# Grant Agreement no. 226967

# Seismic Hazard Harmonization in Europe

# Project Acronym: SHARE

**SP 1-Cooperation**

**Collaborative project: Small or medium-scale focused research project**

**THEME 6: Environment**

**Call: ENV.2008.1.3.1.1 Development of a common methodology and tools to evaluate earthquake hazard in Europe**

## D5.5 – Final seismic hazard assessment including de-aggregation

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Revision: 1

| **Dissemination Level** | | |
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| **PU** | Public | X |
| **PP** | Restricted to other programme participants (including the Commission Services) | |
| **RE** | Restricted to a group specified by the consortium (including the Commission Services) | |
| **CO** | Confidential, only for members of the consortium (including the Commission Services) | |

# Table of Contents

# 1 Introduction

SHARE produced more than sixty time-independent European Seismic Hazard Maps (ESHMs) spanning spectral ordinates from PGA to 10 seconds and exceedance probabilities ranging from $10^{-1}$ to $10^{-4}$ yearly probability. The hazard values are referenced to a rock velocity of $vs_{30}$=800m/s at 30m depth. SHARE models earthquakes as finite ruptures and includes all events with magnitudes $M_W \geq 4.5$ in the computation of hazard values. SHARE introduces an innovative weighting scheme that reflects the importance of the input data sets considering their time horizon, thus emphasizing the geologic knowledge for products with longer time horizons and seismological data for shorter ones.

SHARE scientists implemented the proposed strategy with strong collaboration of all workpackage involved in the probabilistic seismic hazard assessment (PSHA). Defining engineering requirements at the beginning of the project served as a guide to assemble appropriate databases and gather scientific and technical knowledge for the selection of ground motion prediction equations as the basis for the assessment of earthquake occurrence probabilities and the calculation of ground shaking parameters. These models, cross-checked for their consistency, were then combined within three different approaches to model the earthquake activity in the assessment of seismic hazard. The proposed hazard model was then translated to the quality-controlled computational infrastructure and the results were handed back to the engineering partners to create risk scenarios and to propose products of European wide impact.

SHARE provides an unprecedented resource of scientific input data and hazard model results that is publicly available in particular for the scientific and engineering community for further developments. This data is available through the European Facility for Earhtquake Hazard and Risk (EFEHR, www.efehr.org). We emphasize that in particular the wealth of input/raw data is of enormous value for scientific developments on the Euro-Mediterranean scale, prone to boost scientific research and result in applicative products for mitigating seismic hazard and risk within Europe.

Seismic hazard results, i.e. exceedance probabilities of a ground motion intensity measure within a specified period, are now available for five different return periods and for at least twelve different spectral periods. The hazard model consists of 60 mean hazard maps, compared to the output of one map by the SESAME project (UNESCO-IUGS IGCP No. 382) for PGA and an exceedance probability of 10% in 50 years. In addition, SHARE generated results that

1) represent the uncertainties of the hazard maps in terms of multiple standard deviations;
2) show detailed site specific information such as hazard curves and uniform hazard spectra for each of the more than 120,000 sites on-land;
3) show disaggregation of the hazard computation to understand at the specific sites which magnitude earthquakes at what distances are the largest contributors to the hazard. This product is of immediate interest for engineering procedures when selecting appropriate time-series for building design.

SHARE thus sets new standards in the output of hazard results that were available in Europe only in a few countries.

This document highlights the achievements of the PSHA. A detailed description is in preparation and will be in the form of a long report as well as manuscripts in scientific journals.

# 2 Progress summary

## 2.1 Progress in the definition of earthquake sources and activity rates

The main results consist of data compilations and data elaborations. Three major databases at the state-of-the-art were compiled, geographically complete as much as possible for entire Europe, homogeneously collected and authoritative. They comprise a fundamental legacy and will become a European reference in the forthcoming years. We foresee that they will be used in the future for SHAs at various scales and other research purposes. The databases are

1) the new SHEEC earthquake catalog (Figure 1) and database (www.emidius.eu/SHEEC), which for the critical window of "earthquakes before 1900" features a) a consensus, full list of events, and b) full parameters for the 645 larger ($M \geq 5.8$) events;
2) the new homogenized European seismic source zone model (SSZM, Figure 2), featuring over 400 source zones, carefully tailored to accommodate differences and inconsistencies across national boundaries (www.share-eu.org);
3) the first pan-European database of active faults and seismogenic sources (http://diss.rm.ingv.it/share-edsf/index.html, Figure 3**Error! Reference source not found.**), which includes about 1,128 fully-parameterized seismogenic sources, for a total fault length of nearly 64,000 Km (98 sources and 8,500 Km at the beginning of the project).

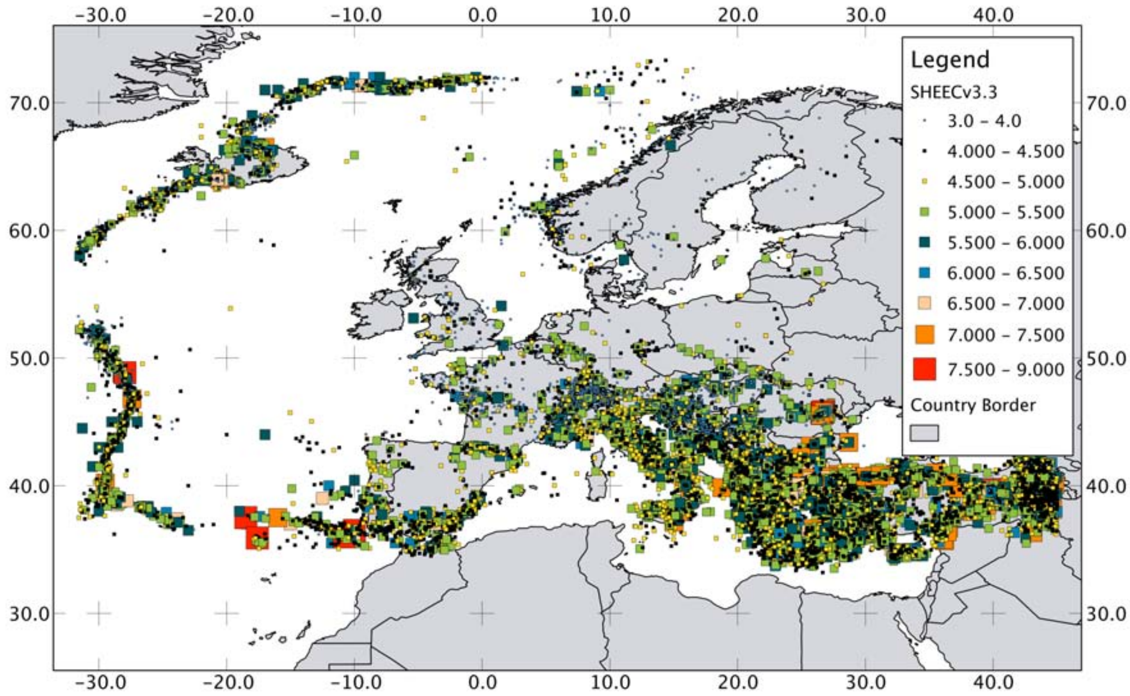

Figure 1: SHEEC v3.3 European Earthquake catalog.

