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Toward a Ground-Motion Logic Tree for Probabilistic Seismic Hazard Assessment in Europe

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Abstract The Seismic HAzard haRmonization in Europe (SHARE) project, which began in June 2009, aims at establishing new standards for probabilistic seismic hazard assessment (PSHA) in the Euro-Mediterranean region. In this context, a logic tree for ground-motion prediction in Europe has been constructed. Ground-motion prediction equations (GMPEs) and weights have been determined so that the logic tree captures epistemic uncertainty in ground-motion prediction for six different tectonic regimes in Europe. Here we present the strategy that we 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. For stable continental regions, two models, both from Eastern North America, have been selected for shields and three GMPEs from active shallow crustal regions have been added for continental crust. For subduction zones, four models, all non-European have been chosen. Finally, for active shallow crustal regions, we selected four models, each of them from a different host region but only two of them were kept for long periods. In most cases, a common agreement has been also reached for the weights. In case of divergence, a sensitivity analysis of the weights on the seismic hazard has been conducted, showing that once the GMPEs have been selected, the associated set of weights has a smaller influence on the hazard.

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1 Introduction

Following the SESAME (Seismotectonics and Seismic Hazard Assessment of the Mediterranean Basin, 1996-2000) project, the Seismic HAzard haRmonization in Europe (SHARE) project (http://www.share-eu.org) is one of the large international research initiatives that have been recently launched to harmonize hazard estimates across political boundaries and to derive procedurally-consistent pan-national hazard models. As a regional program of the Global Earthquake Model (GEM) project (http://www.globalquakemodel.org), the SHARE project aims at defining methods for seismic hazard and loss assessment in the Euro-Mediterranean region which will become standards at global and regional scales.

The team responsible for ground-motion prediction in the SHARE project (WP4 group, see Table 1) has been working on the definition of a reference European model that captures the complete 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.

Within the large geographical area covered by SHARE there is wide variation in terms of the magnitude and distance ranges that influence probabilistic seismic hazard assessment (PSHA). PSHA in Europe is not only controlled by large magnitudes. As a matter of fact, probabilistic disaggregation analyses indicate that in many seismically-active regions of Europe, the seismic hazard for 10% exceedence in 50 years level and short vibration periods (fundamental for Ultimate Limit State verifications of most structures) tends to be controlled by nearby earthquakes (distance < 20 km) in the 4.5-to-5.5 magnitude range. Beauval *et al.* (2008) showed that in active regions of France, magnitudes 4 to 5 are also responsible for a non-negligible contribution to the hazard even for return periods as large as 10,000 years. The above observation is commonly found, for example, for Italian sites in active areas and, obviously, is particularly true for low seismicity regions, i.e. north of the Alps (Faccioli and Villani, 2009). This is why ground-motion prediction equations (GMPEs) that include events with magnitudes down to Mw 4 in their datasets should also be considered. Concerning the influence of the larger magnitudes on hazard, evaluations tend to depend to some extent on the model of earthquake sources adopted, e. g. whether extended zones, or fault sources, or smoothed seismicity. In active regions of Southern Italy (notably the Calabrian Arc), where maximum historical magnitudes exceed 7 and which are certainly among the most active in the Mediterranean area, recent seismic hazard studies for sites lying within source zones indicate that magnitudes > 6.5 in the distance range within 20 km dominate hazard only at return periods of 5000 years and vibration periods of 1 s and larger (Faccioli and Villani, 2009). In such regions, even at return periods as large as 1500 years and at vibration periods of 1 s hazard is typically controlled by magnitudes ≤ 6.0 in the short distance range. On the other hand, again considering Southern Italy, sites lying at few tens of km from the boundaries of model source zones are mostly affected by $M > 6.5$ starting from return periods of 1000 years or so, in the whole range of vibration periods. If smoothed seismicity representations are used instead, things change to some extent, in that - for a given return period - lower magnitudes tend to dominate.

In this paper, we describe the methodology that we adopted to build the logic tree for PSHA in Europe. This process is illustrated in Figure 1. The goal of this strategy is to identify the smallest set of GMPEs to capture the epistemic uncertainty in ground-motion prediction in Europe. The particularity of our approach is that we do not only take into account the judgment of experts to select and rank models but we also use data to guide our choice and weights. Thanks to an increasing amount of strong-motion data, data driven guidance is indeed now feasible and can give valuable information about the ability of GMPEs to predict ground motion in different regions (e.g., Drouet *et al.*, 2007; Allen and Wald, 2009; Delavaud *et al.*, 2012).

The structure of this paper follows the adopted procedure. First, we show how a list of GMPEs for each tectonic regime was selected from the many existing models using exclusion criteria. In a second step, we describe the expert judgment, including the conditions imposed to the experts and the weights that they chose. We pay particular attention to the rationale behind the choices of the experts and expose what we learnt from them. The third step consists in the testing of the candidate GMPEs using data. GMPEs are ranked according to a criteria, the negative average sample log-likelihood, proposed by Scherbaum *et al.* (2009) and based on information theory. In particular, we estimated to what degree the data support or reject a model with respect to the state of non-informativeness defined by uniform weighting. The following section describes how GMPEs were selected taking expert judgment and data testing into account and different sets of weights proposed as a consensus within the SHARE WP4 group. Finally, we present the results of a sensitivity analysis of the weights on hazard maps to help us make a final choice. The goal of this paper is to make the SHARE GMPE logic tree methodology transparent and reproducible.

2 Pre-selection of Ground-Motion Prediction Equations

The pre-selection of GMPEs is first guided by the seismotectonic description of the area covered by the SHARE project (Figure 2). The SHARE source model also influences ground-motion prediction, especially in terms of distance calculation. This 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.

The pre-selection of GMPEs was realized from an already compiled list by Douglas (2008) that contains over 250 published ground-motion models, to retain a subset of the most robust equations for all the existing seismotectonic regimes in the wider European region. Six broad tectonic domains were identified for ground-motion prediction to represent the region covered by the SHARE project (Figure 2): stable continental regions (SCR) include the shield (Baltic) where Precambrian crystalline igneous or metamorphic rocks crop out and is characterized by low wave attenuation and a low deformation rate, and continental crust (most of Europe and Africa) with low deformation rate; oceanic crust include mainly the eastern Atlantic and small patches in the Mediterranean Sea; active shallow crustal regions (ASCR) mainly outline the plate boundaries but occur also in the continental interiors at places with significant rate of deformation; subduction zones (SZ) such as the Calabrian, Hellenic, and Cyprus arcs; areas of deep focus non-subduction earthquakes, such as Vrancea (Romania) or the Betics (Spain); and active volcanoes. For this pre-selection, it was decided to apply the seven exclusion criteria proposed by Cotton *et al.* (2006), briefly: 1. the model is from a clearly irrelevant tectonic regime, 2. the model is not published in an international peer-reviewed journal, 3. the documentation of model and its underlying dataset is insufficient, 4. the model has been superseded by more recent publications, 5. the frequency range of the model is not appropriate for engineering application, 6. the model has an inappropriate functional form and 7. the regression method or regression coefficients are judged to be inappropriate. From the existing GMPEs, six models remained 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 were available in the international literature, but models for ASCR and SCR have been suggested to account for such seismotectonic regimes. The engineering needs, evaluated at the beginning of the project, were taken into account by favoring models well calibrated in the period range between 0.02 s to 10 s. Most of existing models are however not applicable for periods greater than 3 s and, hence, a specific logic tree was built to ensure PSHA computations for periods between 3 s and 10 s.

