SHARE

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1. Introduction

Quality assessment (QA) is a major task for any Probabilistic Seismic Hazard Assessment (PSHA) and needs to be addressed on the procedural, methodological and input / output data level. On each level, quality assessment aims to ensure a benchmarked, transparent and reproducible process and product. Due to time and financial limitations, a regional project such as SHARE is not able to formally fulfill SSHAC level 3 and 4 requirements (Budnitz et al., 1997, Coppersmith and Bommer, 2012). However, some of the SSHAC components are followed as closely as possible. This deliverable is by no means globally comprehensive, yet it is comprehensive in describing the efforts within SHARE.

Requirements for PSHA vary according to the target area and major recurrence periods of interest, i.e. requirements are different when targeting a site-specific PSHA in comparison to a regional scale PSHA. The goal of this document is to outline procedures and methods that are essential and/or optional for the evaluation of a continental scale model such as the SHARE hazard model. However, some of these tests may not be successfully applied due to availability, quality or amount of data as thee may not be adequate for the needs of the evaluation. For example, testing computed hazard results against observed ground motion intensity measure types may be biased because the data against which it is tested was already used for deriving a ground motion prediction equation.

This document discusses the model building process, model documentation and tools for testing the input model and the seismic hazard model. We consider the quality assessment as part of the testing and evaluation process, targeting the procedural, methodological, data and result components of the SHARE model. We do not consider these steps as "validation" of data nor hazard products. "PSHA validation" is difficult to achieve with the present data sets and to us beyond of the current scientific possibilities; for example, the maximum magnitude M_{max} has yet to be observed for many regions of Europe and may only be "validated" after having observed several seismic cycles – hard to achieve during a PSHA experts lifetime.

We envision that large parts of this document may serve as a primary guideline for other regional programs within the Global Earthquake Model initiative (www.globalearthquakemodel.org). SHARE targets to assemble a so-called sandbox of tools with which the PSHA models can be constructed. It should be noted that due to the project setup, there is not a single tool. However, the workpackege responsible for the computation infrastructure WP6 (http://www.share-eu.org/node/19) attempts to integrate all the tools successively in a Source Model Toolkit (SMT) that in future studies may be used by scientists and practitioners to create an input hazard model. This input model is thereafter fed into the seismic hazard computational software OpenQuake (www.openquake.org).

2. Building a community-based, consensus hazard model

SHARE is building a community-based, consensus probabilistic seismic hazard model for Europe. Consensus is "a process of decision-making that seeks widespread agreement among group members" (Wikipedia, http://en.wiktionary.org/wiki/consensus, accessed 07.03.2011). For a regional PSHA, consensus building has several important goals within a regional project and thus serves on various levels.

The prime goal is to generate a Euro-Mediterranean PSHA-model that is homogeneous across the entire area and that will serve as the prime resource for further application in the engineering community such as the revision of the EC8-building codes. The SHARE project is depending upon elicitation of expert opinions as this is seen as best practice for PSHA and as the study area covers a vast number of different tectonic regions ranging from stable shield areas, extensional regimes within the stable continental regions, the alpine collision, fossile subduction (Vrancea), plate boundaries (transform, strike slip, subduction and oceanic ridge), hot spots and volcanic regions. Thus it is necessary that local experts and responsible bodies are involved in the process. The PSHA-model should reflect most of these opinions in its logic tree definition but also considering all the opinions in a way adequate for the project goals.

Consensus within SHARE is targeted at two levels:

- Input data level:
    - Earthquake sources and activity rates
        - Earthquake Catalogue
        - Source Typologies
        - Approaches to define the maximum magnitude M_{max}
    - Strong ground motion modeling
        - Selection, Testing and Evaluation of Ground Motion Prediction Equations (GMPE)
    - Logic tree definition
- Hazard level with resulting PSHA from the various logic tree branches

An extensive feedback process on both of the above levels is critical to strengthen both the consensus building and the quality of the hazard model. Due to time and financial limitations a regional project such as SHARE is not able to formally fulfill SSHAC level 3 and 4 requirements (Budnitz et al., 1997). However, some of the SSHAC components are followed as close as possible.

Due to the limited project time – a common problem for large-scale initiatives such as SHARE - a consecutive procedure to collect data and then perform seismic zoning was not possible. Therefore, data collection and zoning was performed in parallel coordinated with dedicated task leaders and within several workshops that either targeted a specific or multiple types of input data. This setup is in essence not desired but pragmatic. The team responsible for implementing the hazard model was therefore required to attend these workshops actively to understand the diversity of the expert opinions and to clearly state the requirements on the data sets and also to state to which parameters the hazard computation might be sensitive or not.

As an overview, topics on earthquake source zones and activity rates were addressed independently of the GMPE process indicated also by the separation into two workpackages (WP3 and 4). Both workpackages organized workshops with external experts; external experts are defined as well respected researchers not working at one of the funded institutions. At annual meetings of the project, results were presented to all participants for discussion. Essential is also a feedback meeting on the first round of hazard computations held in time to implement modifications for the final hazard assessment. Such a meeting enables the hazard modeling team, in SHARE member of WP5 and WP6, to outline the implementation of the model design and triggers a valuable feedback process.