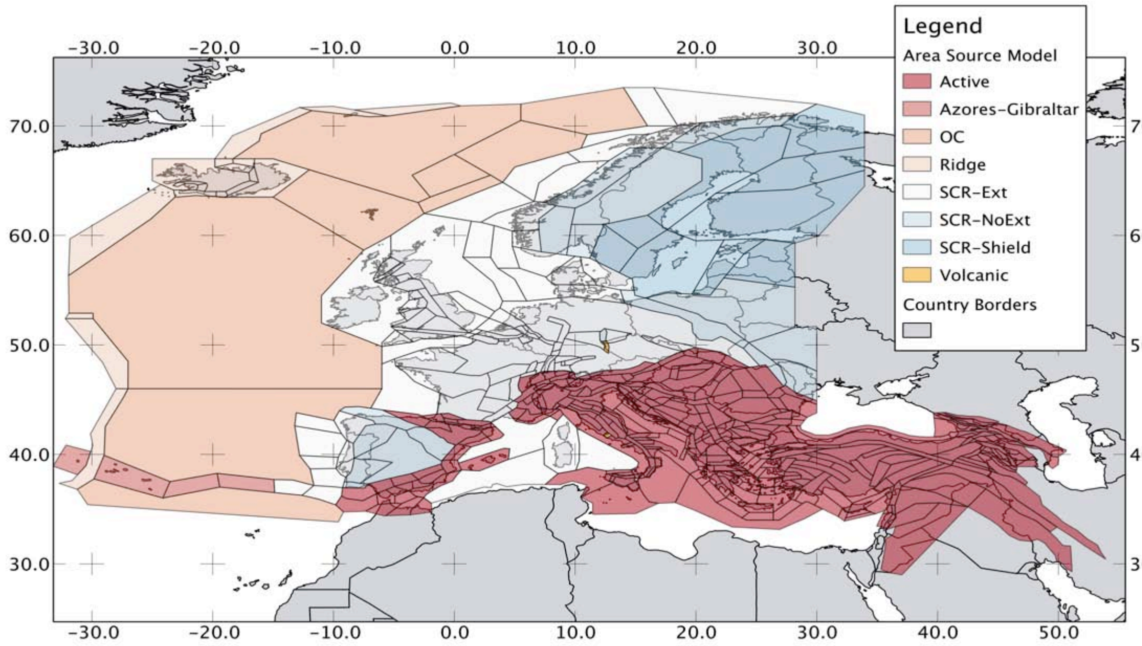

Figure 2: Crustal area Source Model version v6.1 differentiated by tectonic regionalization. The model includes 423 sources.

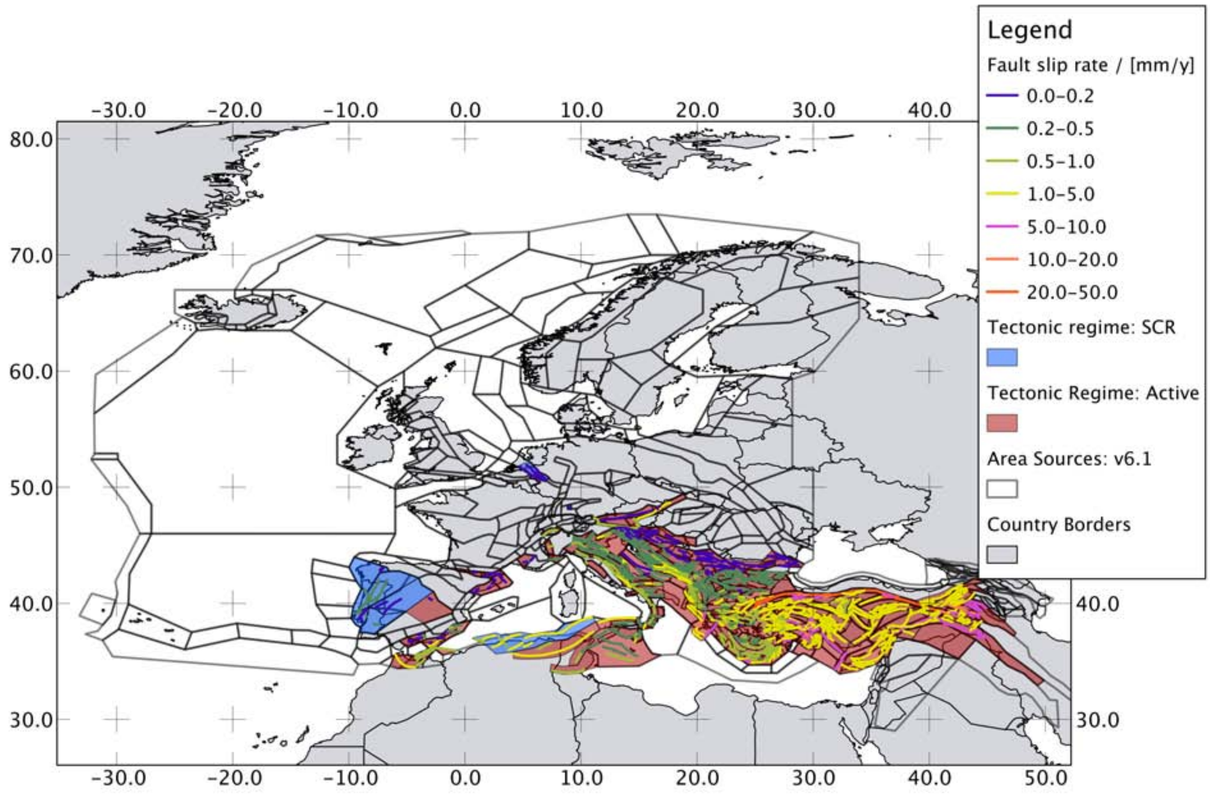

Figure 3: Fault Source + Background model (FSBG) in the final model.

