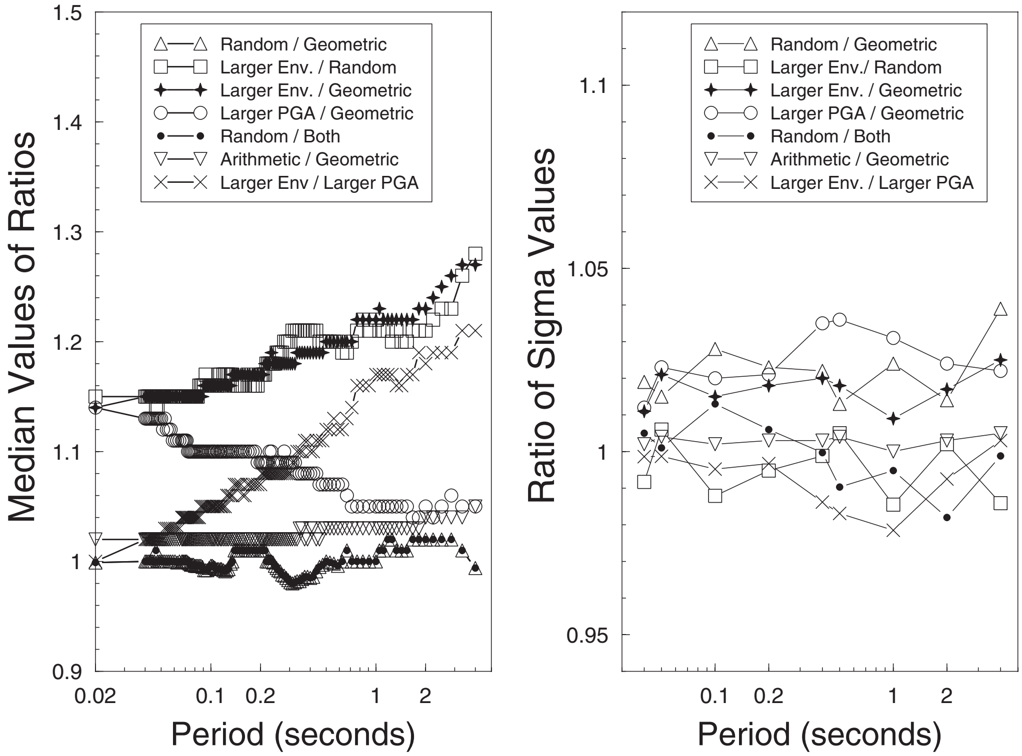

Figure 2. Ratios between horizontal spectral ordinates calculated using different conventions for the treatment of the horizontal components of accelerograms, calculated from a large global dataset of accelerograms (left) and the ratios of the standard deviations obtained using the same definitions for the horizontal component of motion (right).

of the order of 50 Hz. For very hard rock sites, such as encountered in eastern North America, the response acceleration at 100 Hz is likely to be an appropriate surrogate for PGA.

One final issue is worthy of consideration with regard to the definition of the dependent variable. Some of the equations actually predict absolute acceleration response whereas others predict, directly or via pseudovelocity, the pseudo-acceleration response. This distinction can usually be disregarded, except for where the hazard assessment is concerned with very long-period response, for which the differences between the two quantities do need to be considered.

Magnitude Scale Conversions

As noted in Table 1, ground-motion equations use different magnitude scales, and compatibility must be achieved both among the equations and between each equation and the earthquake catalog. Two possible approaches can be adopted, because empirical conversions between magnitude scales are always required to obtain a uniform measure for the earthquake catalog used in a seismic hazard assessment. One option is to create earthquake catalogs, and hence recurrence parameters, in each of the magnitude scales used by the various ground-motion prediction equations and then match these accordingly in the hazard calculations. This, however, will still call for magnitude conversions, so we favor producing a single earthquake catalog, using the most reliable magnitude for that region, and then applying conversions for those ground-motion prediction equations based on other scales.