As a second step, these pre-selected GMPEs have been analyzed and compared in order to identify their weaknesses and limitations in the light of the criteria set proposed by Bommer *et al.* (2010). Considering the rapid increase in published GMPEs for ASCR (in particular), 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. A detailed comparative study between the models of each tectonic regime has been conducted. In particular, they compared the predicted ground-motion amplitudes by the GMPEs for different scenarios (in terms of magnitude, distance and period) and extracted the main characteristics of the models that are summarized in Table 2 for SCR, in Table 3 for SZ and in Table 4 for ASCR. In these tables, we report the type and range for the magnitude and the distance, the spectral period band as well as the inclusion of PGA and/or PGV estimations by the candidate GMPEs. We also indicate whether the site classification is based on a continuous function of v_{S30} or on generic site classes in terms of v_{S30} intervals. The tables also list the horizontal component definitions of the GMPEs that vary among the models. Moreover some of the models do not use style-of-faulting as a predictor variable. In order to combine the GMPEs within a logic tree framework, component and style-of-faulting adjustments have been performed. Horizontal components are converted using the conversion coefficients determined by Beyer and Bommer (2006). For models which 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 in Bommer *et al.* (2003). These factors are given in the tables except for SZ models, which do not explicitly consider the style-of-faulting but differentiate inslab earthquakes from interface earthquakes, taking into account both the mechanism and the depth of the earthquake. The effects of the adjustment strategies are presented in Drouet *et al.* (2010). Finally, we did not take non-linear effects into account as the seismic hazard is computed for rock sites. Our model selection is thus focusing on the rock part of GMPEs.

As a result of the model analysis the members of the WP4 team discussed their concerns about the predictive ability and the weaknesses of the models. Reservations were expressed for the Next Generation Attenuation (NGA) models of Abrahamson and Silva (2008), Campbell and Bozorgnia (2008) and Chiou and Youngs (2008) because they require too many estimator parameters that are not available in all European earthquake-prone regions. This limitation can be partially overcome by using the *a priori* estimations of these unknown input parameters given by the methodology proposed in Kaklamanos *et al.* (2011). Models that suffer from restrictions in the definition of predictive variables were also questioned: the SZ model of Garcia *et al.* (2005) only considers inslab earthquakes, Atkinson and Macias (2009) only consider large interface earthquakes, the NGA model of Idriss (2008) does not cover sites with v_{S30} values less that 450 m/s and finally, Kanno *et al.* (2006) do not provide proportions of normal and reverse faulting events thereby preventing style-of-faulting adjustments. The model of Cotton *et al.* (2008) was also questioned because it does not include style-of-faulting as a predictor variable and they might have included subduction interface events in their ASCR dataset since the selection of earthquakes was based on focal depth only. Finally, reservations were expressed for the models of Tavakoli and Pezeshk (2005) and of Ambraseys *et al.* (2005) as they are similar to Campbell (2003) and Akkar and Bommer (2010) respectively, and for the model of Özbey *et al.* (2004) which was derived from data from the 1999 earthquakes in Turkey that were recorded within a limited area. Although these GMPEs suffer from the above restrictions, they were considered by the experts and in the testing.

There are obviously large differences in terms of number of GMPEs between the three tectonic regimes and also in terms of their host regions. For stable continental regions, all the GMPEs except Douglas *et al.* (2006) were derived from eastern North America (ENA) data whereas ASCR regime includes GMPEs from all over the world (although mainly California, Europe and Japan). The selection for subduction zones includes no European candidate ground-motion model.

Finally, we acknowledge that the pre-selected GMPEs may not be calibrated homogeneously in all the parameter space relevant for PSHA in Europe, especially for low magnitudes (Mw < 5). The development of new GMPEs was beyond the scope of the present project and for this reason and the lack of homogeneous local datasets we have not applied the calibration of existing models using local data, e.g. following the method by Scasserra *et al.* (2009). We recognize that there is a need to start to apply these new methods, at least in Turkey and Italy, where local data are available.

The pre-selected GMPEs have been subsequently evaluated in two parallel steps. In one approach, a group of experts were asked to propose the logic tree weights for these GMPEs. In the other approach, ground-motion records, whenever available, were used to test the ability of the GMPEs to model the overall trends of the ground motions in each tectonic region. We present now these two complementary approaches.

3 Expert judgment

Since the 1970s, there has been an increasing interest in the use of expert judgment to help in decision making by formalizing and quantifying expert judgment on problems that involve uncertainties (e.g., Cooke, 1991; Goossens *et al.*, 2000). Private agencies as well as academia have recourse to this approach especially when data are unavailable or inadequate, and this is why it 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 (SSHAC) in Budnitz *et al.* (1997), there is no clear standard procedure for the selection and weighting of GMPEs by experts. In this section, we present the strategy that we adopted for the determination of logic-tree weights from a group of experts.

We composed a group of six experts working in five different countries in academia or public institutions in

Europe (see Table 1). 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 (the first four authors of the present paper) defined the guidelines and the processing of the expert judgment. We 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 different tectonic regimes in Europe. We did not guide the experts in how to assign their weights (e.g., whether all GMPEs should be weighted or not), since no clear methodology was available at that time. However, we asked them to explain the rationale behind their weighting strategy. Weights had to be assigned for each tectonic regime (with a differentiation between shield and continental crust for SCR and between interface and inslab earthquakes for SZ) for different ranges in spectral frequency (f), magnitude (Mw) and distance (d): $f \leq 1/3$ Hz, $1/3$ Hz $< f \leq 25$ Hz or $f > 25$ Hz, $Mw \leq 5$ or $Mw > 5$ and $d \leq 10$ km, 10 km $< d \leq 100$ km, 100 km $< d \leq 200$ km or $d > 200$ km. By doing so, we wanted to see whether or not the experts would consider the frequency-magnitude-distance dependency for the logic-tree weights. Finally, the experts did not communicate with each other to have independent alternatives for logic-tree weights. They also did not know about the testing results conducted by using the empirical data (see next section). However, they were provided with the characteristics of the GMPEs are presented.

A lesson that we learned from the experts is that assigning weights to GMPEs is not straightforward, especially for such a large number of models and with distinctions in terms of frequency, magnitude and distance. We also realized that the time limit imposed for the entire decision process was quite limited for this task (five weeks). In particular, some experts raised the possibility of assigning zero weights to some of the GMPEs, indirectly raising the question of what logic tree weights represent. This led to a lively discussion between the WP4 members and the experts during a meeting where experts presented their weighting strategy. Experts had a common approach: they selected a set of models which 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. Scherbaum and Kühn (2011) recently showed the importance of treating logic tree weights as probabilities instead of simply as generic quality measures of GMPEs, which are subsequently normalized. In particular, they show the danger of using a performance/grading matrix approach (independently assigning of grades to different quality criteria) where the normalization process can lead to an apparent insensitivity to the weights. In order to achieve consistency with a probabilistic framework, Scherbaum and Kühn (2011) proposed to assign weights in a sequential fashion (e.g., if the first GMPE of three selected gets a 0.6 weight, then the sum of the weights for the two remaining models is 0.4).

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 s $< T \leq$ 10s) 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 which 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. Finally, GMPEs developed from limited datasets are more likely to incorporate random earthquake effects (biases) into their models. Therefore, global predictive models were preferred as compared to regional ones. Finally, experts assigned equal weights for the models that they are not familiar with or for which they lack sufficient information.

For stable continental regions, selecting the models was a particular challenge as all but one are derived for ENA and inadequate information about their applicability for Europe is known. Experts made no distinctions between shield and continental crust. Of the six GMPEs proposed for SCR, the expert selection ranged between retaining three or all six. The SCR models by Campbell (2003) and Toro *et al.* (1997) were selected by all experts. The choice of GMPEs for subduction zones was also a challenging task since none of the pre-selected GMPEs were derived using empirical data from Europe. Due to this particular reason, the experts preferred choosing the global SZ models that cover a wide range of magnitude and distance intervals. Only one expert considered interface and inslab models separately in ranking whereas three experts considered the spectral period ranges while assigning weights. The experts selected two to five GMPEs among the eight models proposed for SZ. Only one model was selected by all the experts, the model of Atkinson and Boore (2003). Contrary to the SCR and SZ regions, the excessive number of GMPEs for the shallow crustal active regions challenged the expert judgment. Regional ASCR models (e.g., Massa *et al.*, 2008; Kalkan and Gülkan, 2004; Danciu and Tselentis, 2008) were either excluded or given small weights (less than 0.1). The expert choices lean towards global and pan-European models in the ranking of ASCR GMPEs. Of the entire expert group only two of them considered magnitude-distance-frequency ranges while assigning weights. The experts selected between three to ten GMPEs among the 18 candidate models. The GMPEs by Akkar and Bommer (2010) and of Boore and Atkinson (2008) were the commonly selected models by all experts. Tables 8, 9 and10 summarize the choice of each expert for the three tectonic regimes under the section *Category based on expert judgment.*

4 Data Testing

To complement the expert opinions described above, testing of the candidate GMPEs against empirical data was undertaken. The goal of this phase was to judge the applicability of candidate models by evaluating their probability to have generated the available data. We used the data-driven method developed by Scherbaum *et al.* (2009) that implemented an information-theoretic approach for the selection and the ranking of GMPEs. The method derived a ranking criterion from the Kullback-Leibler (KL) divergence, which denotes the information loss when a model g defined as a distribution is used to approximate a reference model f (Burnham and Anderson, 2002). The KL divergence between two models represented by their probability density functions f and g is defined as:

$$D(f,g) = E_f\left[log_2(f)\right] - E_f\left[log_2(g)\right] \tag{1}$$

where E_f is the statistical expectation taken with respect to f.