2.1 Consensus on input data level

During SHARE, consensus on the earthquake source data was reached with a number of regional workshops that allowed for input from local and regional experts: the subregions are displayed in Figure 1. For most workshops, data was requested ahead and presented during the meeting focusing the discussion on the most important issues such as the border regions between countries. During and following the workshop, the WP3 task leaders spend additional time in integrating the consensus reached during the meeting with the experts to revise and update the data available (either area source zones or active fault data). The data were then reassessed after the workshop and send for feedback again to the contributors and experts for feedback. The process involved 8 dedicated regional workshops and multiple meetings at other occasions. The first preliminary version was then discussed during an internal SHARE meeting with participants from all workpackages with the scope of evaluating the preliminary model with respect to the needs of building an appropriate logic tree for the hazard model.

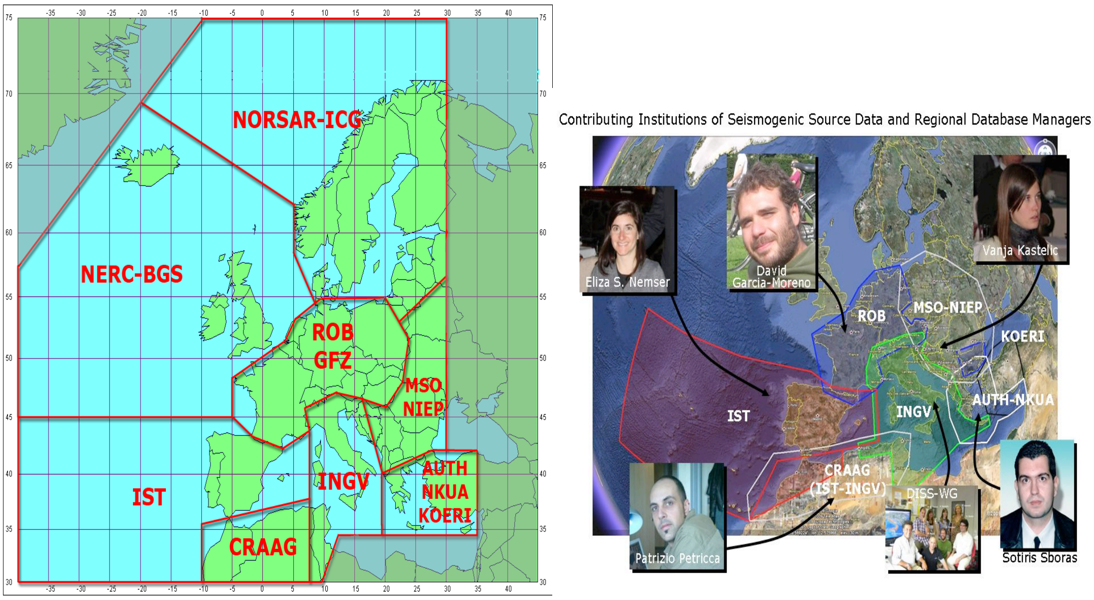

Figure 1: Subregions for data collection within SHARE. (Left) Regions and responsible institution for collecting area seismic source zone data. (Right) Regions and researchers to assemble the active fault data to contribute to seismogenic source definition.

The model thus has been anchored within the SHARE community by being presented and discussed at SHARE meetings such as WP5 model building workshop and the SHARE annual meeting. Thus the levels of consensus for the SHARE PSHA model are:

- Regional and local level through experts participating in regional workshops.
- European level within SHARE.

The workpackage on strong ground motion modelling targeted to update the strong ground motion database (Deliverable D4.1) and then to select, test and adjust the ground motion prediction equations for rock sites. The process also included several meetings of project and external experts. After the selection of GMPEs and testing against European data, the information was provided to five experts: these experts provided their weights and reasoning for the weights at a final workshop including a larger group of SHARE participants. Within this workshop the weights of the selected GMPEs for the logic tree in different tectonic regions where settled and documented.

2.2 Hazard model level

Consensus on the final SHARE hazard model will be sought through a community feedback meeting containing SHARE expertise and with external experts from the PSHA community: Firstly, preliminary hazard calculations are discussed in internal project meetings. Secondly, the model is updated and then presented to project and external experts; this process may be repeated, depending on the available time. Based on this second feedback, the final model for the project will be computed.

3. Documentation

Documentation is a key milestone in QA for any PSHA to ensure a high quality product (Budnitz et al., 1997):

- “Only through adequate documentation can others in the technical community understand or review the analysis and the results.”
- “Only through adequate documentation can a later analysis team with new information or improved models utilize a PSHA to update it, revise it, or validate that it does not need and update or revision.”
- “Only through adequate documentation can the sponsoring organization retain an adequate record of the process it supported.”

The documentation can be split up into several areas like input model, analysis, results, participants and logging of activities.

Input model level – the various steps of the construction of the source models, meetings, and feedback processes are described both in the SHARE data submission form (Danciu and Woessner, 2010) to be included with submission of the model as well as in reports to SHARE and scientific papers.

Analysis level – the different analyses performed should be properly documented and described in scientific papers and reports. This should be done for the methodologies as well as the analysis and results.

Within SHARE a large part of the documentation of the different parts is done through deliverables and publications.