To calculate spectral ordinates for earthquakes specified in terms of moment magnitude, four of the candidate equations in Table 1 need the magnitude to be converted to M_s, and one requires the magnitude to be expressed in the JMA scale. For conversions of M_w to M_s, empirical relationships have been derived by Ambraseys and Free (1997) and Bungum *et al.* (2003) from European data. The conversion to M_L instead of M_s for smaller events when using the Sabetta and Pugliese (1996) equations is not necessary because the authors of that study selected a hybrid scale (M_L if < 5.5, M_s if > 5.5) precisely because they considered it to define a continuous scale approximately equal to M_w over a wide range of magnitude values. Empirical conversions between M_L and M_w, if conversion were to be made, would need to be locally derived because M_L scales are generally different from one region to another, and moreover, such relations are also often nonlinear because of the way in which the corner frequency passes through the frequency band used by M_L (Hanks and Boore, 1984). The equations of Lussou *et al.* (2001) require the M_w values to be transposed to the M_{JMA} scale, for which use can be made of the empirical relationship between M_{JMA} and seismic moment derived by Fukushima (1996), which supports the assertion of Heaton *et al.* (1986) that the two scales are practically equivalent in the range 6–7.

Using these empirical equations, the change in the spectral ordinates obtained compared with those found when simply ignoring the use of different magnitude scales is largest for smaller magnitude earthquakes. The differences obtained using alternative conversions, such as Ambraseys and Free (1997), rather than Bungum *et al.* (2003) are too small to warrant the complication of additional branches in the logic tree. However, the aleatory variability in the empirical equations does need to be considered.

The effect of the error propagation can be illustrated using equation (1). Fukushima (1996) reports a standard deviation of 0.23 associated with the empirical correlation between M_{JMA} and seismic moment. For the Bungum *et al.* (2003) relationship the standard deviation of 0.225 reported by Ambraseys and Free (1997) for their similar relationship is adopted. For the five equations not originally defined in terms of M_w, Figure 3 shows the ratio of the sigma values after propagating the uncertainties to the original values, as a function of response period; the increases are of the order of 5%, which corresponds to a 12% increase in the 84-percentile value with respect to the median spectral ordinate.

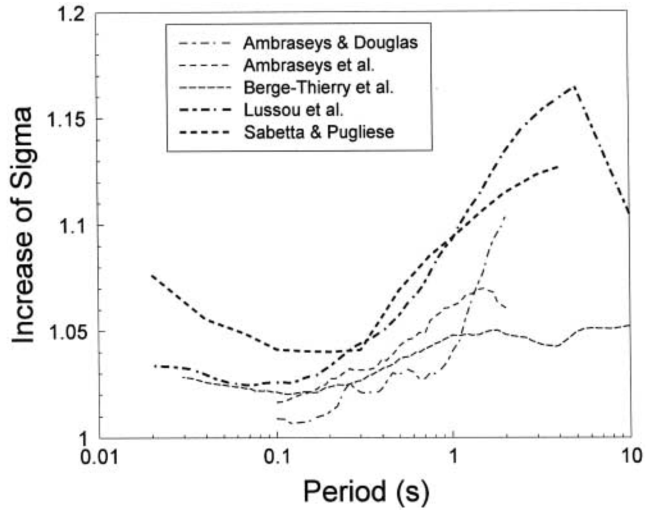

Figure 3. Ratios of sigma values, as function of period, after propagating aleatory uncertainty from magnitude scale conversions to original values.

Distance Conversions

The use of different measures of the distance from the source of seismic energy release to the location of the accelerograph recorder in the candidate prediction equations is probably the single most important incompatibility that exists. Two equations use hypocentral distance and thereby model the earthquake source as a point, which clearly will give very different estimates of the distance for larger earthquakes than those measures based on the fault rupture. In addition to the question of compatibility among ground-motion prediction equations using different distance metrics, there is also an issue of compatibility between the measure used in an equation and the way the earthquake source scenarios are modeled in the code used for PSHA. The widely used programs EQRISK (McGuire, 1976) and SEISRISK (Bender and Perkins, 1982, 1987) implicitly model the sources of individual earthquakes within source zones as points and, hence, the distance from each earthquake scenario to the site under analysis is essentially the epicentral distance. Although often overlooked in practice, the use of a ground-motion prediction equation based on the distance from the rupture or the surface projection of the rupture, without appropriate conversion, will consistently underestimate the ground motions from larger ($M > 6$) earthquakes and hence underestimate the hazard.