In the case of GMPE selection, f represents the data-generating process (nature) and is only known through observations. Consequently, the term $E_f\left[log_2(f)\right]$ called the self-information of f cannot be calculated. However, the second term, $-E_f\left[log_2(g)\right]$, can still be approximated via the observations. This approximation is the negative average sample log-likelihood, noted LLH and defined by:

$$\mathrm{LLH}(g,\mathbf{x}) := -\frac{1}{N}\sum_{i=1}^{N} log_2\left(g(x_i)\right) \tag{2}$$

where $\mathbf{x} = \{x_i\}$,$i = 1, ..., N$ 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 used 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. 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 were compared to the uniform weight $w_{\mathrm{unif}} = \frac{1}{M}$, 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. It is expressed by the data support index (DSI) which gives the percentage by which the weight of a model is increased (positive DSI) or decreased (negative DSI) by data. The DSI of model g_i with LLH-value based weight w_i is:

$$\mathrm{DSI}_i = 100 \ \frac{w_i - w_{\mathrm{unif}}}{w_{\mathrm{unif}}}\ , \tag{3}$$

where

$$w_i = \frac{2^{-\mathrm{LLH}(g_i,\mathbf{x})}}{\sum_{k=1}^{K} 2^{-\mathrm{LLH}(g_k,\mathbf{x})}} \tag{4}$$

This ranking method has been recently used by Delavaud *et al.* (2012) to test the global applicability of GMPEs for active shallow crustal regions. The LLH divergence was computed for eleven GMPEs for different regions and magnitude and distance ranges to assess their validity domain.

The LLH-based weights defined by eq. (4) cannot be automatically regarded as probabilities as the LLH values are independently determined for each model (Kolmogorovs axioms of mutual exclusiveness and collective exhaustiveness are not respected) and only subsequently made to sum up to one (see Scherbaum and

Kühn, 2011 for more details about this subject). Therefore, we advise not to directly use them as logic tree weights but to use them in combination with expert judgment. The purpose of using empirical data was not to replace expert judgment but rather to help the judgment process by providing additional information about the applicability of GMPEs, especially in regions where no indigenous model exists.

Although the amount of empirical ground-motion data is rapidly increasing worldwide, we faced some limitations while testing GMPEs with the compiled data. We considered the distribution of empirical ground-motion data in terms of magnitude and distance. We also accounted for the reduction in available data size in terms of their usable period range in order to reduce the filter cut-off influence on the spectral ordinates. The country-based distribution of the data was also considered to examine the similarities between the original datasets of the tested GMPEs and our database used for testing these GMPEs because we wanted to prevent biased evaluations due to similarities between our dataset and those of the GMPEs.

A homogenous dataset was not available for SCR and, therefore no tests for this tectonic regime were made.

For subduction zones, we had available a restricted dataset that only consisted of inslab strike-slip earthquakes along the Hellenic arc with a total number of 65 recordings. Moment magnitudes of SZ data range from 5.2 to 6.7, their depth mainly varies from 40 km to 90 km and the hypocentral distances are mostly from 70 km to 300 km. All the GMPEs from Table 3 have been tested against this Greek dataset except for the models of Atkinson and Macias (2009) and Garcia *et al.* (2005). The former model only considers interface events with magnitudes greater than 7.5 whereas the latter model is only derived for inslab earthquakes and hence its applicability for PSHA is limited. 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 s and 2 s. Table 5 shows the ranking using the chosen spectral periods. The first 2 models in the ranking are the models of Lin and Lee (2008) and Zhao *et al.* (2006). These modes were derived from the data pertaining to Northern Taiwan and Japan, respectively. They are equally supported by the Greek data with a DSI of about 29% each. On contrary, the global model of Atkinson and Boore (2003) appears particularly inconsistent with the present Greek dataset with a DSI of about -50%. The Atkinson and Boore (2003) model was sensitive to the changes in the period range considered as it predicted the Greek ground motions fairly well for periods below 0.16s. The overall results of the testing for subduction zones are summarized in Table 9 under the section *Category based on data-testing results*. They are presented in more detail in Beauval *et al.* (2012).

For active shallow crustal regions, we considered two databases that are composed of recordings from Europe (DB1) and from other ASCR around the world (DB2). The majority of recordings in DB1 are in the magnitude and distance range: $4 < \mathrm{Mw} < 7$ and $1\ \mathrm{km} < \mathrm{RJB} < 200$ km, respectively. Due to the lack of large magnitude events in DB1, GMPEs were also tested against DB2 which is mainly composed of magnitudes between 6 and 8. The main assumption while running these analyses was the weak regional dependence of GMPEs. Both databases were extracted from the SHARE strong-motion databank (Akkar *et al.*, 2010) that is compiled from various original databases (Ambraseys *et al.*, 2004; Luzi *et al.*, 2008; Chiou *et al.*, 2008; Cotton *et al.*, 2008; Sandikkaya *et al.*, 2010;). The European dataset is presented in Figure 3. It contains 1533 recordings, mainly from Turkey. The major reason for the larger number of Turkish recordings is the fact that the other European databases do not contain site classification in terms of v_{S30} and lack complete information on some of the distance measures used by the candidate GMPEs. Other observations mostly come from Italy and Greece. The non-European dataset is presented in Figure 4. It mostly contains recordings from the USA and Taiwan that were extracted from the NGA database. Rankings based on PSAs at five spectral periods (0.1 s, 0.2 s, 0.5 s, 1 s and 2s) are presented in Tables 6 and 7 for DB1 and DB2 respectively. A total of 14 GMPEs have been tested: all the models in Table 4 except for the GMPEs of Idriss (2008), Kanno *et al.* (2006), Özbey *et al.* (2004), McVerry *et al.* (2006) and Pankow and Pechmann (2004). The Italian model of Bindi *et al.* (2010) is ranked first, closely followed by two non-European models, Cauzzi and Faccioli (2008) and Cotton *et al.* (2008), with DSIs larger than 60%. The testing results of the Akkar and Bommer (2010) model appear to be quite robust as it is well ranked for both datasets DB1 and DB2. The model of Kalkan and Gülkan (2004) and the NGA models are better able to predict ground motions from the large earthquakes that compose DB2 than ground motions from DB1. The results of the data testing for active shallow crustal regions are summarized in Table 10 under the section *Category based on data-testing results.*

5 Ground-Motion Logic Tree

Based on the results of both the expert judgment and the testing, a consensus set of GMPEs was determined for each tectonic regime. Tables 8, 9 and 10 were used to guide the selection, especially when expert judgment and empirical data testing results were available. Models supported by the empirical data testing and the experts' choices (first category) were selected while the models that were not supported by the data testing and not chosen by the experts (fourth category) have been rejected. For rest of the models (second and third categories), discussions were held between the experts and ground-motion modeling group to decide on their rejection or selection. Weights were also determined but different propositions were retained for sensitivity analyses.

