Construction of a ground-motion logic tree for PSHA in Europe within the SHARE project

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SUMMARY:
The Seismic HAzard haRmonization in Europe (SHARE) project aims at establishing new standards for probabilistic seismic hazard assessment in the Euro-Mediterranean region. In this context, a logic tree for ground-motion prediction in Europe has been constructed. Ground-motion prediction equations and weights have been determined so that the logic tree captures epistemic uncertainty in ground motion for six tectonic regimes identified in Europe. We present the strategy that we have adopted to build such a logic tree. This strategy has the particularity of combining two complementary and independent approaches: expert judgment and data testing. A set of six experts was asked to weight pre-selected GMPEs while the ability of these GMPEs to predict available data was evaluated with the method of Scherbaum *et al.* (2009). Results of both approaches were taken into account to commonly select the smallest set of GMPEs to capture the uncertainty in ground-motion prediction in Europe.

Keywords: Logic trees, Ground-motion prediction equations, Expert judgment, Model selection, Seismic hazard assessment

1. INTRODUCTION

The Seismic Hazard Harmonization in Europe (SHARE) project (http://www.share-eu.org) is one of the large international research initiatives, such as the Global Earthquake Model (GEM) project (http://www.globalquakemodel.org/), that have been launched to harmonize hazard estimates across political boundaries and to derive procedurally consistent pan-national hazard models. The SHARE project aims at defining methods for seismic hazard and loss assessment in the Euro-Mediterranean region that will become standards at global and regional scales. The team responsible for ground-motion prediction in the SHARE project has been working on the definition of a reference European model that captures as much as possible the center, body and range of possible ground motions in Europe and tackles the unresolved question of regional variations in ground motions. The construction of logic trees that express this variability and the associated epistemic uncertainty is a multi-step procedure that required a common effort in characterizing ground shaking in Europe and identifying reliable equations for the prediction of ground-motion parameters of interest together with measures of uncertainties. This task is especially important for regions that do not have an indigenous ground-motion prediction equation (GMPE), such as France. With this paper, we want to share our experience in the construction of a ground motion logic tree. We propose a new strategy that combines information from experts' judgment and from the evaluation of GMPEs based on data.

2. REQUIREMENTS

The construction of a ground-motion logic tree needs a close interaction with the other parts of the seismic hazard assessment process.

The first step in the construction of a ground-motion logic tree, the pre-selection of candidate GMPEs, is first guided by the seismotectonic description of the area covered by the seismic hazard. The seismotectonic map of the Euro-Mediterranean area developed for the SHARE project is shown in Figure 2. Six broad tectonic domains have been identified for ground motion prediction: 1. Stable continental regions (SCR), 2. Oceanic crust, 3. Subduction zones (SZ) 4. Active shallow crustal regions (ASCR), 5. Areas of deep focus non-subduction earthquakes, such as Vrancea (Romania) or the Betics (Spain) and 6. Active volcanoes.

The source model also influences ground motion prediction, especially in terms of distance calculation. The SHARE source model combines modern source types (area, fault, and point sources) within a logic tree to account for the inherent uncertainty in the expert views on seismicity. The source logic tree considers the different source types within the principal methodologies used: the zone- based (Cornell 1968) and the kernel-smoothed approach (Grünthal *et al.* 2010; Hiemer *et al.* 2011). Final details on the source models can be found within the reports of the SHARE project at http://www.share-eu.org or within a yet to be written manuscript on the new Euro-Mediterranean hazard model.

Before starting the construction of a ground motion logic, it is also crucial to know which magnitude range will be considered for the hazard calculation. The range in spectral frequency should also be known. These requirements are important because the prediction ability of GMPEs depends a lot on the distribution in magnitude, distance and spectral frequency of their dataset. If the hazard calculation allows for extrapolation of GMPEs, this extrapolation should be also taken into account for the selection of GMPEs.

