Seismic Hazard Estimates for the Euro-Mediterranean Region: A community-based Probabilistic Seismic Hazard Assessment

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SUMMARY

The EU-FP7 project Seismic Hazard Harmonization in Europe (SHARE) aims to provide an updated state-of-the art time-independent seismic hazard model envisioned to serve as a reference model for the revision of the EC8 building code revision. We present in short the main ingredients of the hazard model and how uncertainties are treated within the logic tree of source models and ground motion prediction equations. The hazard model is evaluated within a pan-European feedback process and the final model will be presented by the end of the year 2012.

Keywords: Probabilistic Seismic Hazard Assessment, Uncertainty treatment

1. INTRODUCTION

Probabilistic seismic hazard assessment (PSHA) is one of the most useful products seismology offers to society. PSHA characterizes the best available knowledge on the seismic hazard of a study area, ideally taking into account all sources of uncertainty. Results form the baseline for informed decision-making, such as building codes or insurance rates, and provide essential input to each risk assessment application.

The latest Euro-Mediterranean project SESAME, the UNESCO-IUGS International Geological Correlation Program Project no. 382, published a homogenized seismic hazard map for the Euro-Mediterranean region (Jiménez et al., 2001; Jiménez et al., 2003) in terms of peak acceleration at a 10% probability of exceedance in 50 years. Although this result was a major step towards a borderless approach complying with the approach taken in the Global Seismic Hazard Assessment Program (GSHAP; Giardini, 1999), the conducted PSHA is assumed to be outdated for several reasons: many EU-funded projects in recent years have generated valuable input data for the Euro-Mediterranean region, much progress has been made to develop, select and process ground motion prediction equations, the treatment of uncertainties within a PSHA has been improved and new model ideas have been developed. In addition, the required input for an earthquake resistant design of structures from the engineering community has been extended in order to mitigate the seismic risk not only of important infrastructures but also for individual homes.

For these reasons, the European Commission funded the project "Seismic Hazard Harmonization in Europe" (SHARE, www.share-eu.org) in the Framework Program 7 (FP7) to generate a community-based probabilistic time-independent seismic hazard model for the Euro-Mediterranean region by 2012, including new data, models and requirements (Giardini et al, 2009). SHARE, in addition, contributes its results to the Global Earthquake Model (GEM, www.globalquakemodel.org), a public/private partnership initiated and approved by the Global Science Forum of the OECD- GSF, aiming to provide a uniform and hazard and risk model around the globe. SHARE is a 3.5-year project with a consortium of 18 partners in the Euro-Mediterranean region that started in June 2009. The primary goals of SHARE are to build a framework for PSHA across all disciplines, by involving participants, competences and experts spanning all involved fields from earthquake engineering to geology to engineering seismology, and for integration across national borders, to compile earthquake data and assess seismic hazard without the burden of political constraints and administrative boundaries. An authoritative community-based Euro-Mediterranean time-independent hazard model is the target by seeking extensive expert elicitation and national participation through community feedback. The model is envisioned to form the base reference input from the hazard community to the engineering community for the revision of the European building code EC8.

SHARE inherits knowledge from national, regional and site-specific PSHAs, assessed new data, assembled the data in a homogeneous fashion, and builds comprehensive hazard relevant databases, rigorously selected the best suited ground motion prediction equations (Delavaud et al., 2012; Drouet et al., 2010; van Houtte et al., 2011) and implements the model in a suitable computational framework. The newly assessed data within the project allows to explore and include, for the first time, additional views on the earthquake rupture process into a regional scale Euro-Mediterranean PSHA: First, the homogeneous assessment of the fault database to include fully parameterized seismogenic sources into modeling earthquake occurrence considering geologic information is a major advancement (Basili et al., 2008; Basili et al., 2009; Haller & Basili, 2011). Second, SHARE introduces contemporary applied approaches to assess sources of uncertainties within its logic-tree including for the first time kernel-smoothed seismicity approaches (Chung-Han and Grünthal (2010); Hiemer et al, 2012; Woo et al, 1996).

The SHARE-PSHA aims to generate results for various return periods in the range of hundreds to thousands of years, i.e. 475y-2500y, that are of engineering interest. Various ground motion intensity measures, such as peak ground acceleration (PGA) and spectral acceleration (SA) at various periods; the range for the ordinates of SA are bounded by the selected ground motion prediction equations (GMPEs, Delavaud et al., 2012) and cover up to 4s as required by EC8 on the Euro-Mediterranean scale. This is an important advancement in comparison to the SESAME model that only resulted in a PSHA for PGA of 10% in 50years. In addition, details on single sites of interest such uniform hazard spectra and disaggregation will be available and accessible via an online portal as the front end of the computational infrastructure for an integrated European PSHA model (www.share-eu.org).