For stable continental regions, for which no testing could be performed due to a lack of data, a distinction between shield and continental crust was taken into account. For shields, the two models supported by all the experts were selected with equal weights: Toro (2002) model which is an updated version of Toro *et al.* (1997) and the model by Campbell (2003). For continental crust, three GMPEs for ASCR were adopted (Akkar and Bommer, 2010; Cauzzi and Faccioli, 2008; Chiou and Youngs, 2008) in addition to the models of Toro (2002) and Campbell (2003). This accounts for uncertainty in knowing if ground motions in continental crust are more like those in ASCR or in SCR. Equal weights were assigned to the five GMPEs selected for continental crust. The Toro (2002) and Campbell (2003) models were decided to be adjusted for the generic rock site condition in Europe, established within the framework of SHARE project, that is described with a shear-wave velocity of $v_{\mathrm{rock}} = 800$ m/s and $\kappa = 0.03$ following Van Houtte *et al.* (2011). The proposed weighting scheme for SCR is presented in Table 8.

For subduction zones (Table 9), the results of the empirical data testing and the choices of the experts were quite divergent. Only the model of Zhao *et al.* (2006) was supported by the majority of experts and the data-testing results. This model has been selected. The McVerry *et al.* (2006) model was neither supported by the experts nor the empirical data testing and consequentially it was rejected. The models of Atkinson and Boore (2003) and Youngs *et al.* (1997) that were the consensus selection of the experts as well as the Lin and Lee (2008) and Zhao *et al.* (2006) models that were ranked the best in the testing were considered in the weighting scheme. A weight of 0.4 was assigned to the Zhao *et al.* (2006) model whereas the other 3 models were weighted equally with 0.2. An other weighting scheme where the four selected GMPEs have equal weights has been proposed. We decided to make a sensitivity study to investigate the differences between the two weighting schemes. No difference in weights between interface and inslab earthquakes was made, due to a lack of data. However, this may be a critical issue in PSHA and further research is needed in the future. The proposed weighting schemes are presented in Table 9.

For active shallow crustal regions (Table 10), two models were supported by both the experts and the empirical data testing: the models of Akkar and Bommer (2010) and Cauzzi and Faccioli (2008). These models were directly considered in the logic-tree weighting scheme. In addition, we selected two other models: the Zhao *et al.* (2006) model, which was favored by the majority of the experts, and the NGA model of Chiou and Youngs (2008), which was supported by the testing using non-European recordings. This selection is in agreement with the recent study conducted by Delavaud *et al.* (2012) to test the global applicability of GMPEs using the global dataset of Allen and Wald (2009). For PGA and PSA at 1 Hz in Europe and the Middle East, the four best-ranked models according to Delavaud *et al.* (2012) are the models of Akkar and Bommer (2010), Chiou *et al.* (2010), Cauzzi and Faccioli (2008) and Berge-Thierry *et al.* (2003) that are followed by the models of Chiou and Youngs (2008) and Zhao *et al.* (2006). Note that the model of Chiou *et al.* (2010) is an extension of the Chiou and Youngs (2008) model for small-to-moderate magnitudes. It is consistent with the Chiou and Youngs (2008) model for large magnitudes ($\mathrm{Mw} \geq 6$) but has new coefficients for smaller magnitudes.

This result suggests that Delavaud *et al.* (2012) would have ranked first the four models that we selected for ASCR if they had not considered the model of Chiou *et al.* (2010) and the model of Berge-Thierry *et al.* (2003). The model of Chiou *et al.* (2010) was not published when we started the selection of GMPEs. It is also defined only for a limited number of periods. We considered moreover that the model of Berge-Thierry *et al.* (2003) is obsolete. For longer periods, between 3 s and 10 s, only the models of Cauzzi and Faccioli (2008) and Chiou and Youngs (2008) were selected and given equal weights (0.5) because the Akkar and Bommer (2010) and Zhao *et al.* (2006) models are not defined for periods up to 10 s. For periods lower than 3s, different weighting schemes have been proposed, as shown in Table 10. The weighting scheme WS6 was however preferred, that assigns higher weights to the two models that are supported by both the experts and the empirical data testing. It was also decided to make a sensitivity analysis to better understand the influence of the weights on the computed hazard.

For active regions in oceanic crust, GMPEs from ASCR were chosen (Table 11). 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 instead of the empirical model of Sokolov *et al.* (2008), which is directly derived from the recordings of Vrancea. The model by Sokolov *et al.* (2008) is too complex for regional PSHA because it models azimuthal variations of ground motion (Table 12). 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)) rather than using the model of McVerry *et al.* (2006), which only seeks to model higher attenuation in volcanic zones rather than ground motions from volcano-related events. This approach consists of introducing separate GMPEs within a seismic source zone of limited extension surrounding a volcano with well-documented historical evidence of damaging earthquakes, such as the Mount Etna volcano, in Sicily. Such GMPEs should be able to deal with events of shallow focal depth, from 2 to 5 km. An analysis expressly carried out on acceleration records from recent moderate earthquakes ($3.2 < M_w < 4.5$) of recent years in Italy, notably in the Mount Amiata (southern Tuscany) and Mount Etna areas, has shown that the use of the recent attenuation model of Faccioli *et al.* (2010) was appropriate, and its adoption was therefore agreed to by WP4 of SHARE (Table 13).

With logic trees containing between two and five GMPEs for each tectonic regimes (except for volcanic zones), the SHARE WP4 group, aimed at better taking epistemic uncertainties into account. In comparison, for the SESAME project which provided the first homogeneous assessment of seismic hazard for the whole Mediterranean region, only three GMPEs were considered: the model of Ambraseys *et al.* (1996) for all crustal sources, the model of Musson (1999) for Vrancea and the model of Papaioannou and Papazachos (2000) for intermediate-depth seismic activity sources in the Hellenic Arc (Jiménez *et al.*, 2001).

6 Sensitivity Analysis

Logic tree and sensitivity analyses are generally run simultaneously. The results of a preliminary sensitivity analysis usually offer guidance for an iterative revision of the final logic tree structure (Scherbaum *et al.*, 2005; Bommer and Scherbaum, 2008). As different weighting schemes were proposed for SZ and ASCR, a sensitivity analysis was necessary to explore the impact of the assigned weights on the final hazard results. We briefly report the main results of this analysis and refer to Danciu (2011) for more details.

The sensitivity analysis was performed by considering the selected GMPEs for each tectonic regime (as presented in Tables 9 and 10) and a set of fictitious seismic sources. Two types of seismic sources were considered: an area source zone (ASZ) and a fault source (FS). A fictitious ASZ was used to simulate the seismicity in an ASCR and also on subduction intraslab sources. A virtual FS was used to model an active shallow crustal fault as well as a subduction interface source.

Four ground motion intensity measures were considered: peak ground acceleration, peak ground velocity (PGV) and pseudo-acceleration spectra at the spectral periods of 0.2s and 1.0s. Seismic hazard maps for each weighting scheme were obtained for two reference return periods: 475 and 2475 years; the former corresponding to 10% probability of exceedance in 50 years, and the latter indicates a 2% probability of exceedance in 50 years. Additionally, individual hazard maps for each GMPE were produced. All the resulting hazard maps were estimated for a reference rock site, defined by $v_{S30} = 800\text{m/s}$. The seismic hazard software (Pagani *et al.*, 2010) developed within the prototype of GEM, namely the GEM1 project, was used for the calculations. Details of the source characterization and hazard calculation settings are presented in more detail in Danciu (2011).

The difference between the hazard maps of the preferred weighting schemes and those computed from alternative weights was quantified by the mean of the percentage differences. Percentage difference for each grid point was computed by:

$$\text{PerDiff}(\%) = \frac{\text{WS}_{(\text{proposed})} - \text{WS}_{(\text{preferred})}}{\text{WS}_{(\text{preferred})}} \times 100 \qquad (5)$$

where $\text{WS}_{(\text{preferred})}$ are the estimated expected ground motion at each grid point from the preferred weighting scheme and $\text{WS}_{(\text{proposed})}$ contains the values using the alternative weighting schemes. For example, for active crustal regions the preferred weighting scheme is WS6 and the alternative weighting schemes are WS1, WS2, WS3, WS4, WS5 and WS7 as reported in Table 10. Maps showing the percentage difference were produced for all ground-motion intensity measures and for the specified return periods. Due to the limited space, the percentage difference maps are not reproduced herein but a summary of the percentage differences for PGA, PSA (0.2s) and PSA (1s) for different weighting schemes are summarized in Table 14 for ASCR and in Table 15 for SZ.