4. Quality assessment of the earthquake catalogue

The earthquake catalogue is one of the prime data sets for a thorough hazard assessment. An earthquake catalogue generally combines information gathered in various ways, depending on the time period the data covers, e.g. paleo-seismic, archeo-seismic, historical or instrument period. The earthquake catalogue is thus a result of a process combining decisions based on prior knowledge of scientists (seismologists, geologists and historian) for early periods mainly and as well methodological decision on the processing chain of instrumental earthquake data. The parametric information on each earthquake should in the end be as comprehensive as possible and useful for the envisioned PSHA including data on location, time, size in terms of magnitude or seismic moment, focal mechanism, etc, together with estimated uncertainties for these parameters. Useful for PSHA also means that one preferred solution is given for each earthquake assuming that the given uncertainties cover the range of possible solutions.

In addition to the various periods covered, a regional scale project faces the issue to combine catalogues from local authorative data providers. This requires decisions on the authorative regions of a data provider and to calculate magnitude-magnitude conversion relations as one single homogenized magnitude, generally a moment magnitude (M_W), should be used in the PSHA. Different strategies can be implemented for this such as described in Faeh et al. (2003) and Stromeyer et al, (2004).

Since the issues of the both, time and space issues are multifold for each different dataset, the catalogue generation requires a dedicated working group in a regional project. In SHARE , homogenizing the earthquake catalogue was targeted by a dedicated task in which scientists across multiple disciplines worked together with the focus on different time periods (see Deliverable 3.2).

Declustering was performed, following the method by Grünthal (1985) and mentioned by Burkhard and Grünthal (2009).

Given the homogenized catalogue, a space-time completeness model needs to be derived. A common strategy is to start analyzing large regions with a statistical method(s) (Albarello et al., 2001; STEPP, 1972; Stucchi et al., 2004) and then, for the early periods, consult the data providers that have greatest insight in the original sources documenting the earthquakes (Faeh et al., 2003, Stucchi et al., 2004). In the end, a space-time completeness model needs to be obtained for each source to be used in the PSHA. Within SHARE, this work was conducted by the catalogue working group that devided up the SHARE region in various subregions . Details can be found at http://www.emidius.eu/SHARE/task3_1/.

5. Quality assessment of the input model

QA of the input model will be important for assuring the quality of the SHARE hazard results. The QA efforts can be sub-divided into five main topics:

- Assessment of source typologies
- Area sources (AS)
- Fault source and background sources (FS+BG)
- Activity rate and frequency-magnitude relations
- M_{max}

5.1 Source typologies: Constructing an area source model

The construction of the area source model is based upon typologies described in SHARE deliverable 5.1. The seismotectonic process of an area is an important part of the determination of seismic source zones. The seismotectonics, however, differ substantially across the European-Mediterranean region between stable continental regions (large scale seismotectonic provinces often coinciding with older tectonic regimes) and active areas (presently forming structures). In general, in the construction of area source zones it is essential to understand the genesis of earthquakes for a given region to prioritize the available data base. . Example data sets are the earthquake catalogue, the geological / rheological units, geodetic data, faults, archeoseismolog, paleoseismicity, Moho depth, topography, etc. Prioritizing the data means to categorize the available information regarding the seismotectonic process, in as e.g. in Wiemer et al. (2009) who used three classes (most useful, moderately useful, marginally useful) to define a zonation model. The objective then is to use the information and match the assumption of an area source model that seismicity is following a spatial Poissonian distribution; epicentres are therefore homogeneously distributed within a single source zone.

Considering tectonic constraints in addition to the earthquake catalogs information reflects that the time periods covered by the seismicity record is very short in geological terms and do not represent full seismic cycles.

Important for a regional scale project that integrates pre-existing area source models is to assess and document which priority scheme was used in constructing the prior models. Since SHARE faced the task to assemble an area source model as an aggregate of previous assessments with its own considerations (see SHARE deliverable D3.1), a scheme description such as proposed in Wiemer et al. (2009) is essentially not possible because these are not documented in the previous assessments.

5.1.1 Geometrical considerations

A regional scale project receives data at various quality levels. Area sources are basically polygons that need to be assembled and geometrically homogenized with an appropriate tool. Most of these issues can be addressed with a Geographic Information System (GIS) in which the polygon properties can be assessed.

SHARE resolves the geometric issues with the Source Model Toolkit (SMT, www.share-eu.org/node/77) which uses QGIS as its GIS backbone. The following issues were addressed:

- the polygon discretization size
- the order of the data points (clockwise or anticlockwise)
- unification of polygon points of adjacent polygons to avoid empty or overlapping coverage of the polygons (manually and automatically)
- synthesis of two or more polygons to one polygon

Moment balancing, discussed below in section 5.2, is also used as a tool for reviewing the soundness of construction of the areal sources.

Homogeneity tests of seismicity within single source zones have been proposed Budnitz et al. (1997) and performed by Musson and Winter (2008) to obtain a statistical measure of homogeneity of the observed seismicity within an area source zone.

The use of Monte Carlo location tests (Musson and Winter, 2008) is being recognized as a useful research tool. However, due to the in many cases short time periods for the earthquake catalogs leading to incomplete data coverage in space we include a review of this type of test for the sake of completeness.