SHARE is a procedural example on how to perform a regional scale PSHA addressing divers demands from the general public, seismologists, engineers and decision makers. In this paper we present the model assumptions and treatment of uncertainties within the hazard assessment. We outline as an example for the homogenization efforts the strategy to assess the maximum magnitude and point out how this is connected to the usage of GMPEs. As up to date the hazard results are not final, we are not elaborating on the hazard results since these will undergo further feedback process until their final presentation.

2. COMPONENTS OF THE SHARE SOURCE MODEL

2.1 Zone-based approaches

A well-defined source models captures aleatory and epistemic uncertainties in its logic tree to assess various descriptions and concepts about the stationarity of seismicity and fault behavior. The involved geological and seismological community suggested multiple basic source typologies that include tectonic, geologic, geodetic and seismologic data model the occurrence rate of earthquakes in the Euro-Mediterranean regions. These can be differentiated in two different principal methodologies: Subcategories of the zone-based methods are 1) the classical area source model (AS-branch) (Figure 1) and 2) a hybrid model that combines fault sources (FS) and background sources (BG) (FS+BG branch). The AS-branch inherits and expands the area source model that has been developed during SESAME. The area source model branch has been constructed as a community-based, consensus model. Within several dedicated regional workshops project participants and external experts reached consensus to construct the ASs in the entire region. Area source models are frequently used (e.g., Grünthal et al., 1999a; Grünthal et al., 1999b; Jimenez et al., 2003) and often in an advanced stage (e.g., Grünthal et al., 2009; Meletti, 2008; Wiemer et al., 2009a). If several models are provided for a region then this part can in principal be branched accordingly to number of models provided (Wiemer et al., 2009b); however, this option has not been applied in any region of the SHARE model.

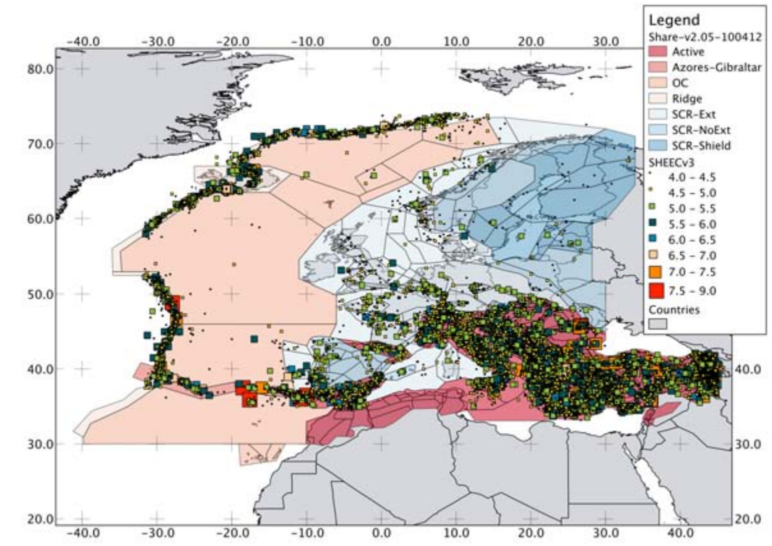

Figure 1: Seismotectonic differentiation mapped on area source zones. The seismotectonic differentiation has homogeneously been used in the assessment of Mmax and GMPEs. Area Sources are depicted with the associated tectonic setting. Superimposed is the earthquake catalog prepared within SHARE.

The FS+BG branch prominently introduces the geologic record within the Euro-Mediterranean region and emphasizes the knowledge on active faulting collected within the project. Fault sources are defined as seismogenic sources in Basili et al (2008): they represent fully parameterized fault structures, however, they do not represent single fault segments that rupture once or repeatedly the same segment. The easiest way to understand the fault database is to think of various layers of the database: the first layer contains information about single faults aggregated from the principal investigators, voluntary contributions to the database and from literature. The second layer is a compilation, the seismogenic source layer, that represents a fault structure larger than a single fault segment, containing all parameters needed to characterize the activity rate on the fault structure – this is the important information for the PSHA calculation. Each seismogenic source includes parameters of the geometry, slip rate, moment rate, etc. together with uncertainties, defined as maximum and minimum values. The extent of the seismogenic source is generally larger than the expected maximum magnitude of single faults based when considering scaling relations such as Wells and Coppersmith (1994). For the following, we call a seismogenic source used for the PSHA a fault source (FS).