Questions should however remain open because they need to be discussed during the construction of the logic tree between the participants. This concerns for example the possibility of distinguishing interface and intraslab earthquakes for subduction zones, or whether the logic tree should depend on the magnitude or the spectral frequency ranges. Each project needs to identify its priorities and requirements. For instance, for the SHARE project, due to the large area covered by the project, global GMPEs were preferred to local ones.

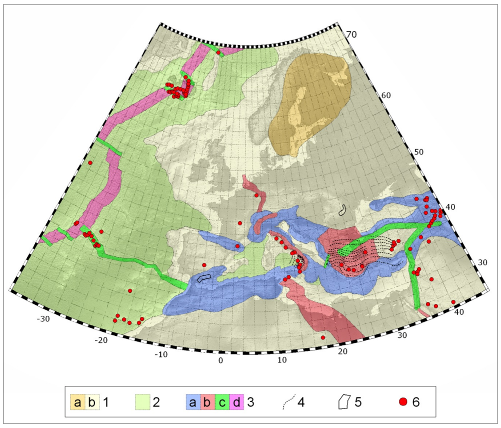

Figure 2. Seismotectonic map of the Euro-Mediterranean area. SCR, shield (a) and continental crust (b); 2 oceanic crust; 3 ASCR, compression-dominated areas (a), extension-dominated areas (b), major strike-slip faults and transforms (c), and mid oceanic ridges (d); 4 subduction zones; 5 areas of deep-focus non-subduction earthquakes; 6 active volcanoes and other thermal/magmatic features

3. PRE-SELECTION OF GMPES

The first step in the construction of a ground motion logic tree is the pre-selection of candidate ground-motion prediction equations (GMPEs). From the more than 250 GMPEs listed by Douglas (2011), not so many actually meet the selection criteria of Cotton *et al.* (2006) updated by Bommer *et al.* (2011), especially the former ones derived before 2008. Most recent GMPEs published in an international peer-reviewed journal respect the criteria of Cotton *et al.* (2006), especially as it is standard now to include saturation with magnitude, a magnitude-dependent distance scaling and anelastic attenuation terms in the functional form. Bommer et al. (2010) updated the exclusion criteria of Cotton *et al.* (2006) to reflect the state-of-the-art in ground-motion prediction. The new exclusion criteria especially aim at identifying the robust and well-constrained models based on new quality standards in the formulation and derivation of models as well as considering their applicability range in terms of spectral ordinates, magnitude, and distance. In particular, magnitude and distance ranges should be large enough so that the need for extrapolations when conducting PSHA is minimized. In addition, the number of earthquakes per magnitude and the number of records per different distance intervals should be maximized. Delavaud *et al.* (2012a) showed the importance of a well-distributed dataset to obtain robust GMPEs. This information is unfortunately not always available and therefore, authors should be compelled to provide the dataset they used when publishing a new GMPE. The application by Bommer *et al.* (2010) of their criteria leaves only a small list of 8 GMPEs: the models of Abrahamson and Silva (2008), Akkar and Bommer (2010), Atkinson and Boore (2006), Boore and Atkinson (2008), Campbell and Bozorgnia (2008), Chiou and Youngs (2008), Toro *et al.* (1997), as modified by Toro (2002) and Zhao *et al.* (2006).

We believe that the GMPE pre-selection should be wide enough in order to better capture epistemic uncertainty. Some degree of liberty should also be let for the experts' judgment and the data-based testing. Therefore GMPEs that do not meet all the criteria can be pre-selected, while being conscious of their limitations and weaknesses. We applied this rule for the pre-selection of GMPEs for the each of the tectonic regimes in the Euro-Mediterranean region. These GMPEs are listed in Tables 3.1, 3.2 and 3.3. For the SHARE project, six models have been pre-selected for SCR, eight for SZ, nineteen for ASCR including six regional or local models, one model for volcanic zones (McVerry *et al.* 2006), and one for areas of deep focus non-subduction earthquakes (Sokolov *et al.* 2008). No model for the prediction of ground motions from oceanic crustal earthquakes was available in the international literature, but models for ASCR and SCR have been suggested to account for such seismotectonic regimes.