The issue of obtaining compatibility among ground-motion prediction equations using different distance metrics has been addressed in detail by Scherbaum *et al.* (2004b), who determined explicit distance conversion relations using regression analysis on simulated data based on well-established scaling laws. The functional forms of these relations are magnitude and distance dependent and are expressed as polynomials with associated distributions. A question that needs to be answered is which measure of the relationship between different distance metrics should be used to make the conversions, the usual choices being the mean, the mode, or the median of the distribution. We favor using the median, because it is the least sensitive to the tails of the distribution and, unlike the mean, the median takes account of the skewness in the distribution.

When applying any of the conversions, it is important to keep in mind any interdependence of the parameters and apply the conversions in an appropriate order. Clearly, any magnitude conversions that are required should be applied before applying distance conversions.

The changes in the median values that result from these conversions are strongly distance dependent, reaching values on the order of 40% close to the earthquake source, which is likely to be very significant for hazard at low annual frequencies of exceedance for which such scenarios will have a dominant influence. Large differences are found even for small magnitude ($M \sim 5$) events, which may at first seem surprising, especially because, for such earthquakes, it is frequently assumed that Joyner-Boore and epicentral distances can be considered equivalent; it is important to bear in mind that, in this case, the two point-source measures are hypocentral rather than epicentral distances; hence, the focal depth is the controlling factor.

When converting distance measures, the corresponding uncertainties map onto the estimated ground motions according to the laws of error propagation, as discussed previously. Figure 4 shows the ratio of sigma values due to application of the distance conversions to the original values. Note that conversion of the distance metrics can cause the uncertainties in the adapted ground-motion model to increase significantly, and also to become magnitude and distance dependent, even if they are not in the original relation.

Conversion to a Reference Style-of-Faulting

The influence of style-of-faulting on the amplitude of earthquake ground motion is a subject about which much research remains to be done, a fact which is reflected in the disparate way this variable is treated by the candidate equations considered in this study. Only two of the equations in Table 1 (Abrahamson and Silva, 1997; Boore *et al.*, 1997) include the style-of-faulting as an explanatory variable, although the latter also allows the user to make mechanism-independent predictions.

Bommer *et al.* (2003) have developed a scheme for introducing style-of-faulting into ground-motion prediction equations that does not include this parameter. The method is based on the distribution of the records used to drive the equation with respect to the three basic style-of-faulting categories (normal, reverse, and strike-slip) and the assumption that the aleatory variability of the data within each group is equal to the overall aleatory variability of the data. The ratios of spectral ordinates for different rupture mechanisms have been inferred from several published studies and from predictive equations that explicitly include the effect of style-of-faulting. Figure 5 shows the effect of applying the best-estimate conversion of Bommer *et al.* (2003) to the predicted median spectral ordinates to adjust all the equations to reverse faulting earthquakes.

As a result of the way that the ratios between different motions from earthquakes with different styles-of-faulting have been derived by Bommer *et al.* (2003), there is no associated measure of the standard deviation; hence, equation (1) cannot be used to propagate the error unless a subjective estimate of the standard deviation is made. In such cases it is necessary to include additional logic-tree branches; for each branch carrying an equation for which a style-of-faulting conversion needs to be made, three branches, for example, could be added to capture the uncertainty in the conversion.

The application of a style-of-faulting conversion to an equation that does not include this factor as a predictor variable is effectively increasing the number of variables in the equation, for which reason it would be correct, in a strict sense, to reduce the aleatory variability. However, the reduction is likely to be much too small to make this necessary.