For ASCR, the sensitivity analysis shows that the absolute difference between the preferred and the proposed weighting schemes varies within the range of 5% to 10% for the ASZ and 5 to 15% for the FS. Most of the differences occur when the proposed weighting scheme

WS7 is compared with the preferred one (WS6). The examination of individual hazard maps for each selected GMPE suggest that the equations proposed by Akkar and Bommer (2010) and Chiou and Youngs (2008) dominate the hazard in the areal zones of active shallow crustal tectonic regimes because they yield higher values when compared to the other remaining two GMPEs (roughly 30% larger). Cauzzi and Faccioli (2008) and Chiou and Youngs (2008) predict larger ground motions in shallow crustal fault sources (roughly 60% larger than the other two GMPEs), thus dominating the hazard for such cases.

In the case of subduction zone the percentage difference varies between 4 and 10%. The differences decrease with increasing period values for subduction inslab sources. Contrary to this observation the hazard differences become larger as the vibration period increases for subduction interface cases. By contrast, for subduction interface sources the difference increases as the return periods increase. Zhao *et al.* (2006) and Youngs *et al.* (1997) were found to be responsible for the larger values in the seismic hazard for the subduction sources (predicting roughly six times larger ground motions than the other two GMPEs).

The overall results of the sensitivity analysis on different weighting schemes suggest that for the considered seismic sources there is a moderate impact on the hazard results. Sabetta *et al.* (2005) also concluded that if four or more GMPEs are used in the logic tree, the assigned weights do not significantly affect the hazard results. Scherbaum *et al.* (2005) also indicated that the selection of the GMPEs seems to be more important than the choice of weighting strategy.

In essence, the practical conclusion of this preliminary sensitivity analysis led us to keep the present structure of the ground motion logic tree together with the preferred weights.

7 Conclusions

Although it is now common practice to treat uncertainty in ground motion prediction with a logic tree approach, there is no standard procedure that describes how the tree should be constructed. In this paper, we shared our experience on this subject by presenting the strategy that was adopted to build a logic tree for Europe within the SHARE project. This task involved roughly a dozen institutions with the goal, in a limited amount of time (18 months), to commonly define a logic tree that would capture the center, body and range of ground motion in six different tectonic regimes in the Euro-Mediterranean region.

The principal idea that guided our strategy was to gather as much knowledge as possible from independent sources and different methods. Based on the characteristics of the available GMPEs determined by Douglas (2008), recently updated by Douglas (2011), we first identified the best candidates using the rejection criteria of Cotton *et al.* (2006) and Bommer *et al.* (2010). Afterwards, expert judgment highlighted sets of GMPEs that were, according to the experts, capable of capturing epistemic uncertainties, while testing using observational data showed GMPEs capable of closely predicting past ground motions. The integration of these different approaches was undertaken to propose logic trees that were then subjected to a sensitivity analysis to see the impact on the seismic hazard.

From this experience, we have learnt lessons and identified weaknesses in our methodology. First a great effort should be dedicated to the collection of data and meta-data in order to get as much information as possible from the GMPE testing. In our case, data were not sufficient to cover the center, body and range of ground motions in Europe. Secondly, the procedure for the selection and weighting of GMPEs by experts should be clearly defined. Within the SHARE project, most experts required more guidance and information (e.g., what do weights represent?, how will they be used afterwards?). Selecting GMPEs and assigning weights is still not an obvious task, although Scherbaum and Kühn (2011) have recently proposed a method. To build a logic tree is not to give a quality measure to each candidate GMPE independently from the others but rather to identify the set of models that together, with a certain weighting, can capture the perceived epistemic uncertainty. In the context of the SHARE project that covers a large area, the set of GMPEs had to be the smallest one.

The robustness of the proposed logic tree is a crucial property. For ASCR, the SHARE GMPE selection is in agreement with the data testing of Delavaud *et al.* (2012) who used an independent dataset to rank candidate GMPEs for Europe and Middle East. Their study also showed that for this particular dataset, the recent model of Chiou *et al.* (2010) but also the model of Berge-Thierry *et al.* (2003) were both able to predict ground motion in Europe and Middle East reasonably well. Regular updates of the logic tree should be planned to take new data and new GMPEs into account.

Each project is unique and it is important to be aware of its particularities. However, we think that the procedure described above is reproducible and that at least it contributed to the reflections on the way a logic tree for ground-motion prediction should be built.

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Table 1 SHARE WP4 group involved in the building of the logic tree for ground-motion prediction.

Coordinators and Methodology definition	Elise Delavaud	ISTerre, Grenoble, France / ETH, Zürich, Switzerland
	Fabrice Cotton	ISTerre, Grenoble, France
	Sinan Akkar	METU, Ankara, Turkey
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	Fabian Bonilla	IFSSTAR, Paris, France
	Hilmar Bungum	NORSAR/ICG, Kjeller, Norway
	John Douglas	BRGM, Orléans, France
	Ezio Faccioli	Politecnico di Milano, Milano, Italy
	Nikos Theodoulidis	ITSAK, Thessaloniki, Greece
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	Céline Beauval (Data testing)	ISTerre, Grenoble, France
	Stéphane Drouet (Models pre-selection)	ISTerre, Grenoble, France
	John Douglas (Models pre-selection)	BRGM, Orléans, France
	Roberto Basili (Zonation map)	INGV, Roma, Italy
	Abdullah Sandikkaya (Data testing)	METU, Ankara, Turkey
	Margaret Segou (Data testing)	METU, Ankara, Turkey
	Ezio Faccioli (Volcanic zones)	Politecnico di Milano, Milano, Italy
	Nikos Theodoulidis (Data testing)	ITSAK, Thessaloniki, Greece
	Donat Fäh	ETH, Zürich, Switzerland
	Benjamin Edwards	ETH, Zürich, Switzerland
	Pierre-Yves Bard	ISTerre, Grenoble, France
	Kyriazis Pitilakis	University of Thessaloniki, Thessaloniki, Greece
	Marco Pagani	GEM Foundation, Pavia, Italy

Table 3 Description of the ground-motion prediction equations for subduction areas.

Name	Mag Type	Mag	Dist Type[1]	Dist [km]	Depth [km][2]	Period [s] + PGA and/or PGV	Site Classification based on v_{S30}[3]	sof[2]	H Comp Type[4]	Main region(s)
Atkinson and Boore (2003)	M_w	5.5 - 8.3	RUP	11 - 550	F:0-50, B:0-120	0.04 - 3.0 + PGA	4 classes	F, B	Random	Worldwide
Atkinson and Macias (2009)	M_w	7.5 - 9.0	RUP	30 - 400	6-60	0.05 - 10.0 + PGA	760 m/s	F	GMEAN	Cascadia
Garcia *et al.* (2005)	M_w	5.2 - 7.4	RUP	4 - 400	35-138	0.04 - 5.0 + PGA	1 classe	B, normal events	GMEAN	Central Mexico
Kanno *et al.* (2006)	M_w	5.5 - 8.0	RUP	30 - 450	F:0-30, B:30-185	0.05 - 5.0 + PGA	cont. function	F, B	VectComp	Japan
Lin and Lee (2008)	M_w	4.1 - 8.1	HYP	15 - 630	F:5.54-30, B:39.9-161	0.01 - 5.0 + PGA	2 classes	F, B	GMEAN	Northern Taiwan
McVerry *et al.* (2006)	M_w	5.08 - 7.09	RUP	6 - 400	F:10-25, B:25-150	0.075 - 3.0 + PGA	3 classes	F, B	GMEAN	New Zealand
Youngs *et al.* (1997)	M_w	5.0 - 8.2	RUP	8.5 - 550.9	F:10-50, B:13-229	0.075 - 3.0 + PGA	2 classes	F, B	GMEAN	Worldwide
Zhao *et al.* (2006)	M_w	5.0 - 8.3	RUP	0 - 300	F:10-50, B:20-122	0.05 - 5.0 + PGA	5 classes	F, B	GMEAN	Japan

[1] RUP: rupture, HYP: hypocentral distance (Abrahamson and Shedlock, 1997)
[2] B: inslab earthquakes, F: interface earthquakes
[3] cont. function: continuous function of v_{S30}
[4] Horizontal component type. GMEAN: geometric mean, VectComp: vectorial composition

Table 2 Description of the ground-motion prediction equations for stable continental regions.