As a matter of fact, catalogues are in many areas of rather short duration leading to difficulties for conclusive tests with regard to the homogeneity of the seismicity within source zones. Nevertheless, keeping in mind this limitation, certain tests can be performed:

Budnitz et al (1997) propose a test using a synthetic earthquake catalog assuming activity rate parameters and M_{max}. From these assumptions catalogs can be pulled out from the "complete" datasets to correspond to the level of observed activity within a source zone. The coverage of the synthetic catalog and the observed seismicity can then be compared for any given source zone. Musson and Winter (2008) performed a test where the spatial distribution of earthquakes in a synthetic catalog (derived from the zonation and the associated activity rates) is compared to the observed distribution.

The use of the above tests is to achieve a statistical measure for the homogeneity of seismicity within source zones. It is not obvious that this type of test will be conclusive for all source zones because discrepancies can be due to too few earthquakes within a source zone to enable a reliable test. The lack of seismicity can be a result of too few seismic cycles needed to produce a homogeneous spatial coverage of seismicity in a seismotectonically homogeneous area.

5.2 Activity rates and frequency-magnitude distribution (FMD)

Within SHARE, activity rates will be determined for area sources, combined fault and background sources; smoothed seismicity model(s) may deliver their output as either activity rates or as synthetic catalogs. Testing activity rates can be performed on differently for fault sources compared to area source zones. Below we describe bootstrapping as stability test of activity rates, moment balancing and CSEP type testing; the latter is a shared effort between the CSEP European Testing Center (www.cseptesting.org). All methods are based upon seismicity for determining activity rates. Activity rates are checked against observed seismicity and against independent geological and geodetic constraints, in particular the total moment release or moment release rate. Important is to ensure that double counting of activity from seismicity and fault sources is avoided.. Within SHARE we have chosen to perform this with moment balancing and test described in CSEP for the occurrence rates..

5.2.1 Stability of activity rates

A simple optional test, not planned within SHARE, is to check the stability of the earthquake data within source zones is to apply bootstrapping. A recursive procedure is by removing a specific event from the data set, computing the activity rate. Next insert the event again and remove another earthquake and recomputing the activity rates and so on. This provides a measure of the stability of the activity rate calculations. Similarly, parts of the catalog can be removed from the calculations as a check of the stability.

Subcatalogs of a simulated long-term synthetic catalog can be used for testing activity rate parameter stability by randomly drawing data for a comparable in time period as the the observed seismicity catalog and then assess whether the derived activity rates are in agreeement with the full synthetic catalog (which may be of much larger time span). This can then be used to infer the stability of activity rates determined from the observed catalog. This type of test is also dependent upon Mmax.

5.2.2 Moment balancing

Moment balancing targets to check estimates of seismic moment or moment rate, normalized to some area or volume and time period, of independent data sets – seismicity, geologic, geodetic and models inferred from either single or combinations of the given data sets. A hazard model relies in addition on different source typologies and each of them should be evaluated in comparison to observed independent data or models. In the following, we will use moment M_0 as comparison parameter. Moment rate or strain rate are e.g., equally well suitable.

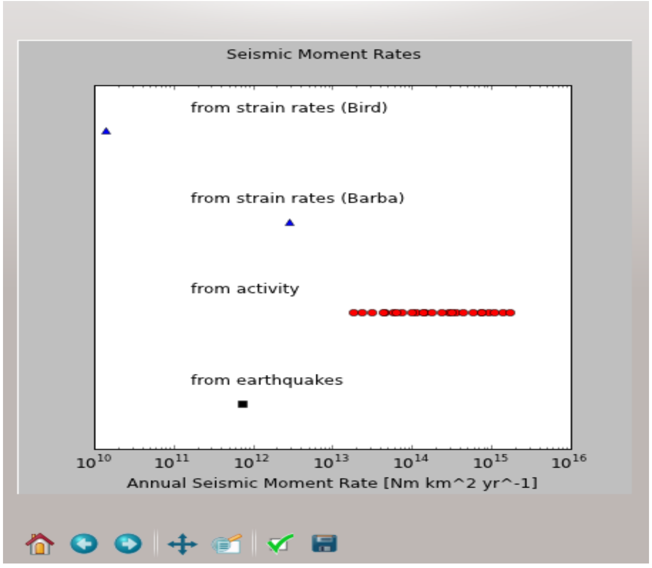

Figure 2: Moment balancing of an area source using (in)dependent data sets. Moments are given from two strain rate models, from activity rate calculations and from the catalog.

The following generic cases (non-exhaustive) exist:

- For an area source (AS) model, the total seismic moment from a geodetic model(s), the observed seismic moment and activity parameters can be compared (Figure 2).
- For fault and background sources, the seismic moment from the catalog, the combined activity from the zones and the total strain rate should be compared. The geologically determined moments provides the insight on contribution of the fault sources. Depending on the fault model parameterization, moments can also be provided with uncertainties in the activity parameters though this should match the geologic estimates from slip rates..

Moment balancing does not have a single solution and it may well be the case that e.g., the seismic moment may over- or underestimate the geodetic moments – the decision whether a balanced model exists lies in the expertise of the hazard modelers.

SHARE recognizes moment balancing as one of the most important parts in the model building and will perform this task using the Source Model Toolkit.