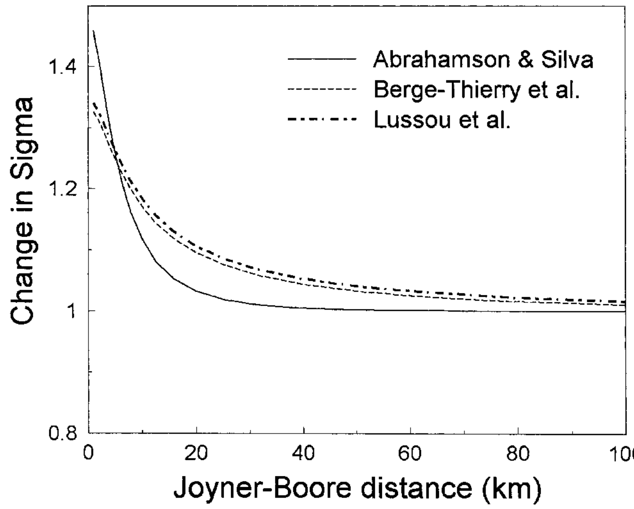

Figure 4. Ratios of sigma values corresponding to the spectral response at 1 Hz, as function of distance, for a M 7 earthquake, after propagating aleatory uncertainty from distance metric conversions to original values.

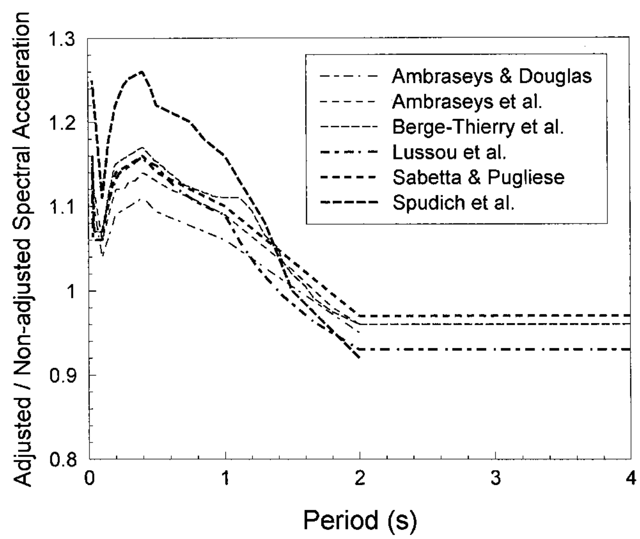

Figure 5. Ratios of median acceleration spectra from the candidate equations due to application of conversions to a common style-of-faulting (reverse) mechanism using the conversions of Bommer *et al.* (2003). The conversion is independent of magnitude and distance.

Conversion for Site Class and from Host-to-Target Region

At the beginning of this section it was stated that for illustrative purposes it would be assumed that the equations are to be used in a hazard assessment for a rock site. Clearly, the definition of rock used in each of the equations (Table 1) is different, and hence there is another additional source of incompatibility that needs to be considered.

To perform conversions to a common reference site, first, the representative V_{s30} value for each equation must be defined. For most of the equations in Table 1, only a range of shear-wave velocities is known for the rock class, and furthermore, this range will often be a nominal range rather than the actual values encompassed by the data. In general, the publications in which the equations are presented include relatively little of the source information on which the site classifications are based, which hampers the interpretation of the defined rock category in each equation. Considerable uncertainty clearly exists in arriving at the best estimate V_{s30} values, which may lead some to conclude that applying any crude correction on the basis of these values is as likely to add uncertainty as to compensate for its influence.

To make conversions to a common site profile or V_{s30} two methods can be applied. First, simple site condition conversions can be made using factors derived from attenuation equations, for example, Boore *et al.* (1997), which predict spectral ordinates as a function of V_{s30} values and which can be used therefore to infer spectral ratios between two sites of known 30-m shear-wave velocity. A limitation to this approach is that the equations of Boore *et al.* (1997) provide coefficients for a rather narrow range of frequencies. An alternative approach consists in using 1D site-response analysis. Several methods can be used to build the velocity profiles to be used in the 1D site-response analysis. Generic rock models with V_{s30} as a single free parameter can be constructed (e.g., Boore and Joyner, 1997) or, alternatively, real shear-wave velocity profiles can be used.