Name	Mag Type	Mag	Dist Type[1]	Dist [km]	Period [s] + PGA and/or PGV	Site Classification based on v_{S30}	sof[2] or pN, pR[3]	H Comp Type[4]	Main region(s)
Atkinson (2008)	M_w	4.3 - 7.6	RJB	10 - 1000	0.1 - 5.0 + PGA, PGV	760 m/s	N, R, S, U	GMRotI50	ENA
Atkinson and Boore (2006)	M_w	3.5 - 8.0	RUP	1 - 1000	0.025 - 5.0 + PGA, PGV	2000 m/s, 760 m/s	0.01, 0.81	GMEAN	ENA
Campbell (2003)	M_w	5.0 - 8.2	RUP	0 - 1000	0.02 - 4.0 + PGA	2800 m/s	0.01, 0.81	GMEAN	ENA
Douglas *et al.* (2006)	M_w	4.5 - 7.5	RJB	1 - 1000	0.02 - 2.0	2800 m/s	N, R, S	GMEAN	Southern Norway
Tavakoli and Pezeshk (2005)	M_w	5.0 - 8.2	RUP	0 - 1000	0.05 - 4.0 + PGA,	2900 m/s	0.01, 0.81	GMEAN	ENA
Toro *et al.* (1997)	M_w	5.0 - 8.0	RJB	1 - 1000	0.03 - 2.0 + PGA	2800 m/s	0.01, 0.81	GMEAN	ENA

[1] RUP: rupture, RJB: Joyner-Boore distance (Abrahamson and Shedlock, 1997)
[2] Style-of-faulting: N: normal, R: reverse, T: thrust, U: undefined
[3] pN: proportion of normal faulting, pR: proportion of reverse faulting needed for the style of faulting adjustment method of Bommer *et al.* (2003)
[4] Horizontal component type. GMEAN: geometric mean, GMRotI50: new geometric mean used in the PEER NGA Project

Table 4 Description of the ground-motion prediction equations for active crustal regions.

Name	Mag Type	Mag	Dist Type[1]	Dist [km]	Period [s] + PGA and/or PGV	Site Classification based on v_{S30}[2]	sof[3] or pN, pR[4]	H Comp Type[5]	Main region(s)
Abrahamson and Silva (2008)	M_w	5.0 - 8	RUP	0 - 200	0.01 - 10 + PGA,PGV	cont. function	N, R/T, S	GMRotI50	California, Taiwan
Ambraseys *et al.* (2005)	M_w	5.0 - 7.6	RJB	0 - 99	0.05 - 2.5 + PGA	3 classes	N, R/T, S, O	LRGENV	Europe and Middle East
Akkar and Bommer (2010)	M_w	5.0 - 7.6	RJB	0 - 99	0.05 - 3.0 + PGA, PGV	3 classes	N, R/T, S	GMEAN	Europe and Middle East
Boore and Atkinson (2008)	M_w	4.27 - 7.9	RJB	0 - 280	0.01 - 10.0 + PGA, PGV	cont. function	N, R, S, U	GMRotI50	California, Taiwan
Campbell and Bozorgnia (2008)	M_w	4.27 - 7.9	RUP	0.07 - 199.27	0.01 - 10.0 + PGA, PGV	cont. function	N, R, S	GMRotI50	California, Taiwan
Cauzzi and Faccioli (2008)	M_w	5.0 - 7.2	HYP	15 - 150	0.05 - 20 + PGA	4 classes or cont. function	N, R/T, S	GMEAN	worldwide
Chiou and Youngs (2008)	M_w	4.27 - 7.9	RUP	0.2 - 70	0.01 - 10.0 + PGA, PGV	cont. function	N, R, S	GMRotI50	California, Taiwan
Cotton *et al.* (2008)	M_w	4.0 - 7.3	RUP	5 - 100	0.01 - 3.33	4 classes	0.0525, 0.3150	GMEAN	Japan
Idriss (2008)	M_w	4.5 - 7.7	RUP	0 - 200	0.01 - 10 + PGA	2 classes	N, R/T, S	GMRotI50	California, Taiwan
Kanno *et al.* (2006)	M_w	5.0 - 8.2	RUP	1 - 450	0.05 - 5.0 + PGA	cont. function	No information	VectComp	Japan
McVerry *et al.* (2006)	M_w	5.08 - 7.09	RUP	6 - 400	0.075 - 3.0 + PGA	3 classes	N, R/T, S	GMEAN	New Zealand
Pankow and Pechmann (2004)	M_w	5.0 - 7.0	RJB	0 - 100	0.1 - 2.0 + PGA	2 classes	0.45, 0.00	GMEAN	Extensional regime
Zhao *et al.* (2006)	M_w	5.0 - 8.3	RUP	0 - 300	0.05 - 5.0 + PGA	5 classes	N, R, S	GMEAN	Japan
Bindi *et al.* (2010)	M_w	4.0 - 6.9	RJB	2.8 - 100	0.03 - 2.0 + PGA, PGV	3 classes based on sediment thickness	0.47, 0.16	LRGENV	Italy
Danciu and Tselentis (2008)	M_w	4.5 - 6.9	EPI	0 - 136	0.1 - 4.0 + PGA, PGV	3 classes	N, R/T, S	AMEAN	Greece
Douglas *et al.* (2006)	M_w	4.5 - 7.5	RJB	1 - 1000	0.02 - 2.0	1870 m/s	0.1875, 0.1875	GMEAN	Southern Spain
Kalkan and Gülkan (2004)	M_w	4.0 - 7.4	RJB	1.2 - 250	0.1 - 2.0 + PGA	cont. function	0.1574, 0.0463	LRGENV	Turkey
Massa *et al.* (2008)	M_w	4.0 - 6.5	EPI	1 - 100	0.04 - 2.0 + PGA	2 classes	0.0, 0.5	LRGENV	Northern Italy
Özbey *et al.* (2004)	M_w	5.0 - 7.4	RJB	5 - 300	0.1 - 4.0 + PGA	3 classes	0.0366, 0.0244	GMEAN	Northern Western Turkey

[1] RUP: rupture, RJB: Joyner-Boore, HYP: hypocentral, EPI: epicentral distance (Abrahamson and Shedlock, 1997)

[2] cont. function: continuous function of v_{S30}

[3] Style-of-faulting: N: normal, R: reverse, T: thrust, O: oblic, U: undefined

[4] pN: proportion of normal faulting, pR: proportion of reverse faulting needed for the style of faulting adjustment method of Bommer *et al.* (2003)

[5] Horizontal component type. GMEAN: geometric mean, LRGENV: larger envelop, VectComp: vectorial composition, GMRotI50: new geometric mean used in the PEER NGA Project

Table 5 Ranking of the candidate GMPEs for subduction zones based on LLH values for PSA at 0.05s, 0.3s, 0.5s, 0.8s, 1s, 1.5s and 2s

Subduction zones - PSA 0.05s to 2s

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	-9.641	Kanno *et al.* (2006)
5	2.500	-9.704	McVerry *et al.* (2006)
6	3.344	-49.70	Atkinson and Boore (2003)

Table 6 Ranking of the candidate GMPEs for ASCR based on LLH values for PSA at 0.1s, 0.2s, 0.5s, 1s and 2s from DB1 (European database)