The pre-selected GMPEs have been analyzed and compared in order to identify their weaknesses and limitations. The following characteristics are particularly important to judge the applicability of a GMPE in a region of interest, regarding the requirements established previously for the seismic hazard calculation: magnitude type and range, distance type and range, spectral frequency range, site classification, style of faulting, horizontal component type, host region and the distinction between interface and inslab earthquakes for subduction zones. Limitations and weaknesses of the pre-selected GMPEs for the SHARE project are given in the second column of Tables 3.1, 3.2 and 3.3.

Finally, a special attention should be paid to the adjustment of the GMPEs so that they can be combined within a logic tree framework. These adjustments concern the horizontal component definition, the style-of-faulting incorporation and the rock definition. Within the SHARE project, horizontal components are converted using the conversion coefficients determined by Beyer and Bommer (2006). For models that do not consider the style of faulting, adjustment factors depending on the proportions of normal and reverse events in the underlying database of each model are applied using the approach proposed by Bommer *et al.* (2003). We followed the method of Van Houtte *et al.* (2011) to adjust hard rock definition used by the GMPEs from SCR (Vs30 > 2000 m/s) to European rock definition (Vs30 around 800 m/s).

Table 3.1. Ground-motion prediction equations for stable continental regions

GMPEs	Limitations	Host region
Atkinson (2008)	-	ENA
Atkinson and Boore (2006)	-	ENA
Campbell (2003)	-	ENA
Douglas *et al.* (2006)	-	Southern Norway
Tavakoli and Pezeshk (2005)	Similar to Campbell (2003)	ENA
Toro *et al.* (1997)	-	ENA

Table 3.2. Ground-motion prediction equations for subduction zones

GMPEs	Limitations	Host region
Atkinson and Boore (2003)	-	Worldwide
Atkinson and Macias (2009)	Only considers large interface earthquakes	Cascadia
Garcia *et al.* (2005)	Only considers inslab earthquakes	Central Mexico
Kanno *et al.* (2006)	-	Japan
Lin and Lee (2008)	-	Northern Taiwan
McVerry *et al.* (2006)	-	New Zealand
Youngs *et al.* (1997)	-	Worldwide
Zhao *et al.* (2006)	-	Japan

Table 3.3. Ground-motion prediction equations for active shallow crustal regions

GMPEs	Limitations	Host region
Abrahamson and Silva (2008)	Many predictive variables	California, Taiwan
Ambraseys *et al.* (2005)	Superseded by Akkar and Bommer (2010)	Europe and Middle East
Akkar and Bommer (2010)	-	Europe and Middle East
Boore and Atkinson (2008)	-	California, Taiwan
Campbell and Bozorgnia (2008)	Many predictive variables	California, Taiwan
Cauzzi and Faccioli (2008)	No saturation term (min. distance is 15 km)	Worldwide
Chiou and Youngs (2008)	Many predictive variables	California, Taiwan
Cotton *et al.* (2008)	No style of faulting and might include subduction earthquakes	Japan
Idriss (2008)	Defined for Vs30 > 450 m/s	California, Taiwan
Kanno *et al.* (2006)	No information about style of faulting	Japan
McVerry *et al.* (2006)	-	New Zealand
Pankow and Pechmann (2004)	-	Extensional regimes
Zhao *et al.* (2006)	-	Japan
Bindi *et al.* (2009)	-	Italy
Danciu and Tselentis (2008)	Uses epicentral distance	Greece
Douglas *et al.* (2006)	-	Southern Spain
Kalkan and Gülkan (2004)	-	Turkey
Massa *et al.* (2008)	Uses epicentral distance and is too local	Northern Italy
Özbey *et al.* (2004)	Uses only data from the 1999 earthquakes in Turkey	Northern Western Turkey

4. EXPERT JUDGMENT

Because of a lack of data, expert judgment has been, until recently, the only method used to select and weigh GMPEs for probabilistic seismic hazard assessment. Although guidance for expert judgment is given by the Senior Seismic Hazard Analysis Committee in Budnitz *et al.*

(1997), there is no clear standard procedure for the selection and weighting of GMPEs by experts.