Both of these approaches assume that the differences in motion between observations from the generic rock site represented by the equations and the target site are entirely due to differences in the stiffness of the near-surface materials at the site. The second approach of using generic profiles allows the influence of materials below 30 m to be at least approximately accounted for, but neither approach is able to include the influence of different crustal properties between the region for which the equation was derived and the region for which the SHA is being performed. To make the host-to-target conversion for site effects (as separate from differences in whole path attenuation characteristics) necessitates consideration of both differences in amplification due to variation in stiffness of surface geology (V_s) and differences in high-frequency attenuation in the upper crust (kappa, κ). A clear example of the simultaneous influence of these factors is given by Atkinson and Boore (1997), who present the following equation for transforming ground motions from hard rock sites in eastern North America ($V_{s30} = 2800$ m/sec) to rock sites in California ($V_{s30} = 620$ m/sec):

$$\mathrm{SA_{WNA}} = \mathrm{SA_{ENA}} \sqrt{\frac{2800}{620}}\, e^{-\pi f/100}, \tag{2}$$

where SA is spectral acceleration. The simultaneous conversion for site stiffness and for upper-crustal diminution is considerably more complex than making only conversion for V_{s30}, not least because the representative kappa values for the candidate equations cannot be inferred directly from the information provided on the strong-motion dataset used in the regressions. The application of such host-to-target region conversions in conjunction with conversions to a common reference site is discussed in detail by Cotton, Scherbaum, Bommer, and Bungum, unpublished manuscript (2004).

Effect of Conversions on Aleatory Uncertainty

In making the necessary conversions for the equations to be compatible—and also compatible with the seismicity model used in the hazard calculations—there is inevitably an increase in the aleatory uncertainty in the ground-motion predictions because all the conversions involve random variability. The final effect on the sigma values of applying all the conversions discussed in the preceding subsections is illustrated in Figure 6 for a rock site at 5 km from an M_w 5 earthquake.

For the style-of-faulting conversion, as mentioned previously, the aleatory uncertainty cannot be measured, so a value is estimated from the variation in predicted ratios among the various models considered by Bommer *et al.* (2003). The variability was estimated to result in 84-percentile values about 20% higher than the median; hence, the sigma in logarithmic space is taken as 0.08. The increase in some of the sigma values is appreciable (despite neglecting the changes due to component conversions) even if not very large; the effect on the hazard, however, could be significant, in particular, for low annual frequencies of exceedance (e.g., Restrepo-Vélez and Bommer, 2003).

Criteria and Procedures for Assigning Weights

Once the equations to be included in the logic tree have been selected and appropriate conversions applied to achieve compatibility, the final stage of setting up the logic tree is to assign weights to the branches.

General Considerations

It may be highly advisable not to adopt a single set of relative weights applicable to the selected equations but rather to allow the weights to vary in different magnitude-distance bins. For example, at short distances, the equations of Ambraseys and Douglas (2003) may be assigned higher weights because they are derived specifically for near-source conditions; the same equations would logically be assigned very low (or even zero) weights for distance ranges beyond the limit of the dataset from which they were derived (i.e., 15 km). Similarly, those equations based on point-source distance measures, which are Berge-Thierry *et al.* (2003) and Lussou *et al.* (2001), may be given very low weights for bins defined by large magnitudes and short distances, for which such distance metrics may be considered inappropriate; the need to reduce weights for this reason will be much less for smaller magnitudes and greater distances.

Another reason for assigning weights that vary across magnitude-distance bins is that the ranges of magnitude and distance covered by the hazard integrations will be dictated by the configuration of the seismicity model and may extend significantly beyond the limits of applicability of some of the equations. For example, a hazard study for Italy may logically assign the highest weight to the equations of Sabetta and Pugliese (1996); however, the maximum magni-