WP3 has also supplied a number of elaborations, including:

- a European-scale finite element strain model (Figure 4) that implemented the largest faults studied within SHARE, the subduction interfaces, realistic rheology, and a crustal structure with varying thickness. The integration of the subduction zones and the faults allowed an unprecedented level of detail for the Central Mediterranean (Apennines and Dinarides);
- a set of activity rates for all seismogenic source zones encompassing the entire area covered by SHARE, calculated using a common statistical approach that employs a penalized maximum likelihood procedure (Task 3.7);
- a set of commonly derived activity rates for the based on the assessed geological parameters of single fault sources;
- a set of Mmax independently calculated using the SHEEC catalogue for the zone of the final seismic zonation model, for all sources of the seismogenic source model and for 44 “superzones” encompassing the entire are covered by SHARE separated due to their primary tectonic regime (Figure 5);
- a simplified 3D geotectonic model suitable for calibrating the ground motion prediction equations to be used in the different tectonic setting of Europe.

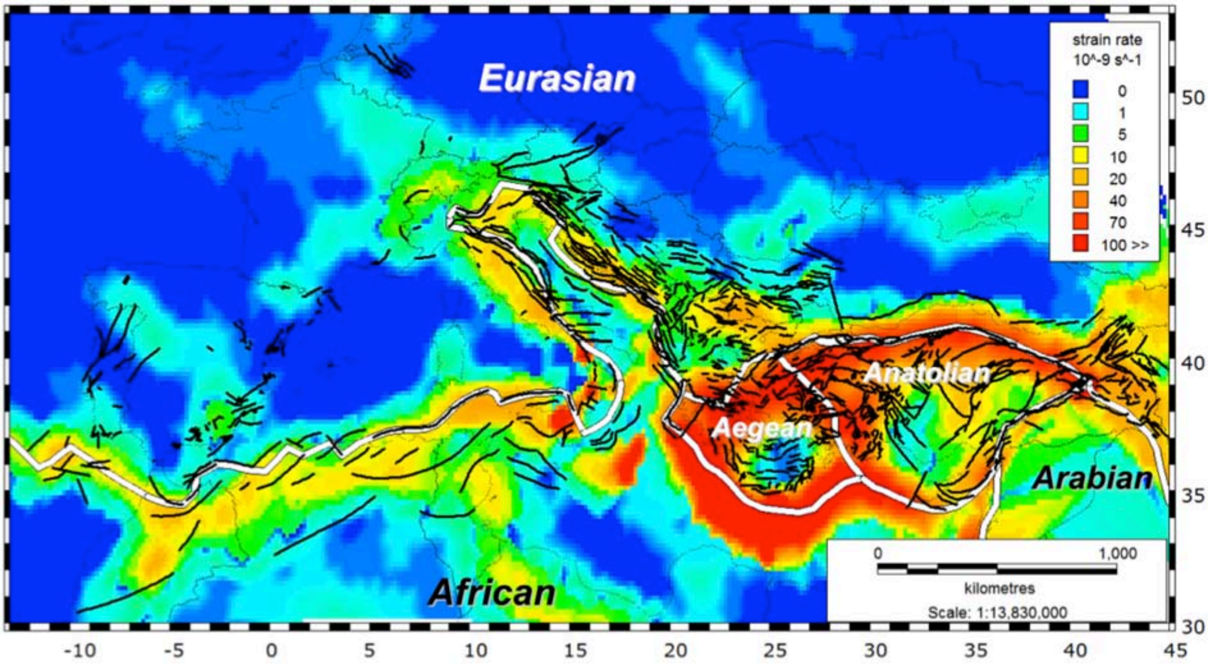

**Figure 4: European strain rates as determined from the finite element model. Black lines represent the projection at the surface of SHARE faults.**

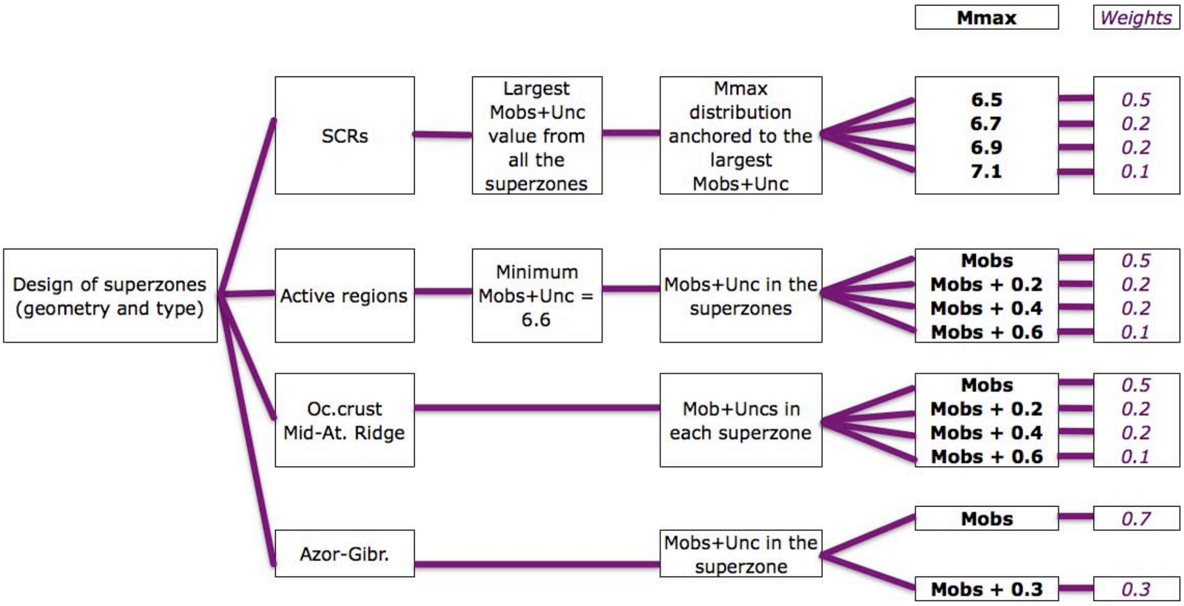

**Figure 5: Logic-tree for the determination of Mmax-values in the different tectonic regimes.**

## 2.2 Progress in strong ground motion modeling

SHARE produced a first consensus ground motion model for the Euro-Mediterranean region on the basis of a rock velocity of vs30=800m/s. From the very large number of existing ground-motion predictions equations (GMPEs), a pre-selection of the most relevant ones following exclusion criteria by Bommer et al. (2010) was performed. Provided the updates large SHARE strong motion database, a testing procedure has been combined with standard expert analysis to compare the performance of each model against the SHARE database. This methodology, the ground motion logic-tree structure and logic tree weights are described in Delavaud et al. (2012) (Figure 6). This procedure is innovative and closely follows requirements for SSHAC-level 3 formal expert elicitation.