We have composed a group of six experts working in different countries in academia or public institutions: Julian Bommer (Imperial College, London, UK), Fabian Bonilla (IFSSTAR, Paris, France), Hilmar Bungum (NORSAR/ICG, Kjeller, Norway), John Douglas (BRGM, Orléans, France), Ezio Faccioli (Politecnico di Milano, Milan, Italy) and Nikos Theodoulidis (ITSAK, Thessaloniki, Greece). Six seemed to be a good number, to have enough different points of view without too much redundancy. They were chosen for their great experience with GMPEs (e.g., some of them developed GMPEs) and also for their experience of PSHA in specific countries such as Italy, France, or Greece. Four people of the SHARE ground-motion logic tree group defined the guidelines and the processing of the expert judgment. They asked the experts to propose logic tree weights expressing their degree of belief in the ability of candidate GMPEs to predict earthquake ground motions in each tectonic regime. They were provided with documents summarizing the characteristics of the candidate GMPEs. They had the possibility to propose logic trees depending on magnitude and spectral frequency. Finally, they had five weeks to propose their logic trees, which appeared to be a too short period.

Experts had a common approach: they selected a set of models that enabled them to capture epistemic uncertainty as much as possible. For some of the experts, a small number of GMPEs (two to four) was sufficient (not all models are used although they could be appropriate). On the other hand, some experts selected many or all the candidate GMPEs assigning small weights (< 0.1) for the less favorable ones. Although logic trees are now widely used, we realized that it is not clear yet how weights should be assigned and what they should be assumed to represent. We refer to Scherbaum and Kühn (2011) for a discussion on this subject.

The first conclusion of the experts was that the number of selected GMPEs should be kept as small as possible (between two and five) to prevent the logic tree for ground-motion prediction being too complex, which is especially important for such a wide area considered by the SHARE project. In addition, most of the experts gave weights that are independent of the magnitude, distance, and frequency, except for long periods ($3 \text{ s} < T \leq 10 \text{ s}$) for ASCR. The main motivation behind this choice was to prevent having a discontinuity due to the transition from one logic tree to another one in the uniform hazard spectra produced by PSHA.

The experts selected GMPEs that are sufficiently robust to cover a wide range of magnitudes, distances, and spectral periods. Such GMPEs are indeed better able to capture the magnitude scaling of ground motion that decreases when magnitude increases (Cotton *et al.* 2008; Atkinson and Morrison 2009). Moreover, Bommer *et al.* (2007) strongly recommended not to apply GMPEs outside and even close to their magnitude limits. Global predictive models were preferred as compared to regional ones, as these formers are more likely to incorporate random earthquake effects (biases) into their models. Finally, experts assigned equal weights for the models that they are not familiar with or for which they lack sufficient information.

5. GMPE TESTING BASED ON DATA

To complement the expert judgment described above, testing of the candidate GMPEs against empirical data was undertaken within the SHARE project. The goal of this phase is to judge the applicability of candidate models by evaluating their probability of having generated the available data. We used the data-driven method developed by Scherbaum *et al.* (2009) that proposes an information theoretic approach for the selection and the ranking of GMPEs.

This method derives a criterion according to which GMPEs are ranked. This criterion is the negative average sample log-likelihood noted LLH and defined by:

$$\mathrm{LLH}(\mathrm{g}, \mathrm{x}) = -\frac{1}{N}\sum_{i=1}^{N} Log_2(g(x_i))$$

Where x={x_i}, i=1, …, N are the empirical data and g(x_i) is the likelihood that model g has produced the observation x_i. In the case of GMPE selection, g is the probability density function given by a GMPE to predict the observation produced by an earthquake defined by a magnitude M (and by other characteristics such as the style of faulting) at a site i that is located at a distance R from the source.