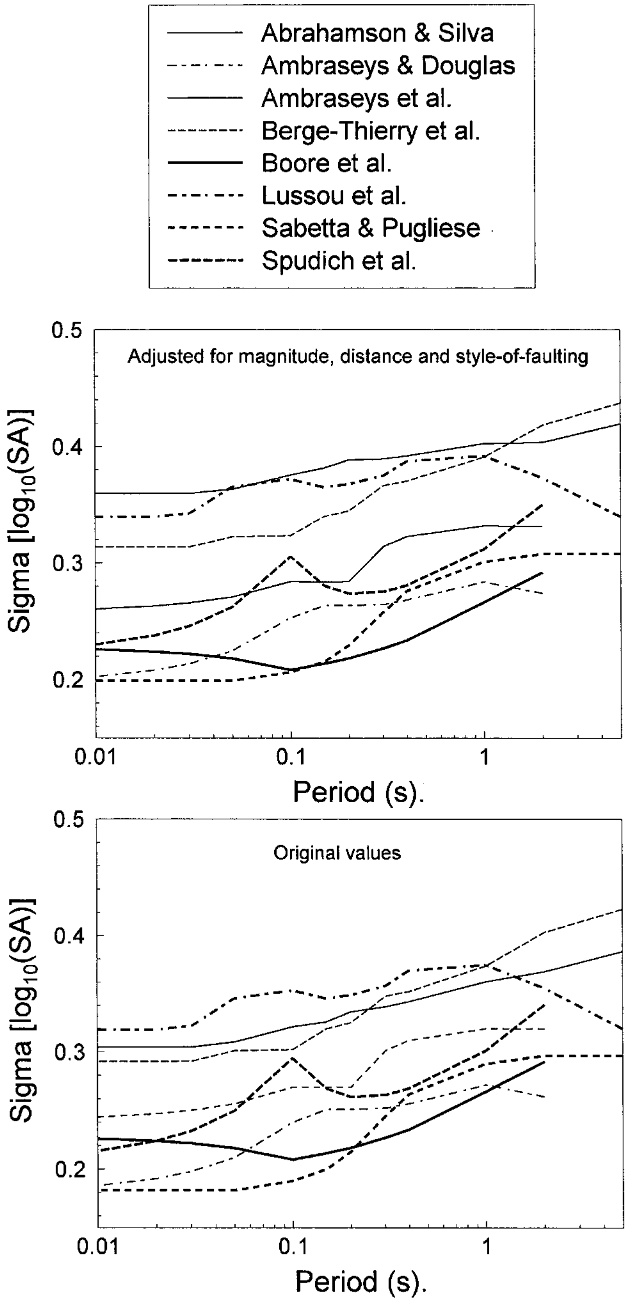

Figure 6. Sigma values for the candidate equations for sites at 5 km from a M 5 earthquake. The lower panel shows original values; the upper panel shows the values after propagating the errors associated with the magnitude, distance, and style-of-faulting conversions. The aleatory variability associated with the style-of-faulting conversion has been estimated as 0.08 on the logarithmic values of spectral acceleration (see text).

tude in the dataset from which these equations are derived is M_s 6.8. If for some seismic source zones in Italy, maximum magnitudes of the order of M_s 7.5 were specified, it could be advisable to assign lower weighting to the Sabetta and Pugliese (1996) equations for magnitudes above 7 and, in this range, assign a relatively higher weight to, for example, the equations of Ambraseys *et al.* (1996) that are calibrated to higher magnitudes.

The degree of dependence between branches of the logic tree should also be considered. For an application in, say, California or eastern North America, one may tend to simply include equations derived for the region in question, the differences in their predictions representing the epistemic uncertainty in the ground-motion model. There would actually be good arguments for including equations from outside California as well, such as the equations derived by Gülkan and Kalkan (2002) from a database dominated by the records of the 1999 Turkish earthquakes, because there are no recordings from Californian earthquakes in the same magnitude range in the datasets used to derive most current WNA ground-motion models. For hazard assessment in many parts of the world, it will not be possible to identify a directly analogous region from which there are abundant strong-motion data, whence equations from several regions may be included in the logic tree. In such cases, it may be advisable to check that the overall weighting given to each region represented by these equations is not disproportional. For the equations in Table 1, this could be achieved by looking at the total weight for equations derived mainly from European data (Ambraseys *et al.*, 1996; Berge-Thierry *et al.*, 2003; Sabetta and Pugliese, 1996) and similarly for those derived mainly from Californian records (Abrahamson and Silva, 1997; Ambraseys and Douglas, 2003; Boore *et al.*, 1997).