5.2.3. CSEP earthquake rate testing

Testing seismicity rate forecasts for grid-based models follows the methodology proposed in the Collaboratory Study for Earthquake Predictability (CSEP) and is planned for all branches of a hazard model. The grid-based approach provides well-defined testing metrics though it also includes limitations in its testing procedures. A variety of likelihood-based testing procedures for various aspects of earthquake activity rate forecasts were developed before and during the CSEP project (Jackson, 1996; Rhoades et al., 2010; Schorlemmer et al., 2010; Zechar, 2010): these tests evaluate the spatial distribution, the total rate, and the agreement with the frequency-magnitude distribution.

The CSEP testing procedures will be applied retrospectively and also for the single model components. This will shed light on the consistency with the data of the various hazard model ingredients and give a ranking based on objective measures. Prospective testing of the SHARE model and its parts is envisioned within the framework of the European testing center at ETH Zurich in collaboration with the GEM testing and evaluation facility at GFZ (http://www.globalquakemodel.org/node/1494).

With respect to the requirements of a long-term hazard model and the construction of the model itself, the CSEP tests will incorporate to test the forecast in the area sources as defined in the source typologies. This is to respect the different assumptions that enter a hazard model. In particular for SHARE, the tests will be run against the global CMT catalog to which the moment magnitudes are calibrated.

5.3 Maximum magnitude (M_{max})

M_{max} can be determined via two parallel data sets, either from longest observed faults or from seismicity.

To assess the maximum magnitude from long-observed faults the modeller might consider answering the following questions:

- Has the longest fault been trace been observed?
- What is the true depth extent?
- What is the maximum possible slip for a single event?
- Do the fault continue outside of the observed trace?
- Can largest event have occurred on several segments?
- Do the largest event rupture the whole or only part of the fault?

M_{max} from seismicity can be estimated either directly from the data or assuming that the largest observed event is equal to M_{max} or from global analogies. For stable continental regions it is common to use the EPRI methodology (Coppersmith, 1994, SHARE deliverable

D3.3) which tries to overcome the problem of too short observational time periods of the seismicity catalogs together with the observed seismicity using global statistical analogies (Coppersmith, 1994). Questions to be addressed when assessing M_{max} from seismicity are among others:

- Is the catalog complete in terms of containing the maximum earthquake for the studied area/source?
- Maybe the fault on which this “largest observed” earthquake occurred only ruptured partially?
- Maybe the fault ruptured before strain had accumulated for maximum slip.
- Maybe maximum slip is dependent upon whether nearby faults have ruptured or not?
- It could possibly be that several cycles of seismic strain release must be observed before the “true” Mmax is observed. If so, Mmax cannot be determined from seismicity for large parts of the SHARE model.

Understanding the limitations of the present seismicity and faults are thus important in order to not underestimate M_{max}.The quality assessment of the M_{max} checks whether the relevant methodologies were applied within specific tectonic environments and also how Mmax determinations compare to previous studies – yet this does not imply that the same values should be taken. An example for the consequences of underestimating M_{max} was tragedly show with the 2011 M9.0 Tohoku earthquake off cost of Japan.

The importance of uncertainty in M_{max} can be tested through a sensitivity analysis, investigating the effect of using different M_{max} values on the hazard output. This uncertainty will be accounted for in the hazard result through the integration of several logic tree branches with different M_{max} values. The SHARE approach is described in more detail in deliverable D 3.3 (Meletti et al., 2011).

An optional test of the appropriateness of designed M_{max} values can be by employing synthetic earthquake catalogs. For a given synthetic catalog, with a given activity rate and $M_{max,}$ a catalog of shorter duration is pulled, similar to catalogs within the European area and test if the applied procedure will result in a realistic M_{max}. If not the procedures for estimating M_{max} must be adjusted. This test could be useful for not under-estimating M_{max}.

As the topic of maximum magnitude has received increasing interest due to recent large event and SHARE targets to compute hazard values also for long return periods, it is essential to analyze the possible distribution of M_{max}. The statistical seismology community and extreme value theory provide additional statistical methods to compute confidence levels on the maximum magnitude of a power-law distribution (Hohlschneider et al., 2011; Pisarenko and Rodkin, 2010).

5.4 Fault source tests

Quality controls within SHARE follows strictly the DISS methodology as implemented within SHARE by INGV (Basili et al., 2008) whereas testing of fault source within SHARE will mainly be focused on the use of moment balancing, see section 5.2, Some optional QA controls that the fault sources have been properly assessed can be done as (Basili, personal communication):

- A comparison of faulting parameters assigned to seismogenic sources to those of observed earthquakes.
- The reliability of the seismogenic sources location can be tested by comparisons with the location of the observed earthquakes and/or seismic moment release. However, this is dependent upon how complete (in time and space) the earthquake catalogue is and also how large the location errors of earthquakes are.
- A sensitivity study can be to investigate the effect of considering only the best solution for seismogenic sources, as is common practice in DISS (i.e., not including other interpretations by other scientists in a logic tree, or similar). The effect on the hazard of considering various interpretations for selected structures can be done as a sanity test of the fault data. Within the DISS methodology quality indicators are assigned for faults, indicating the reliability of present earthquake activity. These could be assigned by the analyst considering whether the fault is defined based on the occurrence of a previous brittle earthquake slip (as seen from observations of e.g., slickensides and / or known earthquakes) or the fault being part of an active fault system.