We use the LLH divergence as a criterion to rank the candidate GMPEs. Due to its negative sign, the negative average sample log-likelihood is not a measure of closeness but a measure of the distance between a model and the data-generating process (in our case, nature). A small LLH indicates that the candidate model is close to the process that has generated the data while a large LLH corresponds to a model that is less likely of having generated the data.

In order to interpret the rankings, weights obtained from the LLH values can be compared to the uniform weight w_unif=1/M, where M is the number of GMPEs. This comparison tells us to what degree the data support or reject a model with respect to the state of non-informativeness for which a uniform weight would be assigned to all candidate GMPEs (because we have no information about the GMPEs, we do not know them). It is expressed by the data support index (DSI) that gives the percentage by which the uniform weight is increased (positive DSI) or decreased (negative DSI) by the data to be equal to the weights based on LLH values using these data. The DSI of model g_i with LLH-value based weight w_i is:

$$DSI_i = 100\ \frac{w_i - w_{unif}}{w_{unif}}\ \text{, where } w_i = \frac{2^{-LLH(g_i, x)}}{\sum_{k=1}^{K} 2^{-LLH(g_k, x)}}$$

We refer to Delavaud *et al.* (2012a) for a complete introduction of the LLH method. In this paper, the LLH method is applied to evaluate the applicability of GMPEs at a global scale.

Even if larger amounts of data are now available, data remain limited and even very sparse in many regions. Therefore, the use of data should be handled with care, because what will come out of them will reflect the characteristics of the dataset. Results of data-based testing should be presented with the following characteristics of the dataset: distribution in magnitude, distance and spectral frequencies, number of data per earthquake, origin of the data. The dataset should be as homogeneous as possible. Any bias should be identified. For example, if the testing dataset is the same as the dataset used to develop a GMPE, this GMPE will appear better than they really are.

Within the SHARE project, we have evaluated GMPEs for SZ and for ASCR (no data were available for SCR when the project started). We only present here the testing for subduction zones. We refer to Delavaud *et al.* (2012b) for more details on the GMPE testing. For subduction zones, we had available a restricted dataset that only consisted of six inslab strikeslip earthquakes along the Hellenic arc with a total number of 65 recordings (two earthquakes have 22 and 25 observations respectively, the other events have less than 7 observations each). Moment magnitudes of SZ data range from 5.2 to 6.7, their depth mainly varies from 40 to 90 km, and the hypocentral distances are mostly from 70 to 300 km. None of the tested GMPEs used Greek data for their derivations. Rankings have been performed for pseudo-spectral accelerations (PSAs) at spectral periods between 0.05 and 2 s. Table 5 shows the ranking using the chosen spectral periods. We see that the first two models in the ranking are the models of Lin and Lee (2008) and Zhao *et al.* (2006).

Table 5.1. Ranking of the candidate GMPEs for subduction zones based on LLH values for PSA at 0.05, 0.3, 0.5, 0.8, 1, 1.5, and 2 s

Rank	LLH	DSI	Model
1	1.979	29.57	Lin and Lee (2008)
2	1.988	28.76	Zhao et al. (2006)
3	2.206	10.71	Youngs et al. (1997)
4	2.499	-9.64	Kanno et al. (2006)
5	2.500	-9.70	Mc Verry et al. (2006)
6	3.344	-49.70	Atkinson and Boore (2003)

6. DEFINITION OF THE LOGIC TREES

The final logic trees have been determined as a consensus between the results of the expert judgment and the testing.

Models supported by the empirical data testing and the experts' choices were automatically selected. Models that were not supported by the data testing and not chosen by the experts have been rejected. For the rest of the models, discussions were held between the experts and the ground-motion modeling group to decide on their rejection or selection. Weights were also determined but different propositions were retained for sensitivity analyses.