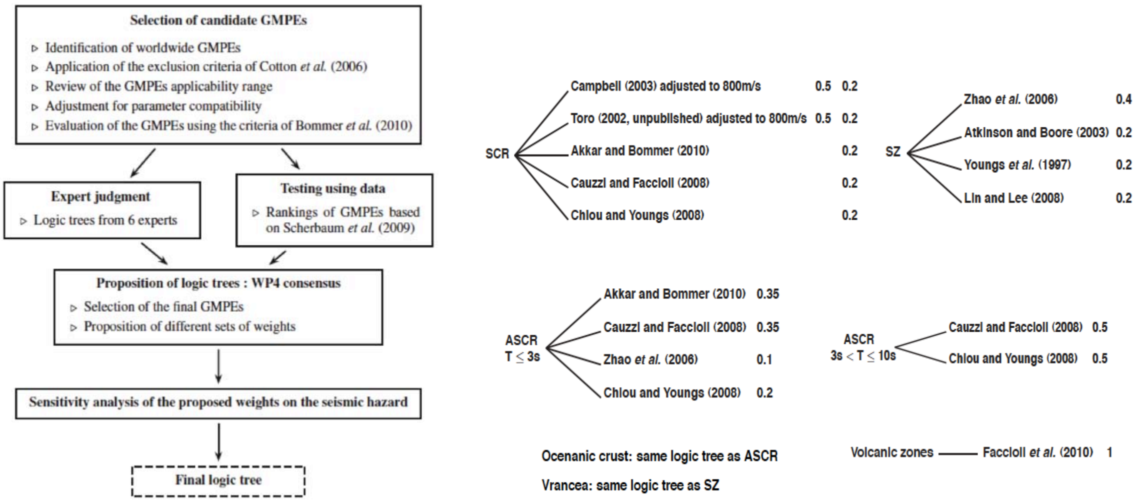

**Figure 6: Process adopted for the construction (left) and the proposed ground motion prediction equation logic-tree for Europe (from Delavaud et al., 2012)**

SHARE has achieved progress along two directions in the definition of new site amplification factors: (1) keeping the EC8 site classification criteria unchanged and proposing the corresponding "optimal" spectral shapes and/or amplification factors (Pitilakis et al, 2013), (2) exploring new tracks for new site classification, and proposing site amplification factors accordingly (Sandikkaya et al., 2013).

SHARE made considerable progress in understanding European wide proxies to site conditions. Correlations between vs30 and topographic slope were examined; the results show that the method only provides an information gain for class B (rock) and to a certain extend for class C (stiff soil) in stable areas (Lemoine et al, 2012). SHARE thus concluded that vs30-slope correlations proposed by Wald & Allen (2007) are only useful for smaller scale SHAs in active parts of Europe and only in the absence of more detailed information. Thus, SHARE sticks to provide only rock hazard.

The engineering seismologists within SHARE used the synergies with the hazard modeling team and presented work on the influence of hazard estimates when using GMPEs with erroneous source-to-site distance metrics. A key point is to use the same metrics in the computation of the hazard and in the derivation of GMPEs (Bommer and Akkar, 2012). New ways of physically sound predictive ground motion models based on fully data driven approaches are developed (Derras et al., 2013) and also include predictive equations for alternate ground motion parameters such as Arias intensity and strong motion duration, both of special interest by the engineering community. The new models in development also target larger ranges of spectral ordinates.

## 2.3 Progress in seismic hazard assessment

SHARE has achieved regional harmonization of a probabilistic hazard assessment program at a level never reached before on the European scale. During the course of the project, more than fifty workshops have been held across Europe to collect data and provide the participants with the modeling intentions and preliminary results of the PSHA. The project has benefitted from the enthusiasm of the wider seismological, geological and engineering community and leveraged this by including much more expert expertise as was expected at the beginning of the project. SHARE thus has worked across national boundaries and multiple disciplines disregarding traditional administrative and disciplinary borders existent in the previous programs.

We implemented a formal procedure to involve expert elicitation when building of the hazard model. As guideline, we used the recommendations of the Senior Seismic Hazard Analysis Committee (SSHAC, NUREG-2117), yet could not on all levels implement the formal procedures equally. The strong ground motion modeling work-package used a defined strategy to prepare the ground motion prediction equation logic-tree (Delavaud et al., 2012). The seismic source logic-tree has been assembled involving the wider community and several feedback rounds. The modeling team organized two Model Review workshops in 2013 and similarly prepared for the final meeting of SHARE, thus having feedback on the source model three times. Each time, material was provided before the workshops so that appropriate preparation time was given. The topics were then discussed with consortium members and external experts and the conclusions were implemented in the modeling procedure. The WP leaders and the modeling team functioned as mediators in this procedure.

The SHARE model explicitly treats uncertainties, epistemic and aleatory, by using the logic-tree approach. This is implemented by within the GMPE logic–tree and the logic-tree of the source model. For the first time, a European wide model considers three views on the stationary process of earthquake activity: 1) an Area Source (AS) Model, 2) a model that combines activity rates based on fully parameterized faults imbedded in large background seismicity zones, the Fault-Source & Background (FSBG) Model, and 3) a kernel smoothed model that generates forecasts based on fault slip and smoothed seismicity (SEIFA). These three principal models show the various models for seismic activity in the European region. Uncertainties are handled with different approaches for the distinct tectonic regimes: for example, the maximum magnitudes within the tectonic regimes are assessed differently using either a global analogue approach for stable continental regions (EPRI, 1984) in contrast to a observation driven approach in active tectonic regions.

SHARE implemented a weighting scheme of three source model options (Table 1) that reflects the base data used to build each one. The AS-model is given the largest weight for the various exceedance probability levels and the weight increases with decreasing exceedance probability levels. We increase the weight of the FSBG-model for decreasing exceedance probability levels due to the importance of the geologic information for the estimation of activity rates. The contribution of the SEIFA model decreases with decreasing exceedance probability levels because SEIFA itself considers the contribution of seismicity stronger than the fault information. For exceedance probabilities larger than 10% in 50y, believe that the SEIFA-model and the AS-model should be equally weighted. We define the combination 0.5 AS-model, 0.2 FSBG-model, and 0.3 SEIFA-model as the average weighting scheme used to generate hazard curves.

| **Return Period**<br>**Exeedance Probability in 50y** | **T=100y T<474y**<br>**P=39% P>10%** | **T≥475y T=975y**<br>**P≤10% P=5%** | **T≥2475y T=4975y**<br>**P≤2% P=1%** |
|---|---|---|---|
| **Area Source** | 0.45 | 0.50 | 0.60 |
| **Fault Source + Background** | 0.10 | 0.20 | 0.30 |
| **SEIFA** | 0.45 | 0.30 | 0.10 |

Table 1: Percentage weighting scheme for the source model options in the source model logic-tree.