Active shallow crustal regions - DB1 - PSA 0.1s to 2s

Rank	LLH	DSI	Model
1	2.378	68.29	Bindi *et al.* (2010)
2	2.396	66.20	Cauzzi and Faccioli (2008)
3	2.427	62.67	Cotton *et al.* (2008)
4	2.588	45.49	Akkar and Bommer (2010)
5	2.680	36.50	Douglas *et al.* (2006)
6	2.800	25.61	Zhao *et al.* (2006)
7	2.938	14.15	Chiou and Youngs (2008)
8	3.158	1.99	Ambraseys *et al.* (2005)
9	3.271	-9.38	Danciu and Tselentis (2008)
10	3.869	-40.13	Abrahamson and Silva (2008)
11	4.121	-49.72	Boore and Atkinson (2008)
12	4.785	-68.27	Campbell and Bozorgnia (2008)
13	4.921	-71.12	Kalkan and Gülkan (2004)
14	5.332	-78.28	Massa *et al.* (2008)

Table 7 Ranking of the candidate GMPEs for ASCR based on LLH values for PSA at 0.1s, 0.2s, 0.5s, 1s and 2s from DB2 (non-European database)

Active shallow crustal regions - DB2 - PSA 0.1s to 2s

Rank	LLH	DSI	Model
1	1.558	29.49	Akkar and Bommer (2010)
2	1.592	26.43	Chiou and Youngs (2008)
3	1.620	24.00	Boore and Atkinson (2008)
4	1.672	19.65	Abrahamson and Silva (2008)
5	1.678	19.15	Kalkan and Gülkan (2004)
6	1.710	16.45	Campbell and Bozorgnia (2008)
7	1.761	12.50	Bindi *et al.* (2010)
8	1.813	8.477	Danciu and Tselentis (2008)
9	1.835	6.81	Cauzzi and Faccioli (2008)
10	1.850	5.75	Zhao *et al.* (2006)
11	2.331	-24.25	Ambraseys *et al.* (2005)
12	2.545	-34.67	Douglas *et al.* (2006)
13	2.897	-48.82	Cotton *et al.* (2008)
14	3.288	-60.97	Massa *et al.* (2008)

Table 8 Expert choices and the final logic trees for stable continental regions. Names in bold are the selected models. WS stands for weighting scheme.

Category based on expert judgment	*Models*
Models supported by all the experts	**Campbell (2003)** **Toro *et al.* (1997)**
Models chosen by a majority of experts	Atkinson and Boore (2006) Douglas *et al.* (2006) Atkinson (2008)
Models chosen by a minority of experts	
Models not chosen by the experts	Tavakoli and Pezeshk (2005)

Selected models for shield	*WS*
Campbell (2003)	0.5
Toro (2002)	0.5

Selected models for continental crust	*WS*
Campbell (2003) adjusted to 800m/s	0.2
Toro (2002) adjusted to 800m/s	0.2
Akkar and Bommer (2010)	0.2
Cauzzi and Faccioli (2008)	0.2
Chiou and Youngs (2008)	0.2

Table 9 Expert choices, data-based testing results and logic trees for subduction zones. Names in bold are the selected models. The preferred weighting scheme (WS) is shown in bold.

Category based on expert judgment	*Models*
Models supported by all the experts	**Atkinson and Boore (2003)**
Models supported by a majority of experts	**Youngs *et al.* (1997)** **Zhao *et al.* (2006)**
Category based on data-testing results	*Models*
Models supported by the testing for long periods (T > 0.16s)	**Lin and Lee (2008)** **Zhao *et al.* (2006)**
Models supported by the testing for short periods (T ≤ 0.16s)	Atkinson and Boore (2003) **Zhao *et al.* (2006)**
Category based on expert judgment and data-testing results	*Models*
Models supported by the data testing and the experts choices	
Models chosen by a majority of experts and supported by the data-testing results	**Zhao *et al.* (2006)**
Models chosen by a minority of experts or with a low data-testing result	McVerry *et al.* (2006) Atkinson and Macias (2009) Garcia *et al.* (2005)
Models not supported by the data-testing and not chosen by the experts	

Selected Models	***WS1***	*WS2*
Zhao *et al.* (2006)	**0.4**	0.25
Atkinson and Boore (2003)	**0.2**	0.25
Youngs *et al.* (1997)	**0.2**	0.25
Lin and Lee (2008)	**0.2**	0.25

Table 10 Expert choices, data-based testing results and logic trees for active shallow crustal regions. Names in bold are the selected models. The preferred weighting scheme (WS) is shown in bold.

Category based on expert judgment	*Models*
Models supported by all the experts	Boore and Atkinson (2008) **Akkar and Bommer (2010)**
Models supported by a majority of experts	**Cauzzi and Faccioli (2008)** **Zhao *et al.* (2006)**

Category based on data-testing results	*Models*
Models supported by the testing (European dataset)	Bindi *et al.* (2010) **Cauzzi and Faccioli (2008)**
Models supported by the testing (Non-European dataset)	**Akkar and Bommer (2010)** **Chiou and Youngs (2008)**

Category based on expert judgment and data-testing results	*Models*
Models supported by the data testing and by the experts choices	
Models chosen by a majority of experts and supported by the data-testing results	**Akkar and Bommer (2010)** **Cauzzi and Faccioli (2008)**
Models chosen by a minority of experts or with a low data-testing result	Abrahamson and Silva (2008) Ambraseys *et al.* (2005) Campbell and Bozorgnia (2008)
Models not supported by the data-testing and not chosen by the experts	Idriss (2008) McVerry *et al.* (2006) Pankow and Pechmann (2004) Kalkan and Gülkan (2004) Danciu and Tselentis (2008) Massa *et al.* (2008)

Selected models for periods $T \leq 3s$	*WS1*	*WS2*	*WS3*	*WS4*	*WS5*	***WS6***	*WS7*
Akkar and Bommer (2010)	0.30	0.30	0.40	0.25	0.30	**0.35**	0.10
Cauzzi and Faccioli (2008)	0.30	0.20	0.20	0.25	0.25	**0.35**	0.40
Zhao *et al.* (2006)	0.20	0.20	0.20	0.25	0.20	**0.10**	0.10
Chiou and Youngs (2008)	0.20	0.30	0.20	0.25	0.25	**0.20**	0.40

Selected models for periods $3s < T \leq 10s$	***WS***
Cauzzi and Faccioli (2008)	**0.5**
Chiou and Youngs (2008)	**0.5**

Table 11 Weighting scheme for active regions in oceanic crust (same as for ASCR). The preferred weighting scheme (WS) is shown in bold.

Selected models for periods $T \leq 3s$	*WS1*	*WS2*	*WS3*	*WS4*	*WS5*	***WS6***	*WS7*
Akkar and Bommer (2010)	0.30	0.30	0.40	0.25	0.30	**0.35**	0.10
Cauzzi and Faccioli (2008)	0.30	0.20	0.20	0.25	0.25	**0.35**	0.40
Zhao *et al.* (2006)	0.20	0.20	0.20	0.25	0.20	**0.10**	0.10
Chiou and Youngs (2008)	0.20	0.30	0.20	0.25	0.25	**0.20**	0.40

Selected models for periods $3s < T \leq 10s$	***WS***
Cauzzi and Faccioli (2008)	**0.5**
Chiou and Youngs (2008)	**0.5**

Table 12 Weighting scheme for Vrancea (same as for SZ). The preferred weighting scheme (WS) is shown in bold.

Selected Models	***WS1***	*WS2*
Zhao *et al.* (2006)	**0.4**	0.25
Atkinson and Boore (2003)	**0.2**	0.25
Youngs *et al.* (1997)	**0.2**	0.25
Lin and Lee (2008)	**0.2**	0.25

Table 13 Weighting scheme for volcanic zones

Selected Models	WS
Faccioli *et al.* (2010)	**1**

Table 14 Percentage differences for ASCR for three ground-motion intensity measure types, two seismic source types and two return periods. The maximum for each ground-motion intensity measure type, source type and return period is highlighted in bold.