6. QA for ground motion prediction equations

When selecting the ground-motion prediction equations (GMPEs) to be applied in SHARE, several critical questions must be clarified:

- Are there relations sufficiently valid for all tectonic regions of Europe?
- What are the most suitable GMPE/GMPEs for a given tectonic region?
- Can the given GMPE be implemented with the seismic hazard engine and the data from WP3?

The first two questions are being investigated by WP4 by comparing to observed strong motion data from various regions in Europe. The selection of GMPEs is based upon expert opinion and comprehensive testing is done against available observed ground motions. One part of this procedure is described in Drouet et al. (2010). The third question has been resolved through coordination efforts between WP3, WP4, WP5 and WP6.

If GMPEs are used outside of the magnitude range for which they were constructed a rigorous testing must be applied. Otherwise strange artifacts in the seismic hazard as discovered by Musson (2009) may occur. The reason was that the functional form and the construction of σ for a GMPE have a large effect on the probability of small earthquakes causing large ground motions, which may affect the hazard significantly. Whether the functional forms of the chosen GMPE as well as their σ are appropriate, especially in cases where a GMPE is extrapolated outside its bounds of validity, can be investigated by checking the sensitivity of the derived hazard curves to M_{min} and M_{max} for different hazard settings (low vs. high hazard), as described by Musson (2009).

The selected GMPEs were implemented in the seismic hazard engine and details of the overall implementation framework is presented in the next section as well as in the SHARE deliverable D6.4.

Preliminary sensitivity tests were performed to investigate the effects on the hazard results of the different weights assigned to the selected GMPEs by WP4 experts. The sensitivity analysis was performed for two types of seismic sources (area and fault source) and considering various weighting schemes for different tectonic regions. The focus was on active shallow regions and subduction regions. Sensitivity analysis results shown differences on hazard values up to 15% when the proposed weighting schema was compared with other proposed weighting schemes. Additional differences were observed when an area source was modeled considering different types of subsurface ruptures, modeled as a point or line ruptures. The maximum differences of hazard values from the different tested PSHA engines was up to 12-15% (Danciu et al., 2010). As mentioned above SHARE GMPE testing has been performed within the auspices of WP4 whereas the implementation has been done by WP6.

7. QA Hazard Computation

Systematic quality control and quality assurance testing must be performed at all stages of seismic hazard computation. Technically, the seismic hazard computational workflow consists of two stages:

- Assemble of the seismic hazard model and generation of the input files. This is achieved with the help of the newly developed Source Model Toolkit (SMT).
- Hazard Computation using OpenQuake platform developed and maintained at the GEM Model Facility.

The key process of generating the hazard model, embedding all the available data, the adopted assumptions and the logic tree structure, requires thorough quality control. Sanity check of all input data has to be performed accordingly to the criteria presented in Section 5. Moreover, because the data is assembled using newly developed software – SMT – there are quality control/assurance activities toward this package. This implies testing and validating all the SMT computational modules, including:

Activity calculation module

- Seismic Moment calculation modul
- Frequency magnitude distribution calculation module
- Input/Output module
- Batch computation module producing appropriate input for OpenQuake

The SMT development is based on test driven development – TDD- [http://en.wikipedia.org/wiki/Test-driven_development] process that implies to automatically run tests to achieve the software functionality. SMT is a collection of a Python and Fortran plug-ins and the theoretical background of the methods will be found on the SMT blueprint produced by the SHARE team at ETH (https://github.com/feuchner). The main authors of the programming codes provided samples of the input and output and they were used to validate the SMT results. A second aspect at this stage is the preparation of input files for OpenQuake. The input files are based on a predefined eXtensible Markup Language (XML) scheme. This XML scheme, named NRML was defined and adopted to standardize the input/output for seismic hazard, risk and socio-economical impacts by the GEM IT development team. Again, TDD framework that means that the NRML schema is automatically tested and auxiliary tools are provided to handle it (https://github.com/gem/openquake/tree/master/openquake/nrml/schema).

OpenQuake – The Seismic Hazard Computational Engine is constructed from the framework of the OpenSHA - which in turn was one of the hazard softwares evaluated and successfully reviewed by the PEER initiative (Thomas et al., 2010). Also, comparative exercises (single area and fault sources) were conducted for several different seismic hazard software PSHA computational packages including OpenSHA, CRISIS, NSHMP, FRISK88M and SeisRisk IIIM (Danciu et al., 2010). The results of these comparative tests on the area and fault sources show a relative stability of the results of the compared software. However, it can be foreseen to do further cross-checking tests on comparisons of larger areas including difference maps between OpenQuake and the standard software adopted for hazard calculation worldwide - FRISK88M. FRISK88M calculations are planned at GFZ for this purpose. It should be kept in mind that a side-by-side comparison might not be straightforward, due to some limitations on the FRISK88M – lack of selected GMPEs for SHARE project. However, benchmarking will be limited to selected regions, limited logic tree branches using only common GMPEs.

The GMPEs selected by WP4 were implemented in the OpenQuake engine and in summary the GMPE implementation loop consists of writing the main functions for each equation, then run a cross-check validation with an alternative implementation (Matlab, Fortran, etc), write code for testing the values of the present implementation versus table of values supplied by the main GMPE authors. More details of the implementation process and how further GMPEs can be implemented are presented in deliverable D.6.4. Moreover, one might consult an overview of the technical quality control of the OpenQuake with a highlight on the TDD framework in the SHARE deliverable D6.8.