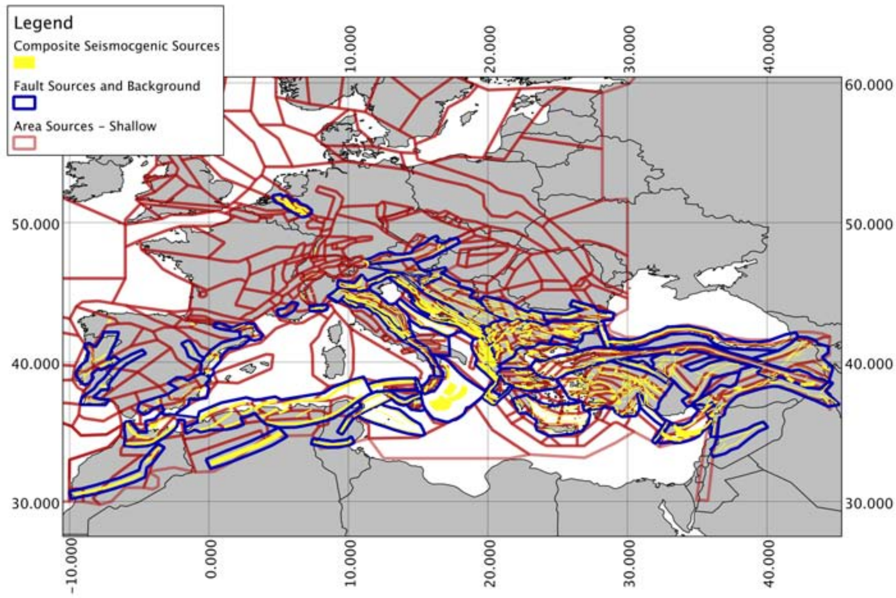

Figure 2: Area Sources (red) , Seismogenic sorces (yellow) and background sources (blue) of the FS+BG branch.

The hybrid model branch combines fault sources and background sources. As the fault sources do not cover the entire Euro-Mediterranean region, this branch includes the area source model in regions not covered with fault sources. As some of the fault sources cut across the area sources, we introduced background sources that fully enclose the fault sources assumed to belong to one fault system (Figure 2). The background sources in the hybrid model do not entirely align with the area sources (Figure 2, blue polygons), thus the area sources where adjusted to the edges of the background zones.

Area sources and background sources are based on different assumptions. While the entire magnitude range of possible future earthquake ruptures is described by one frequency-magnitude distribution, background sources only describe the occurrence of seismicity up to a magnitude that is expected to occur all over the zone and not only along the enclosed fault sources. Both AS and BG sources assume that the distribution of the hypocenters is uniform throughout the given area and follow the assigned depth distribution and faulting styles.

The hybrid model assumes that earthquakes of moderate to large magnitudes ($M_W \geq 6.0$) occur on the identified fault sources while smaller events occur in the background sources. This implies that in the hybrid model does not consider so-called surprises, events with large magnitude on unknown structures, and it assumes that the fault sources are a complete description of the fault network.

We assume a Gutenberg-Richter distribution of activity rates for the AS and BG zones. The activity rate parameters are computed with a Bayesian approach combining a prior b-value and likelihood function for which the parameters of the Gutenberg-Richter distribution is computed with a penalized maximum likelihood method, taking account of various completeness periods following Weichert (1980). The estimated b-values are also used to determine activity rates for the FS, however for these the activity rates are computed with a model proposed by Anderson and Luco (1983) and evaluated together with others in Bungum (2007). There are many details that we have to leave out in the description here, yet the principal difference is obvious as for the FS, the slip rate and source area assessed in the fault data base play a major role in the determination of activity rates.

2.2 Kernel-smoothed approaches

SHARE introduces kernel-smoothed approaches as an alternative branch for the first time on the Euro-Mediterranean scale. We include different approaches 1) a purely seismicity based kernel smoothing methods called hybrid-zoneless approach by Chung-Han and Grünthal (2010) following Woo (1996) and 2) a stochastic earthquake source model that includes both, knowledge of fault moment release and seismicity, in the kernel smoothing process and satisfies observational frequency-magnitude statistics (Hiemer et al., 2012).