Criteria for Grading Candidate Equations

The weights applied to different ground-motion prediction equations in a logic-tree formulation reflect the degree to which each equation is judged to be the best estimate of earthquake ground motions in that particular region. A convenient way to separate the influences that may be considered in assigning rankings to the candidate equations is to group them into two categories, intrinsic and application specific.

The intrinsic factors are those related to the confidence of the user in a particular equation by virtue of how it was derived, regardless of where the model is actually being applied. The grading for these factors should, as indicated previously, be individually applied to different bins of magnitude and distance and to different response frequencies. This will enable maximum advantage to be taken of the strengths of each equation, while reducing the influence of any given equation for cases where it is weakly constrained. The primary basis for assigning the grading for intrinsic characteristics of an equation will be the distribution and quality of the strong-motion data used for the derivation of the equation within each magnitude-distance-frequency bin. This may not be as simple as examining the range of values covered by the dataset. For example, the data used by Ambraseys *et al.* (1996) include data from distances up to 260 km and magnitudes up to M_s 7.9; however, both of these values correspond to a single recording, with no other data at distances beyond 210 km and no other earthquakes of magnitude greater than M_s 7.3. Regarding the frequency coverage, the analyst may also reduce the grading of an equation at low or high frequencies if there are doubts about the processing of the recordings, in particular, if these have been obtained primarily from analog accelerographs (Boore and Bommer, 2005).

The application-specific characteristics can be divided into those related to the conventions adopted for the hazard calculations and those related to the specific environment for which the SHA is performed. The first group of characteristics is essentially related to the conversions required for each equation depending on the definitions of horizontal component of motion, magnitude scale, and distance metric adopted for the hazard calculations and whether style-of-faulting conversions need to be made for each equation. The objective would be to reduce the grading of those equations for which several conversions had been applied, the rationale behind this being that these equations have inevitably become more "uncertain" as a result. However, one could also argue that this is not necessary because the errors have been propagated.

The second category of application-specific characteristics essentially answers the question of how well a particular equation, after conversions, is suited to the particular location at which the hazard is being analyzed. The conversions in this case may include those related to reference site and host-to-target conversions, which are discussed in detail by Cotton, Scherbaum, Bommer, and Bungum, unpublished manuscript (2004). If such conversions have not been made, then judgment can be applied regarding the degree of similarity between the region for which the equation was derived and the region of application, in terms of whole path attenuation, crustal structure, and the stiffness of generic rock sites. Separate grading could be applied for each of these factors. Alternatively, with or without the application of reference site and host-to-target conversions, the applicability of an equation to a particular region can be quantitatively assessed using strong-motion recordings from that region (Scherbaum *et al.*, 2004a).

Ranking and Combining Criteria for Weights

From the preceding discussion it is clear that there are likely to be an appreciable number of factors to consider in assigning the final weights to each candidate ground-motion prediction equation. This gives rise to two further requirements: a hierarchy for the influence of each factor on the final weighting and a transparent system for combining the grading for the different factors into a single weight. The procedure for obtaining the weights should be transparent and reproducible, both to facilitate peer review of the hazard study, an indispensable factor in any PSHA (Budnitz *et al.*, 1997), and also to allow the analyst to easily update the weights should new data or analyses lead to any of the individual grades being modified.

Perhaps the most significant challenge for the analyst is deciding the hierarchy of influence of the factors, both in terms of the balance between intrinsic and application-specific factors, and the relative influence of factors within each category. Clear guidelines are difficult to provide because the decisions cannot be separated from the application. Once the hierarchy is fixed, the analyst needs to assign individual grades and then combine them into normalized weights, summing to unity at each node of the logic tree. In general, the grades are best combined by multiplication so that a very low or zero weighting on an equation in a particular magnitude-distance bin is effective in eliminating the influence of that model where it is judged to be poorly constrained.