We model the Cyprus, Hellenic and the Calabrian arc for the first time as complex fault sources for the interface seismicity of the subduction zone. The inslab seismicity is modeled as volumes at depth. A particular limiting factor in the definition of the activity rates within subduction zones is the large uncertainty in determining focal depth of events which could only be addressed by ad-hoc definitions. The differentiation between crust, interface and inslab seismicity is included in all three source model option and the implementation is the same for the AS- and the FSBG-model. The SEIFA-model takes another approach following its own conceptual setup.

SHARE produces a legacy of more than sixty time-independent European Seismic Hazard Maps (ESHMs). The range of products result from the availability of ground motion prediction equations spanning many spectral ordinates and the range of hazard curves that were calculated ($10^{-1}$y-$10^{-4}$y). The hazard values are referenced to a rock velocity at a depth of 30m, $vs_{30}$=800m/s. SHARE integrates hazard values starting from a minimum magnitude of $M_W$=4.5; all events are treated as extended ruptures, defining the extent of the rupture with the appropriate scaling relation of Wells and Coppersmith (1994). The implementation then uses the correct distance metrics of the ground motion prediction equations.

Figure 7 shows two mean European Seismic Hazard Maps (ESHM). The maps illustrate the probability to exceed a level of ground shaking in terms of the peak ground acceleration in a fifty years period. On the left, the illustrated levels of shaking are expected to be exceeded with a 10% probability in 50 years, on the right it is expected that the level of shaking is only exceeded with a 2% probability in 50 years. This corresponds to return periods of 475 years and 2475 years.

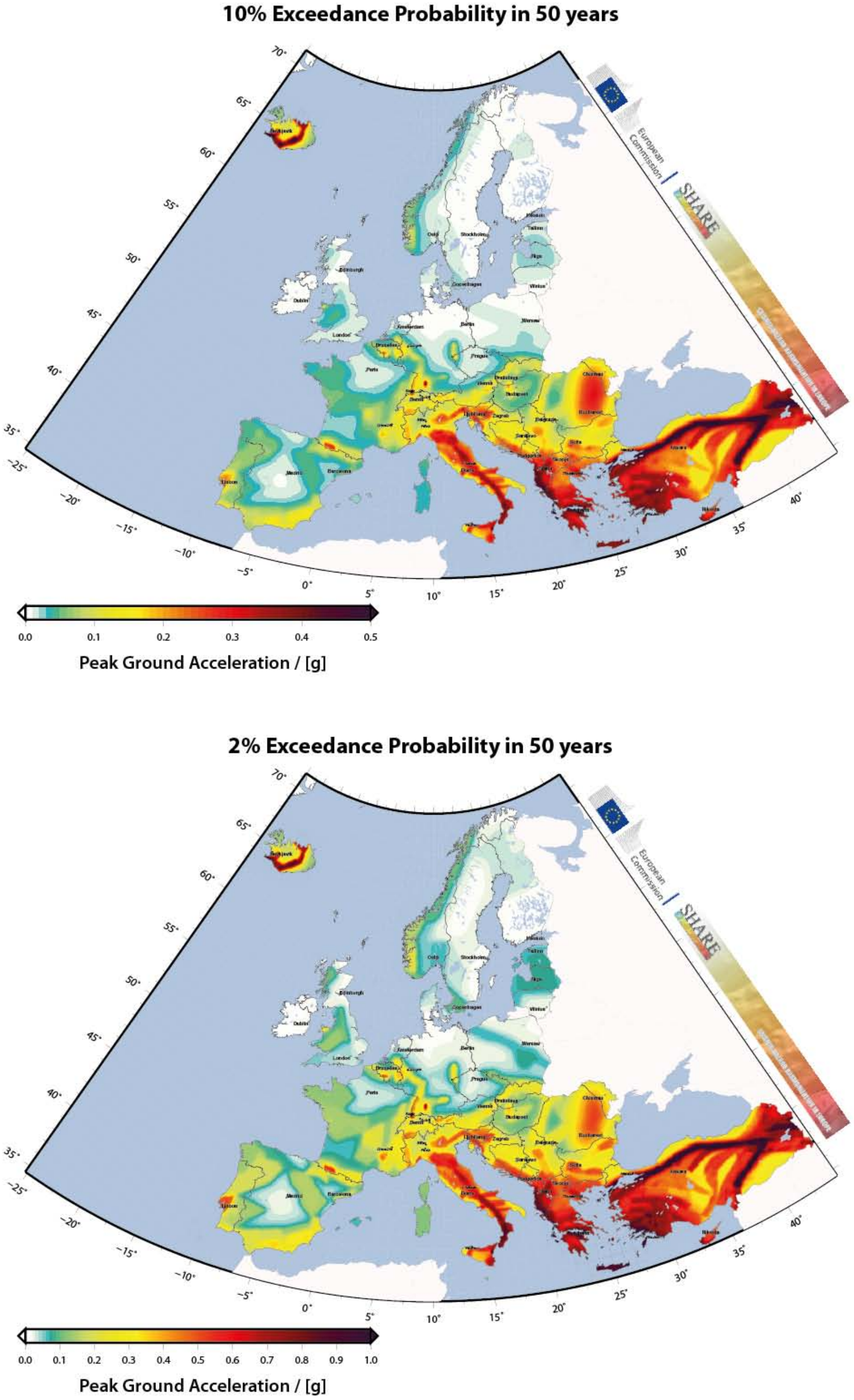

**Figure 7: SHARE Mean European Seismic Hazard Maps in terms of exceeding a peak ground acceleration with a probability of (left) 10% in 50 years or (right) 2% in 50 years.**

### 2.3.1 Logic tree design

The principal design of the SHARE logic-tree (Figure 8) is outlined in deliverable D5.2 that encompasses the logic-tree for the SHARE source model with details given in D3.6. The logic-tree considers the epistemic uncertainty for the various approaches to parameterize the stationarity of seismicity. Within the model building process, all options have been evaluated, yet with different levels of detail.