Purely kernel-smoothed seismicity models describe the occurrence of seismicity assuming that the space-time behavior is not primarily governed considering long-term tectonic and geological features but rather by the time varying clustering process of earthquakes themselves, often being a point of criticism to these methods. However, these models have been implemented in contemporary PSHA studies and also for site-specific hazard assessment such as in the PEGASOS project, a SSHAC level 4 project for the Swiss Nuclear Power Plants (e.g. Burkhard and Grünthal, 2009).

The hybrid-zoneless approach includes seismicity as the prime input data. It deviates from the general smoothed seismicity idea in that the kernel smoothing is performed within tectonic regions based on the assumption that the seismicity follows different distribution in different tectonic regions (Chung-Han and Grünthal, 2010). The hazard is in the original approach calculated as the sum of the hazard of each contributing event on the location of interest. The activity rate parameters are replaced with a bandwidth function resembling the earthquake activity. For comparison, purposes the approach was modified to generate a seismicity rate grid given the frequency-magnitude distribution for the study area with the consequence that the distributions may not resemble a Gutenberg-Richter distribution as this is not an initial assumption.

The stochastic earthquake source model (Hiemer et al., 2012) generates a forecast of activity rates based on two kernel-smoothed probability-density maps: one originates from seismicity and one from the moment rate, the product of the area and the slip on single faults. In short, the approach involves the following few steps: First, the seismicity and the moment rates of the fault sources are smoothed using an adaptive and a Gaussian kernel scaled with the moment rate contribution; this process results in two earthquake probability density maps. The probability density maps are then scaled to the total completene number of events that are recorded in the catalog. We assume that the frequency-magnitude distribution for the entire catalogue is obeyed in regions only characterized by seismicity; in regions for which we have a contribution from both, the seismicity and the moment rate density map, we scale the density maps with the total number of events from the overall Gutenberg-Richter relation. We assume the spatial density map of the smoothed seismicity to represent all events with M_W=5 while M_W=8.5 earthquakes are assumed to be hosted exclusively on faults, in between we interpolate linearly. This introduces variability in the b-value of the model, though the overall b-value fits the global frequency magnitude distribution.

2.3 Maximum magnitude (Mmax) estimation

Estimating the maximum magnitude (Mmax) is following a unified strategy with two principal approaches for different tectonic regimes (Figure 3). Mmax is defined as the ultimately largest magnitude earthquake that can happen in a specific region. We differentiate the following tectonic regimes in accordance with what is used also for the ground motion prediction equation differentiation: 1) For Stable Continental Regions (SCR) we follow the so-called EPRI-approach (with EPRI being the shortcut for Electric Power Research Institute) anchoring Mmax to values assessed within a global study of the same tectonic regime; 2) For active shallow crustal tectonic regimes, we assess Mmax based on the maximum observed magnitude (M_{obs}) events plus three uncertainty values; 3) For all other tectonic regimes, the assessment is based on the Mobs and one uncertainty add-in.

Approaches 2) and 3) are straightforward in that the M_{obs} value of superzone consisting of all area zones of one tectonic regime (Figure 2) into which the area or background zone falls. Uncertainty values have been assessed for the catalogue; the uncertainties are then added to M_{obs} to describe a density distribution of Mmax. The larger the final Mmax value is, the smaller the weight that is associated to this Mmax value (Figure 3).

One of the most common statistical procedures adopted to estimate Mmax in low-seismicity areas is the so-called EPRI approach (Johnston et al., 1994) and has been applied in several studies worldwide (Burkhard and Grünthal, 2009; Schmid and Slejko, 2009; Wiemer et al., 2009a). The approach is based on Bayes' theorem and provides a posterior probability distribution of Mmax taking into account the large relevant uncertainty. It is based on information coming from the analysis of a global data set of seismicity in SCRs (Johnston et al., 1994) – the prior - updated with local data available for the seismic source of interest – the likelihood function. The basic concept is to compensate the small seismicity sample of the study area by considering observations from tectonically analogous regions worldwide. Two prior worldwide normal distributions were derived by Johnston et al. (1994): one for extended and another for non-extended continental crust, which are characterized by different mean and standard error values (i.e. mean Mmax=6.4 vs 6.3, standard deviation=0.84 vs 0.5, respectively). The posterior Mmax probability distribution is then derived by multiplying the prior distribution by the source-specific likelihood function. The posterior probability distribution is finally discretized in four intervals to derive a discrete distribution for Mmax as input to the hazard calculation and weights are assigned by expert judgement to the magnitude values with a relevant probability. In case of the extended crust, magnitude range from 6.5 to 7.1 with weights between 0.5 and 0.1, respectively.