For each of the criteria, relative grades will be applied to the equations. The "neutral" value of a grade may be taken arbitrarily as 10, and the grading is made symmetrical, so that if one equation is judged to merit a grade of 4 for a particular criterion that it meets poorly, an equation judged to be equally as good as the former one was poor will be assigned a grade of 25. The critical issue in this procedure is not the absolute value of the grades but the maximum range of values that the grades are allowed to take for each criterion; the more important the criterion is considered to be, the wider the range of grades assigned to the equations. Once the grades have been assigned for all the criteria selected, the final logic-tree weights are found simply by multiplying the grades for each equation in each magnitude-distance-frequency bin and then normalizing the values within each bin to sum to unity.

Discussion and Conclusions

Logic trees are an immensely useful tool for handling epistemic uncertainty in both probabilistic and deterministic SHA. In general, ground-motion prediction equations are the component of a hazard analysis exerting the greatest influence on the final results; hence, the ground-motion section of the logic tree is particularly important. Careful selection of the appropriate equations to be included on the branches is the vital first step, which needs to balance the desire to include ground-motion models likely to be representative of future ground motions in the region under study and to ensure that the epistemic uncertainty (in this case, variations from the "expected" motions) is fully captured.

Weights are then assigned to the branches to reflect the relative confidence in each of the models being applicable to the setting and objectives of the study; the importance of the weights decreases as the number of branches for different ground-motion models increases, and if only two or three equations are included in the logic tree the weights can exert a strong influence on the results. This article has presented a scheme for deriving the weights based on the grading for intrinsic quality of the equations (on which consensus could, in theory, be achieved) and application-specific merits (which are likely to remain largely the subject of expert judgment). The weights should be assigned for different bins of magnitude, distance, and response frequency to reflect the relative strengths and weaknesses of the equations in different ranges.

Although it is perhaps an obvious point, an issue that is frequently overlooked in practice is that the epistemic uncertainty will not be correctly captured by the logic-tree branches if the ground-motion prediction equations are based on different definitions of the response and predictor variables. Conversions therefore need to be applied to achieve compatibility among the equations within the hazard calculations. Suggestions for making some of the most important conversions have been offered in this article, although the options described are by no means exhaustive and users may well come up with alternative approaches. In generals the conversions will result in smaller variations between models (Fig. 1), although it is equally possible that the use of incompatible variables will actually underestimate the epistemic uncertainty.

The conversions carry their own uncertainty, and this must also be taken account of in the hazard calculations. The epistemic uncertainty represented by competing empirical models for the conversions is usually sufficiently small to be neglected and generally does not warrant the computational cost of additional branching. In some cases, the analyst may also legitimately decide that not all the conversions have sufficient impact to be strictly necessary and certainly it is worthwhile establishing a hierarchy. Magnitude and horizontal component conversions are easy to make and therefore should be applied if needed. The conversion that may be considered indispensable is that for different distance measures, because the impact on the hazard results is very marked.

For any conversions that are made, the propagation of aleatory variability into the scatter of the ground-motion models should not be neglected unless the impact is found to be very small, in particular because this parameter exerts such an important influence on the results of PSHA.

In terms of practical application, the incorporation of the necessary conversions is straightforward for DSHA. For PSHA, it is recognized that for the users of most freely or commercially available software for SHA, it will not be possible to apply many of the parameter conversions described herein, especially the critically important conversions for different distance metrics. Similarly, the recommended approach of assigning different weights in various magnitude-distance bins will clearly be difficult for users of most existing hazard software, although applying weights that vary with magnitude and distance could be achieved with existing software by performing the hazard calculations separately for each magnitude-distance bin and then aggregating the annual exceedance frequencies. We strongly urge future developers of hazard software to facilitate the application of varying weights and conversions for compatibility as discussed in this article.

This article has focused almost exclusively on issues related to planting logic trees. Equally important, however, is the issue of how they should be harvested; although this is beyond the scope of this article, we believe that the mean hazard curve is the least appropriate fruit of the logic tree to be used as the basis for engineering design and that some fractile should be selected instead (Abrahamson and Bommer, 2005). An alternative approach to the harvesting of logic trees is not to focus on the branch tip results, but rather to develop and use composite models for the median ground motion and the aleatory variability, as presented by Scherbaum, Bommer, Bungum, and Cotton, unpublished manuscript, 2004.

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