Final logic trees are shown in Figure 3. For SCR, a distinction is made between shield and continental crust for which three GMPEs for ASCR have been added to two SCR models. For SZ and ASCR, four GMPEs have been selected. For ASCR, only two GMPEs will be used for larger periods, as the other selected GMPEs are not valid for such periods. For active regions in oceanic crust, GMPEs from ASCR were chosen. For areas of deep focus non-subduction earthquakes, such as Vrancea (Romania) or the Betics (Spain), we decided to use the GMPEs selected for subduction. Finally, for volcanic zones, it was decided to adopt an approach similar to that implemented in Italy when creating the currently applied set of seismic hazard maps (see Montaldo *et al.* 2005). As different weighting schemes have been proposed, a sensitivity analysis has been conducted to explore the impact of the assigned weights on the final hazard results. A small sensitivity to the weights was observed. The results of this sensitivity study are presented in Delavaud *et al.* (2012b).

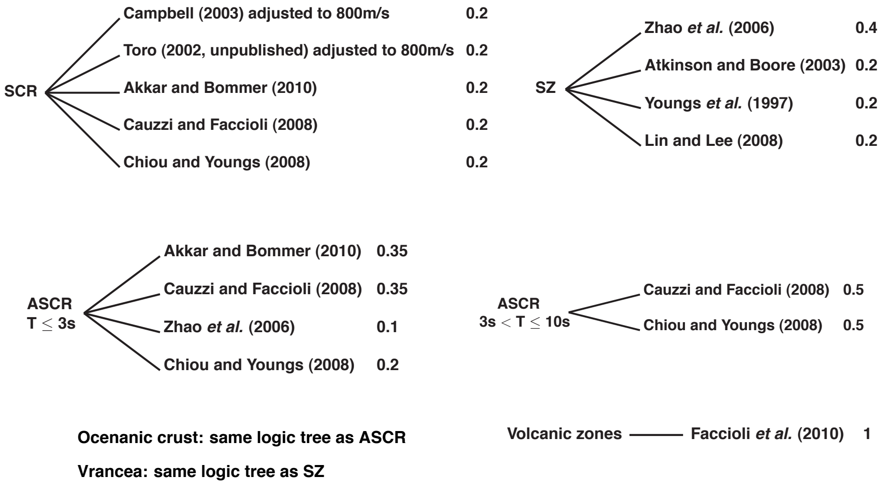

Figure 3. Ground-motion logic trees for the Euro-Mediterranean region

7. CONCLUSION

With this paper, we have presented the strategy adopted within the SHARE project to build a ground motion logic tree for the Euro-Mediterranean region. One logic tree for each of the six tectonic regimes identified in this region has been proposed. The strategy that we have followed is innovative as it includes a testing of candidate GMPEs based on data, in addition to the experts' judgment.

According to our experience, the key element for the construction of a ground motion logic tree is the gathering of as much information as possible from independent sources and different methods. This information can come from experts, from their knowledge and experience, but also from data that are more abundant now. The main challenge for the team responsible for the construction of the logic tree becomes the extraction of this information and its assimilation.

Now that more and more data are available, it is possible to evaluate GMPEs based on data. Scherbaum *et al.* (2009) proposed a method to rank the GMPEs according to their ability to predict the available observations. This tool is powerful but depends on the dataset that is used (e.g., on the distribution in magnitude and distance). Therefore a great effort should be dedicated to the collection of data and meta-data. Data-based testing is not meant to replace the experts but to give additional information. Experts are still needed because they have in particular the knowledge of the behaviour and trend of the GMPEs. This knowledge is crucial to capture epistemic uncertainty.

During this process, we became aware that no clear guidance exists for the construction of a ground-motion logic tree. We wish that our experience that is described in more details in Delavaud *et al.* (2012b) contributes to the definition of such guidance. This is especially important for regions with low seismicity such as France. The regional adaptation of GMPEs proposed by Scasserra *et al.* (2009) and the use of macroseismic intensities to evaluate GMPEs (Delavaud *et al.*, 2012a) could greatly participate to better constrain the construction of a ground motion logic tree in such regions.

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