8. Testing hazard output

An important part of the QA effort will be focused on testing the hazard results against different parameters. Firstly, the hazard results must fulfill the requirements from WP2, as presented in D2.1. This is controlled within SHARE through coordination between WP2, WP4, WP5 and WP6.

The obtained hazard can be tested with either against observed strong motion, observed intensities or modeled synthetic ground motion (strong motion or intensity), other PSHA models and disaggregation.

In some cases the drawback of using the strong motion observations for testing the determined PSHA is that the used data are also employed in the construction of attenuation relationships (which are used in the PSHA). Thus the tests may use same data as being used for construction of GMPEs. Within the SHARE project this is relevant for tests using strong motion data but not for intensity observations since only PGA-based GMPEs are being employed for the SHARE PSHA.

It can still be argued that use of this type of data is important as a sanity control to find out if the whole hazard process at the end gives result in hazard at levels as expected from observations. For the future, prospective tests, i.e., gathering new strong motion for the future will be an important test for the model and for future improvements on the model. This will however not be done within the project but is rather encouraged for future investigators

Available intensity data sets are e.g., the German (Stromeyer and Grünthal, 2009; Grünthal, unpublished data), the Italian DBMI04 (Stucchi et al., 2007), the French (Scotti et al., 2004) and the Swiss (Fäh et al., 2003) high quality catalogues of intensity data points. One advantage with intensities is that the duration of the catalogues is very long compared to strong-motion recordings.

Strong motion data has been gathered within the SHARE project for an updated European strong-motion database. This catalog is the now most complete strong-motion dataset for the Euro-Mediterranean area and is thus a natural choice for strong-motion based tests. The limitation of the strong motion data set, is that at best, it represent a few decades of recording.

We describe below in sections 8.1-8.4 a selected collection studies/tools for testing the determined PSHA.

8.1 Single site tests

Testing hazard results for a single site may in many cases be difficult due to the often limited recording history at single sites (even in terms of intensity). This issue was addressed by Beauval et el. (2008). It was deduced that for single sites in France estimated that the duration of observed data was much shorter than the statistically required time windows for comparing

PSHA hazard estimates against real data. Thus this limitation of using data (intensities or strong-motion) at single sites must be kept in mind when employing single tests as in the following studies:

- Ordaz and Reyes (1999) compare hazard curves to the recorded ground motion history at a site in Mexico. The observed data are converted into annual probability by counting exceedances of different ground motion levels and dividing by the duration of the observation period.
- Mucciarelli et al. (2000) calculate average return periods of different intensity levels from observed intensities at a number of sites in Italy and compare to the average return periods derived from the national hazard map. The ratio of the two return periods at a given site is used as an indication of correspondence between hazard map and observations.
- Stirling and Petersen (2006) compare site-specific hazard at sites in USA and New Zealand to observed intensity histories, converted into PGA, at selected sites. The test was extended from not only being a single site test but also to area based.
- Miyazawa and Mori (2009) compare a Japanese hazard map for 475 years return period to 500 years of observed intensity data. First, the percentage of the map area with maximum observed intensity in a given intensity class is compared to the percentage of the hazard map area predicting the given intensity class. A discussion regarding this study can be followed in Beauval and Douglas (2010) and Miyazawa and Mori (2010).

In order to assure the longest possible data history, single site tests in terms of macroseismic intensity will be desirable. For such tests it can be discussed if it is preferred to derive the hazard curves in terms of intensity directly (using intensity prediction equations) instead of converting observed intensities into e.g. PGA. This would avoid the drawback of introducing additional uncertainties from the intensity to PGA conversions. However, despite this drawback it will be necessary to use intensity to PGA conversions since SHARE will produce PSHA related to PGA. It should be noted that intensity data also might be influenced by local site effects leading to amplified ground motion. If this is the case then use of observed intensity data should give higher prediction of site hazard than the standard PSHA.

Intensity to PGA conversion are available using local data for Italy (Faenza and Michelini, 2010, Cauzzi and Faccioli, 2004)

It should be noted that the use of observations is for single sites (discrete points within an area) are not smoothed whereas as the Cornell PSHA method results in a smoothed PSHA of the seismic hazard.

Another issue is the completeness of data. The intensity data are important because they represent the dataset with longest time span. Strong-motion data on the other hand represents at best a few decades of data.

Within SHARE the single site analysis will be performed for selected sites with long observational time history. However, it should be kept in mind that statistics from single sites as shown by Beauval et al. (2008) is usually based on poor statistical estimates. Thus there are only a few observed events in the time of completeness, few hundred years, clearly not enough for a reliable statistical estimate. It is therefore expected that for single sites the outcome will only be indicative. It is therefore preferential with multi-site analysis.