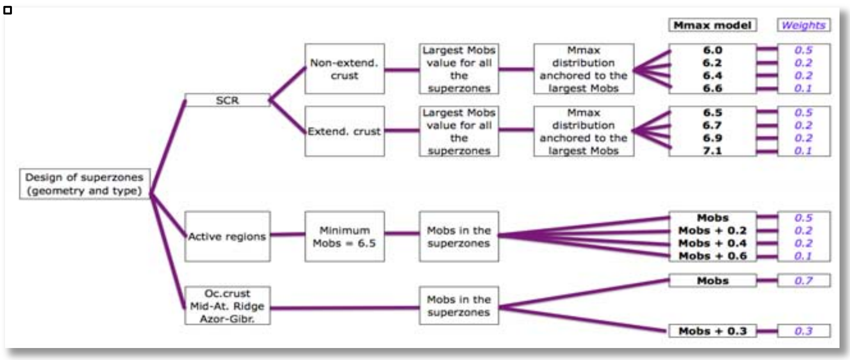

Figure 3: Proposed scheme to for Mmax estimation for different tectonic regions.

3. THE LOGIC TREE FOR GROUND MOTION PREDICTION EQUATIONS: SELECTION, TESTING AND WEIGHTING

The methodology adopted to prepare the logic tree for the pan-European PSHA is outlined in detail in Delavaud et al. (2012). The participating scientist were challenged with two major tasks: 1) To propose a process to prepare a GMPE logic tree for a regional scale PSHA project and suggest guidelines serving future such projects and 2) to identify, within this strategy, the smallest set of GMPEs to capture the epistemic uncertainty in ground-motion prediction in Europe.

The novelty of the selected strategy is to consider expert judgment on the one hand and, on the other hand, use an objective data driven approach to select and rank GMPEs to guide the choice and weight of the models. Data driven guidance is indeed 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).

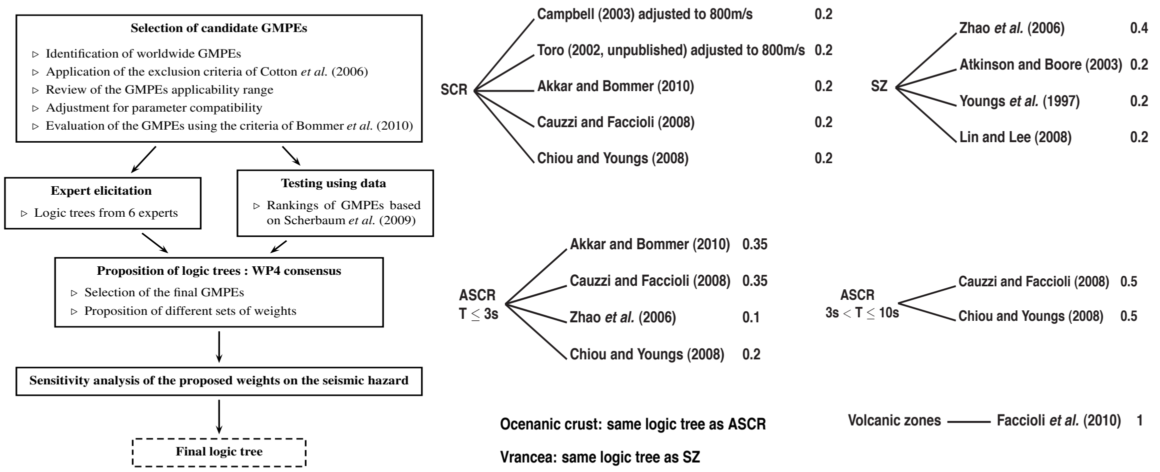

Figure 4: (Left) Process for the construction of the SHARE-GMPE logic-tree (Adopted from Delavaud et al, 2012). (Right) Logic trees for stable continental regions (SCR), subduction zones (SZ), active shallow crustal regions (ASCR), oceanic crust, areas of deep-focus non-subduction earthquakes (Vrancea) and volcanic zones. References are listed. Toro (2002) is unpublished yet a revised version of Toro et al, 1997.