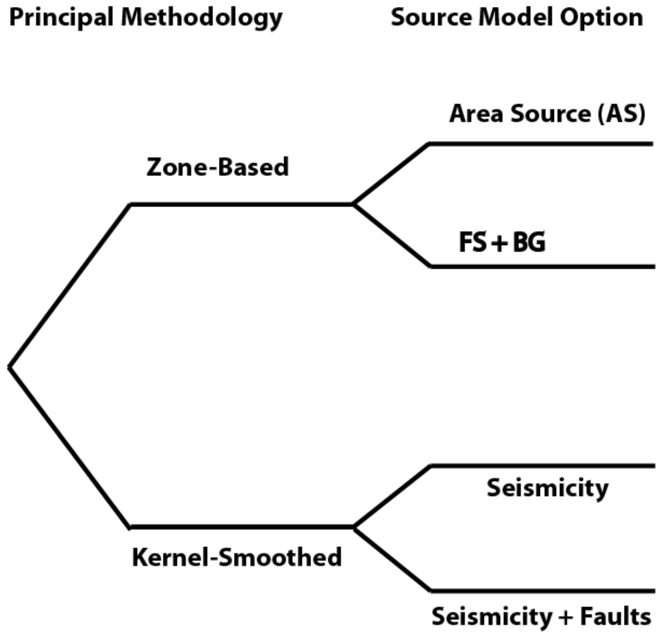

**Figure 8: Principle logic tree for the SHARE source model. The source model options Area Source, Fault Source and Background (FSBG) and the kernel-smoothed approach seismicity + faults enter the final model.**

The Area Source (AS) model has been reviewed in greatest detail, mostly because (a) it is the most widely used source representation, (b) it is the legacy of past projects in the region, (c) almost all national hazard models were built upon these source representation, and hence the expert are very familiar with modeling and characterizing this type of source. The AS-model has undergone several revisions within the feedback process yet in general follows the procedures outlined in the deliverables D3.1, D3.6 and D3.7. A major difference arose in the definition of activity rate as we did not entirely rely on the algorithmically determined values and considered for many sources an expert judgement (details to be described in section Task 5.5).

The Fault Source and Background model (FSBG) introduces knowledge about fault slip rates and geometry to estimate activity rates of each source. It combines with the knowledge of seismic activity with assumptions about the frequency-magnitude distribution. The approach differs in particular in the distribution of events within the background zone, as the largest events starting above some threshold magnitude can only occur on faults. Activity rate estimations were based on the approach proposed by Anderson and Luco (1983) and implemented in Bungum (2007).

The kernel-smoothed approaches, often called smoothed seismicity approaches, introduce a less subjective means to estimate future seismicity rates. Within the project, two models where suggested, one based on the Woo (1996) approach and another one based on the Hiemer et al. (2013) approach. The latter combines smoothing seismicity rates and smoothing the contribution of moment from faults to the overall seismicity taking advantage of the fully parameterized composite seismogenic sources (Figure 9). We consider only the latter in the SHARE model as the usage of only seismicity has not found enough support within the community.

Defining weights for the various branches of the logic-tree is the final step. Since the final computations were performed following the final SHARE meeting in Istanbul (November 19, 2012), the modelling team distributed the results of single branches and ask specific questions to evaluate the trust / believe in the various branches from the beneficiaries. The final proposition is to give the largest weight to the AS-model and then weight the FSBG-model and the kernel-smoothed model that uses seismicity and fault slip information (SEIFA). Note that with this distribution of weights, estimates based on geologic information, enters for the first time on this scale prominently a seismic hazard model.

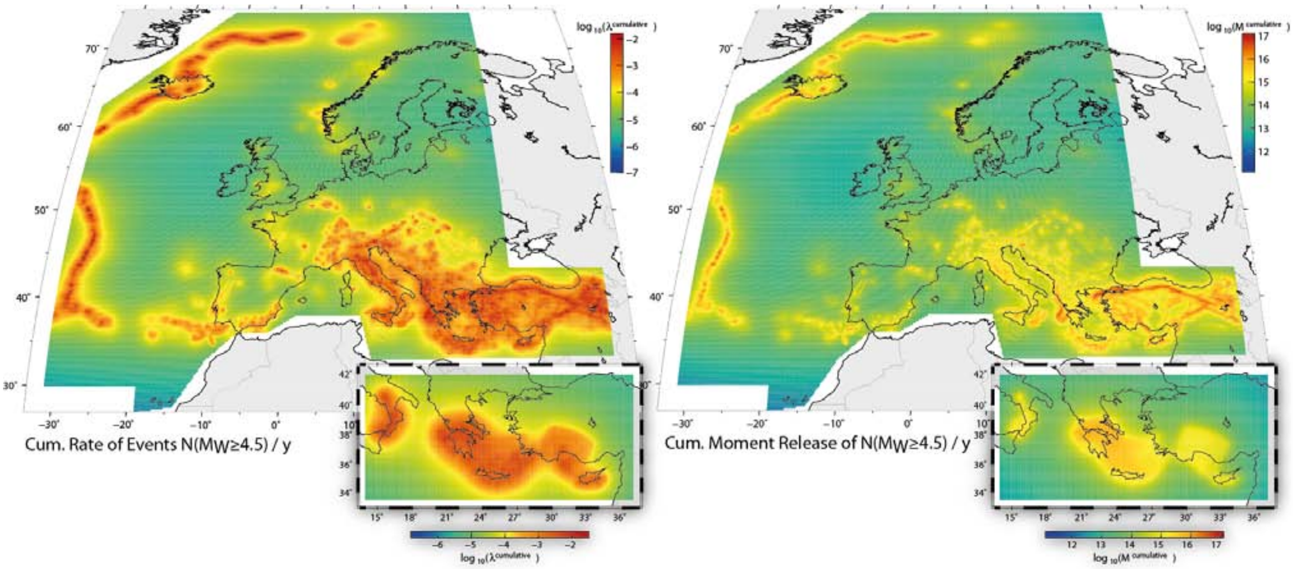

**Figure 9: Forecasted cumulative rates of events N($M_W \geq 4.5$)/year and cumulative moment release for events with N($M_W \geq 4.5$)/year as basis for hazard modeling of the SEIFA-model. Rates are separated for the crustal, subduction and deep Vrancea sources.**

Respecting the various feedback rounds within the project and with the expertise of a detailed knowledge about the data and methods used for the creation of the single branches, SHARE implemented its weighting-scheme (Table 1) that reflects the base data used to build each one. The AS-model is given the largest weight for the various exceedance probability levels and the weight increases with decreasing exceedance probability levels. We increase the weight of the FSBG-model for decreasing exceedance probability levels due to the importance of the geologic information for the estimation of activity rates. The contribution of the SEIFA model decreases with decreasing exceedance probability levels because SEIFA itself considers the contribution of seismicity stronger than the fault information. For exceedance probabilities larger than 10% in 50y, believe that the SEIFA-model and the AS-model should be equally weighted. We define the combination 0.5 AS-model, 0.2 FSBG-model, and 0.3 SEIFA-model as the average weighting scheme used to generate hazard curves.