Weighting Schemes	Area Source		Fault Source	
	475 years	2475 years	475 years	2475 years
PGA				
Preferred WS vs. WS1	3.27%	3.36%	4.22%	3.97%
Preferred WS vs. WS2	**(+)7.68**%	5.95%	5.38%	5.88%
Preferred WS vs. WS3	6.96%	5.20%	7.82%	6.66%
Preferred WS vs. WS4	6.39%	5.43%	5.79%	5.10%
Preferred WS vs. WS5	5.45%	4.33%	4.57%	4.25%
Preferred WS vs. WS7	4.44%	**(-)6.49**%	**(-)8.59**%	**(-)9.51**%
PSA (0.2s)				
Preferred WS vs. WS1	3.28%	3.55%	4.21%	4.60%
Preferred WS vs. WS2	7.80%	6.84%	6.42%	5.79%
Preferred WS vs. WS3	8.93%	7.86%	10.71%	9.78%
Preferred WS vs. WS4	5.91%	6.00%	5.63%	5.87%
Preferred WS vs. WS5	5.49%	5.12%	5.07%	5.02%
Preferred WS vs. WS7	**(-)11.04**%	**(-)8.83**%	**(-)14.57**%	**(-)14.26**%
PSA (1s)				
Preferred WS vs. WS1	3.53%	4.49%	3.31%	4.34%
Preferred WS vs. WS2	3.59%	7.31%	2.65%	6.38%
Preferred WS vs. WS3	3.73%	7.35%	2.48%	4.56%
Preferred WS vs. WS4	4.68%	**(-)7.50**%	4.72%	7.46%
Preferred WS vs. WS5	3.02%	5.89%	2.88%	5.32%
Preferred WS vs. WS7	**(+)4.95**%	4.60%	**(-)5.88**%	**(-)7.48**%

Table 15 Percentage difference values for SZ for three ground-motion intensity measure types, two seismic source types, and two return periods. The maximum for each source type and return period is highlighted in bold.

Weighting Schemes	Subduction Inslab		Subduction Interface	
	475 years	2475 years	475 years	2475 years
PGA				
Preferred WS vs. WS2	**(-)8.80**%	6.81%	6.87%	**(-)6.97**%
PSA (0.2s)				
Preferred WS vs. WS2	**(-)8.70**%	8.51%	6.83%	**(-)8.00**%
PSA (1s)				
Preferred WS vs. WS2	**(-)4.00**%	1.67%	5.45%	**(-)6.21**%

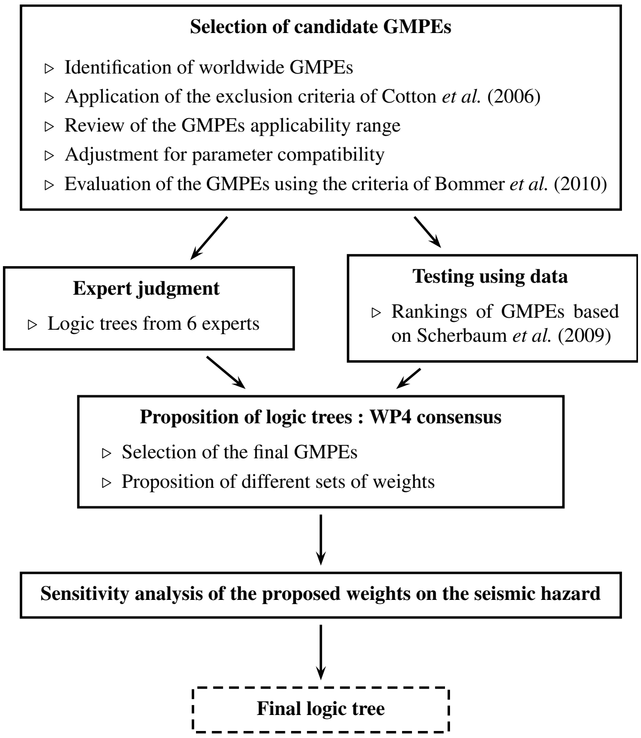

Fig. 1 Process adopted for the construction of the ground-motion logic tree for Europe

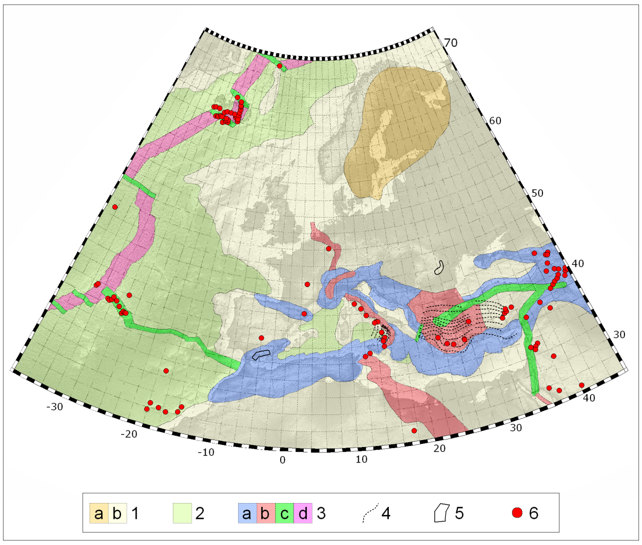

Fig. 2 Seismotectonic map of the Euro-Mediterranean area developed for the SHARE project by WP3.2. 1: SCR, shield (a) and continental crust (b); 2: oceanic crust; 3: ASCR, compression-dominated areas (a) including thrust or reverse faulting, associated transcurrent faulting (e.g. tear faults), and contractional structures in the upper plate of subduction zones (e.g. accretionary wedges), extension-dominated areas (b) including associated transcurrent faulting, major strike-slip faults and transforms (c), and mid oceanic ridges (d); 4: subduction zones shown by contours at 50 km depth interval of the dipping slab; 5: areas of deep-focus non-subduction earthquakes; 6: active volcanoes and other thermal/magmatic features.

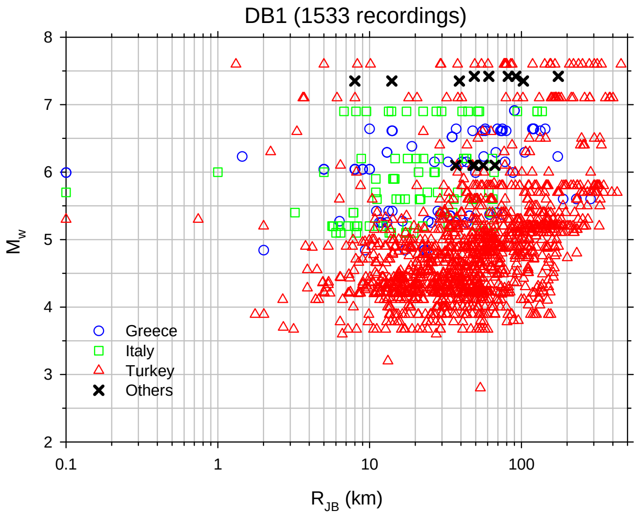

Fig. 3 Distribution of the database DB1 (European database) in terms of Joyner-Boore distance (RJB) and magnitude. For illustrative purposes the recordings with RJB < 0.1km are plotted as 0.1km.

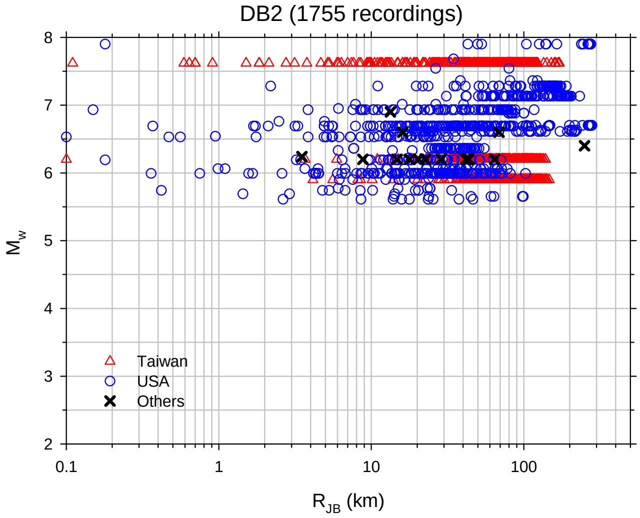

Fig. 4 Distribution of the database DB2 (Non-European database) in terms of Joyner-Boore distance (RJB) and magnitude. For illustrative purposes the recordings with RJB < 0.1km are plotted as 0.1km.