8.2 Multi site tests

- McGuire and Barnhard (1981) validate hazard estimates against observed ground shaking by calculating (from the hazard estimate) the probability of exceeding a given intensity in 50 years at a large number of sites, and then for a number of intensity ranges derive the percentage of sites within the given range, which have actually experienced shaking exceeding the given intensity in a given 50 year period. The so-called "observed" site intensities are derived by combining the earthquake catalog with a GMPE. It could be noted that McGuire (1979) found that a time interval of 50 years is more appropriate than 100 or 200 years at least for China, probably due to periodicity in the earthquake occurrence. This test may be especially useful in regions whith poore ground-motion/intensity observations but with a high quality earthquake catalog.
- Ward (1995) applies in a similar manner area based tests comparing hazard maps (probability of exceeding a fixed ground motion level in a given time) to 'synthetic observed ground motion' (derived from earthquake catalog and GMPE). One test compares the locations of predicted high hazard areas to locations of high observed hazard, the other compares the total area of a predicted hazard level to the observed area of the same hazard level
- Albarello and D'Amico (2008) apply counting and likelihood methods to test hazard results against observed site ground shaking histories and ground shaking distributions. The tests compare the number of sites exceeding a given ground motion level within a fixed time frame to the probability of exceeding this ground motion level according to the hazard model,
- Fujiwara et al. (2009) apply an area based technique to validate a Japanese hazard map for the 10-year period 1997-2006 against K-NET recordings. They compare the percentage of K-NET stations exceeding a given intensity (Ix) to the probability of

exceeding Ix, averaged over all hazard calculation grid points and over the grid points located at places with 1000+ population (since these are the regions where most K-NET stations are located).

- Stirling and Petersen (2006) also included an area based test for the whole model of New Zealand and the continental US. The PSHA was slightly over predicted within New Zealand and California but under predicted within the intraplate U.S. A conclusion was that use of the intensity data was necessary in combination of knowledge of site effects at points of observed intensities.
- Stirling and Gerstenberger (2010) made a study similar to Stirling and Petersen (2006) but instead of using intensity data strong motion data was used. It was found that the national New Zealand PSHA estimates were underdetermined in comparison to observed data in contrast to Stirling and Petersen (2006). However, after correcting for aftershock occurrences in the strong motion data the model as whole as well as single sites were accepted, i.e., not under predicting hazard. They consider intensity data less reliable but suggest combining strong motion observations with intensity data for future tests of the New Zealand PSHA model with lower weight to intensities. Reasons for including intensities are that they constitute a much longer period of observations than the strong motion data set. One limitation of the study was that they were limited to the tests for rather low accelerations (0.1 g).
- PSHA for Italy was tested against intensity based site-approach by considering the spatial distribution of the residuals (Muchiarelli et al. 2008).

Within SHARE we intend to perform multi site analysis (e.g., see Stirling and Petersen, 2006, Albarello and D'Amico, 2008) for the purpose of hazard testing. This is currently studied at GFZ. For a correct evaluation of the results we must understand the possibilities and limitations of the used data sets. The advantage of intensity data is the long duration in time of observations. Intensity data, though, might be suspected of being biased of strong site effects. Strong motion data are on the other hand more controlled in terms of sites but of much shorter duration than intensity observations. Intensity data also covers a much larger number of sites than the acceleration data. These effects of these matters, needs naturally to be addressed in the analysis and the interpretation of the results.

8.3 Testing against existing hazard products

The SHARE hazard model will in addition be controlled against existing products. Here, benchmarking can be made against previous European seismic hazard products, SESAME (Jimemez et al., 2001, 2003) or local and national products (e.g., Grünthal et al., 2009, Musson, 2007, Papaiouannou and Papazachos, 2000, Wiemer et al., 2009a).

8.4 Deaggregation of PSHA results

Disaggregation of seismic hazard is an important tool in order to understand which components and combination of components that can contribute to outliers (e.g., see Budnitz et al., 1997). The disaggregation of the hazard results will allow for the following analyses:

- Control of the main hazard contributors obtained from the disaggregation, in terms of depth and magnitude range.
- Checking of the overall compatibility of results, such as dependence on the adopted GMPEs to the main hazard contributors obtained in the disaggregation.
- Control on contributions to hazard from the different parts of the input source model, area sources, fault sources and diffuse source model.

9. Summary

Within SHARE a large effort of quality control and testing has been performed or are being pursued. Particularly the commitment to a rigorous feedback and consensus should be mentioned but also efforts of securing other QA aspects of the process such as documentation, testing of hazard software and testing of various parts of the input and output model. As an example a new open source seismic hazard engine has been produced allowing researcher world wide access to new hazard calculations including many of the latest GMPEs which has been and is subjected to further testing and validation. However, it should also be mentioned that the project duration of SHARE of three years and limited financial assets have not made it possible to exhaust all testing of the input and output model. The input source model, area and fault sources, have been subject to a rigorous feedback and reviewing process. Nevertheless, testing of area- and fault sources, optional testing of activity rates and of PSHA hazard could be further pursued than what has been the case in SHARE.

Reasons are as stated, lateness of available hazard models coupled with time and money constraints. We have in this document made an attempt to rectify this limitation by pointing out additional tests for future studies. It should also be noted that SHARE is only a three year project and despite financial constraints many researchers have contributed without receiving funding from the project. For those contributions, we are grateful to the single scientists and the community sharing their data and expertise.

Some of the future testing beyond the deadline of SHARE will involve activity rate testing in the framework of CSEP at the EU-Testing center in Zurich. Within the GEM Testing and Evaluation global component, further aspects such as Mmax will be investigated. Results shall be served through these initatives as well as through the continued access to the results via infrastructures financed in FP7-NERA.

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