### 2.3.2 Computation of seismic hazard

The seismic hazard calculations were performed on the computational infrastructure (see WP6, Task 6.3). The preliminary computations were performed with OpenQuake v0.8.1 using a Java-based core. A major drawback of those preliminary computations were the use of a point-rupture representation in the case of area and point sources. Sensitivity analysis performed for each computational model showed that there can be significant differences on the final hazard estimates when excluding the extended rupture options for the area/point sources. The experts recommended the use of the extended ruptures, as a more appropriate representation of the earthquake source characterization. Therefore, the final calculations were performed with the latest version of the hazard library of the OpenQuake package to explore the full model that was suggested for the SHARE region. The use of the latest version allows using extended and complex sources for the FSBG-model (see Deliverable D5.1 for their definition). In addition, with the latest engine, subduction interface regions can be handled as complex sources, while the inslab seismicity in the subduction zones is still handled as volumes at different depth levels.

Due to the complexity, the size and the large scale of the SHARE-model, the computation time for the final model is in total about 15 days on 224 CPUs without pre- and post-processing; this is roughly 40 times less computational time compared to what was estimated for the original engine on the same cluster.

Pre-processing includes all steps to generate the input files for the OpenQuake engine from the files that include the parameterization of each source model. The base files for each source model are either plain ascii-files (for the smoothed seismicity models) or standard shapefiles (http://en.wikipedia.org/wiki/Shapefile), a popular geospatial vector data format for geographic information systems software. The parameters of the files are explained in the deliverable D6.6.

In comparison to the availability of results from other hazard models, the SHARE results are outstanding and are close to the requested list of parameters of the engineering community (Deliverable D2.1). At the time of the final report, hazard estimates for the return period 101y-5000y are computed, for PGA and spectral ordinates between 0.1s-4s. For all grid points of the SHARE model located on-land (126044), hazard curves and uniform hazard spectra are available.

Disaggregation is at this time available for selected sites for which either scenario calculations were proposed at the beginning of the project (WP2) or for which we obtained requests from other projects such as EC-FP7 project PERPETUATE. The cities selected spread across the entire Euro-Mediterranean region representing various tectonic settings, e.g. Basel, Bergen, Lisbon, Thessaloniki, L'Aquilla, Istanbul and so on. Disaggregation is provided in terms of magnitude, distance and epsilon (Figure 10).

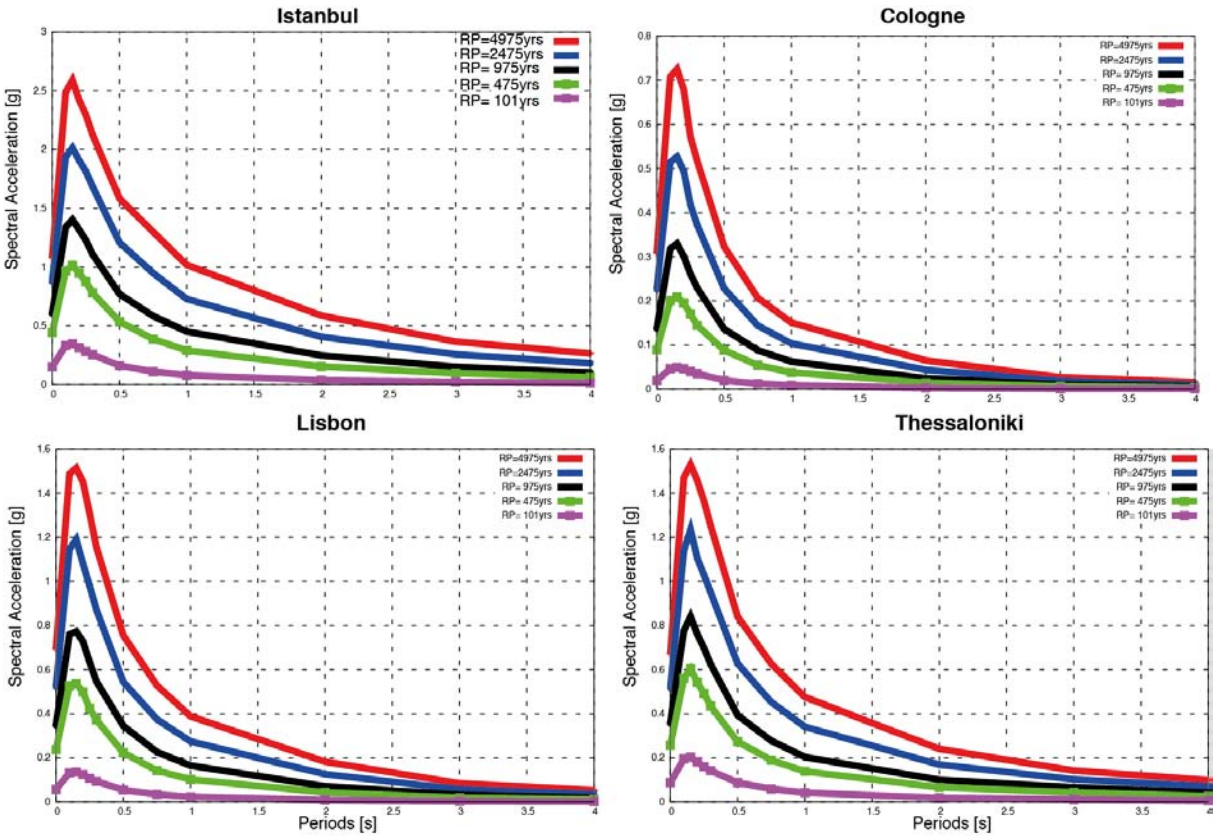

Figure 10: Uniform hazard spectra (UHS) for sites selected in the area of Istanbul, Cologne, Lisbon and Thessaloniki. Colours differentiate five return periods of interest.