The adopted procedure consists of the five steps outlined in Figure 4 (left). The task to prepare the GMPE logic-tree involved roughly a dozen institutions with the goal, in a limited amount of time (18 months), to commonly identify the smallest set of ground motion prediction equations (GMPEs) and associated weights to capture the epistemic uncertainty in ground-motion prediction in six different tectonic regimes in the Euro-Mediterranean region. The limited amount of time and the large geographical area covered by SHARE made this task quite challenging. The novelty of the approach is that we accounted not only for the judgment of experts to select and rank models, as it is commonly done, but we also use data to guide the choices. Thanks to an increasing amount of strong-motion data in part gathered in the strong motion databank generated within the project, data driven guidance is indeed now feasible and can give valuable information about the ability of GMPEs to predict ground motion in different.

The first step consisted in pre-selecting candidate GMPEs for the prediction of ground motion in each existing seismotectonic regime in the wider European region. This pre-selection was realized from an already compiled list (Douglas, 2008) that contains over 250 published ground-motion models, to retain a subset of the most robust equations. Figure 1 shows the broad tectonic domains that have been identified by SHARE Work Package 3 to represent the region covered by the SHARE project. For this pre-selection, it was decided to apply the exclusion criteria proposed by Cotton et al. (2006), and Bommer et al. (2010). From the existing GMPEs, six models remained for stable continental regions (SCR), eight for subduction zones (SZ), nineteen for active shallow crustal regions (ASCR) including six regional or local models, one model for volcanic zones and one for areas of deep focus non-subduction earthquakes. No model for the prediction of ground motion 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.

In second step, a group of six experts was asked to propose logic trees expressing their degree of belief in the ability of the candidate GMPEs to predict earthquake ground motions in each tectonic regime. The experts selected GMPEs that are sufficiently robust to cover a wide range of magnitudes, distances and spectral periods. Therefore, global predictive models were preferred as compared to regional ones. Experts concluded 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. They selected the smallest a set of models that enabled them to capture epistemic uncertainty as much as possible.

To complement the expert opinions, 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 observations. 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. This method uses a criterion, the average negative sample log-likelihood that is a measure of the distance between a model and the unknown process that generated the observations (nature). GMPEs for SZ were tested against Greek data while GMPEs for ASCR were tested against data from Europe and the Middle East as well as worldwide data in order to cover a large range of magnitudes. The approach provides a likelihood based ranking of the candidate GMPEs. An application of the criterion at global scale can be found in Delavaud et al. (2012a). We should keep in mind that this ranking is based on the available dataset that is unfortunately limited (this ranking could change with additional data). Therefore a great effort should be dedicated to the collection of data and meta-data in order to get as much information as possible for the GMPE testing.

Based on the results of both, the expert judgment and the testing, a consensus set of GMPEs was defined. Models supported by the data testing and the expert choices were automatically included in the logic tree. After an extensive expert elicitation with a two-day workshop, the final logic trees were defined and are presented in Figure 4 (right).

4. SUMMARY

We have shortly presented the general approach used within the SHARE-project to provide an update of a regional PSHA spanning the Euro-Mediterranean region. The project will result in a community-based time-independent seismic hazard model to serve as a reference model for the revision of the EC8 building codes. Prime achievements of the project are harmonized and homogeneous data sets for the study region and a harmonized approach to calculate the hazard. The PSHA includes all relevant communities (geology, geodesy, seismology and earthquake engineers) working together to provide a borderless model.

Each project is unique and it is important to be aware of its particularities. We think that the procedures described shortly are reproducible and transparent and are fully documented in the deliverables prepared for SHARE, available at www.share-eu.org or upon request. The performed assessment provides major advances but also reveals that many of the assumptions and decisions taken in the process might be refined in future with increasing quality of data and knowledge.

SHARE is a procedural example on how to perform a regional scale PSHA addressing divers demands from the general public, seismologists, engineers and decision makers. The final results will be presented in the end of 2012 following an extensive feedback process. The results serve as the base for a European Probabilistic Risk Assessment and are already planned to be used in other EC-FP7 funded projects such as SYNER-G (www.vce.at/SYNER-G), PERPETUATE (www.perpetuate.eu), NERA (www.near-eu.org) and GEISER (www.geiser-fp7.eu).

In the end, the main results will be the new Euro-Mediterranean seismic hazard model, a suggestion fo a "Consensus reference Euro-Mediterranean seismic hazard zonation" and a set of guidelines delivered to the members of the EC 8 committee. We thus envision the results to deliver long-lasting structural impact in areas of societal and economic relevance and to serve as a homogeneous baseline input for the correct seismic safety assessment for energy infrastructures and for the re-insurance sector.

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