### 2.3.3 Validation of seismic hazard results

Throughout the project, long philosophical and technical discussion on how to evaluate the seismic hazard results obtained with the new model. In particular, discussions about the correct terming arose, leading to a consensus that “validation” of hazard results in its strict sense is not correct. SHARE therefore focused on a stringent evaluation of the hazard results.

Evaluation of hazard results were performed following each new computation of hazard presented for the model review meetings (see Task 5.6). It is to be noted that due to the introduction of new model types and the usage of a new computational infrastructure, differences to previous models are expected and desired. The major evaluation procedures, with specifications given in deliverable D5.6, included:

1. Sanity checks of the hazard values against existing products
    a. On the regional scale, this was performed against the previous map of SESAME and GSAHP,

b. On the national scale, this was done against the national hazard maps by the modeling team and the consortium members. As an example, results in Switzerland could be compared to the Swiss National Seismic Hazard map (Wiemer et al., 2009);

2. Comparative computation of seismic hazard using the area source model with two different hazard engines: the computations were run at GFZ with their implementation of the FRISK-software and at ETHZ with the OpenQuake engine. The results, computed using point sources, deviate only slightly in a range of up to 5% difference;
3. Evaluation of site-intensity histories at various places;
4. Evaluation of ground-shaking parameters against observed distributions at sample locations;
5. Evaluation of the main contributors to the seismic hazard by means of disaggregation at about 30 sites throughout the study region.
6. CSEP testing procedures were used to assess the data consistency of the earthquake rate forecasts with current seismicity. The SHARE catalog includes events until the end of 2006. For testing, we downloaded the Harvard CMT and the NEIC catalog for the period 2007-2012 and run the CSEP-test data consistency suite for the 5 year period. Figure 11 shows example testing results for the AS-model only.

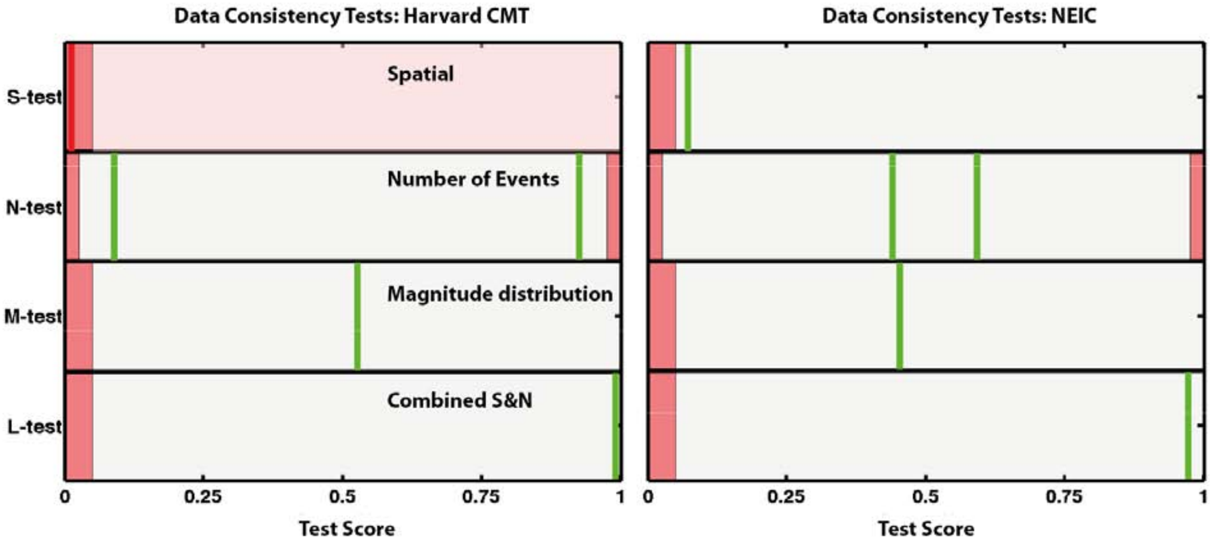

**Figure 11: CSEP data consistency tests for a 5 year period against the Harvard CMT data (2007-2012) (left) and the USGS NEIC data (2007-2012) (right). The likelihood based test are performed against the AS-model rate forecasts only. The test suite evaluates single features, such as the consistency in base, the total number of events, the magnitude distribution of events and a combined space-number of event consistency. Transparent red bars indicate rejection levels, light transparent red boxes rejected tests. Green bars indicate consistency with the data or a non-decisive outcome (L-Tests in both cases).**

### 2.3.4 Community feedback on seismic hazard results

Organizing community feedback in a well-defined procedure was a major task throughout the SHARE project. For the SHARE-project, it was not possible to organize this as a formal expert elicitation procedure as suggested by the Senior Seismic Hazard Analysis Committee (SSHAC) in their documents NUREG/CR-6327 and NUREG-2117. However, these recommendations were used as a guideline for some of the processes within SHARE. Within the possibilities, WP5 was involved in all meetings of WP3 and WP4 to help organize and understand the roles and participation of the various researchers in the project. WP4 organized much of the procedure and documented the procedure in Delavaud et al. (2012) for the selection of the logic-tree for the ground motion prediction equations. WP3 and WP5 worked closely together to define the source model logic-tree, yet there were not several teams that worked on building a multiple-source models, these were rather suggested and iterated on within the two WPs. Details of these source models were then presented to the entire consortium and additional external experts for feedback.

To achieve an adequate feedback, WP5 organized two 2.5 days dedicated review workshops (March 12-14 and September 3/4 2012, see deliverable D5.4) and organized together with WP1 the final meeting in Istanbul that one entire day was dedicated to an additional review of the hazard model. To each of these meeting, we invited external experts from the seismic hazard and earthquake engineering community to consider the perspective from outside the project. All topics of the hazard model were discussed within these meetings: particular focus was on 1) the estimation of activity rates parameters and the models used for this, 2) the concept of using large superzones as the basis to estimate parameters such as data completeness, maximum magnitude and tectonic regionalization, 3) the integration of data uncertainty within the models, 4) the usage of algorithm driven approaches vs. an expert opinion model, 4) the computational implementation of the models. The first review meeting was prior to the final delivery of all datasets, thus included discussions on data issues within the model building process. During the second workshop, preliminary hazard results could be evaluated. During the final meeting in Istanbul, revised hazard calculations were presented and together with the revised models. Due to the granted extension for the project, the final hazard calculations were run in spring 2013. For the final hazard results, we organized a feedback round via email for finally deciding on the full composition of the SHARE hazard model. Within the phase of final reporting, WP2 organized an additional one-day meeting to obtain a feedback of their products based on the latest results. The meeting involved earthquake engineering experts that had followed the SHARE process.