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

D6.4 – Initial OpenSHA engine

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Revision: 1

Dissemination Level		
PU	Public	
PP	Restricted to other programme participants (including the Commission Services)	x
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)	

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1 Introduction

SHARE aims to set and adopt new standards in Probabilistic Seismic Hazard Assessment (PSHA) computations by using the an IT infrastructure that is jointly developed within SHARE and the Global Earthquake Model initiative (GEM). The infrastructure is sited at the European Facility for Hazard and Risk (EFEHR): EFEHR provides access to updated, living seismic hazard and risk models for the Euro-Mediterranean region, to the underlying data and models, and to the software infrastructure for hazard and risk assessment. The model building facility together with the access portal (Deliverable D6.5) are currently constructed in SHARE and will be further enhanced under the FP7-Infrastructure project "Network of European Research Infrastructures for Earthquake Risk Assessment and Mitigation" (NERA). EFEHR is the European component of the OECD-initiated Global Earthquake Model program (GEM, www.globalquakemodel.org).

The starting point for developing the seismic hazard engine (SHE) was the OpenSHA package [Field et al., 2003] and the first development of the SHE was carried out within the GEM1 project [Pagani et al 2010]. The SHE is adopted as the computational core of the IT infrastructure designed within the SHARE project. The main SHE characteristics are summarized in the specification document "D6.1 – OpenSHA design specification document". However, as the project advances and multiple workshops took place for the various work-packages (WP3, WP4 and WP5), new requirements have being identified. Hence additional development of the engine had to be planned and are currently implemented. The further development was planned in two phases:

- In Phase 1 the SHE prototype was installed on the SHARE machines; several calculations were performed [D6.1]. Additional requirements coming from all work packages (WP2-WP3-WP4 and WP5) were collected;

- In Phase 2, the ground motion module of the SHE was updated. All ground motion prediction equations (GMPEs) proposed in WP4 were implemented. Validation process was carried out and ultimately the module has to be integrated with the main computational core.

This document specifies the status of the implementation strategy and activities performed for the two phases. The document is divided in four sections. The first one describes the current SHE status; the second one describes the requirements to be satisfied and the associated deadlines. The third section is about the ground motion prediction equations (GMPEs) to be implemented and the milestones defined. Finally, the fourth section shows the capability of the engine to model common seismic source typologies: area and fault sources.

2 *SHE Overview*

The SHE developed as a first prototype within GEM1 and adopted for SHARE, relies on OpenSHA. Deliverable D6.1 describes the initial requirements for the SHE as well as the main SHE characteristics. This subsection presents an overview of the SHE structure. Furthermore, the required tools and a brief description on how to run the SHE are all described.

2.1 SHE Installation

Using the SHE for calculations or development requires:

- Installation of an integrated development environment (IDE) – such as Eclipse (at http://www.eclipse.org, [2]);

- Eclipse Subversion (SVN) plug-in (at http://www.junit.org ,[3]); S*ubversion* is a version control system. This additional software plug-in provides correction of errors by reverting any changes since it provides users with all versions of a file, which may include java classes or documents.

- Obtain and add the OpenSHA source repository. OpenSHA source repository location: https://source.usc.edu/svn/opensha/trunk

- Obtain and add the SHE from the GEM1 source repository. SHE source repository location: https://gemsvn.ethz.ch/svn/gem

The source code repositories are password-protected and permission can be granted by request. A full tutorial on setting up the IDE environment for OpenSHA can be founded here: http://www.opensha.org/trac/wiki/SettingUpEclipse#a1DownloadEclipse. The engine is platform independent, which means that the software can be installed, and run in all Operating Systems (OS) including Windows, Linux, Mac OS, and Solaris. Mandatory, Java Virtual Machine (JVM) must be installed in the local machines (http://java.com/en/download/manual.jsp).

2.2 SHE structure

The SHE prototype is organized as sets of Java packages. The main structure is hierarchical, with packages developed within GEM1 on top of initial OpenSHA packages. The main elements of OpenSHA are presented in Figure 2-1. These elements have their correspondence as Java packages and were updated and modified to meet the initial requirements. The packages are organized in members that can be sub-packages and/or developed Java classes. A hierarchical software structure is common for object-oriented projects, and current organization of packages reflects the required framework. The naming structure was envisioned to respect the object-oriented style of programming but also to represent the overall GEM standardized and homogenized hazard calculation.

The main structure and organization of the SHE packages can be observed in Figure 2-2. The computational core is contained in the `calc` package, the `data` package includes the input files of the hazard input models, the `output` package groups the output files (the `local`, `commons`, and `util` packages contain general classes for the calculation engine). The temporary files are stored in the `scratch` package. The structure of the `calc` package is presented in Figure 2-2. The real calculation core resides in the g`emHazardCalculator` package, which contains the following Java classes, named as:

- `GEMComputeHazard:` the core class for computing hazard curves over a set of site locations. It accepts a set of GMPEs (each associated to a tectonic region type defined in the seismicity source model) and an Earthquake Rupture Forecast (ERF, full set of earthquake ruptures derived from the seismicity source model, together with their probability of occurrence). For compatibility and uniformity the glossary was retained from the original OpenSHA [http://www.opensha.org/glossary].

- `GEMComputeHazardLogicTree:` this class allows calculation of hazard curves over a set of site locations, for seismicity source models and ground motion models both organized into a logic tree structure. The calculator computes hazard curves for each logic tree end-branch model.

- `GEMComputeModel:` this class implements the main settings for hazard calculation, including, input/output directory, logic tree for GMPEs and ERF, list of sites for hazard calculation, probability level for hazard map, Intensity Measure Type (IMT), options for output – hazard curves or maps.

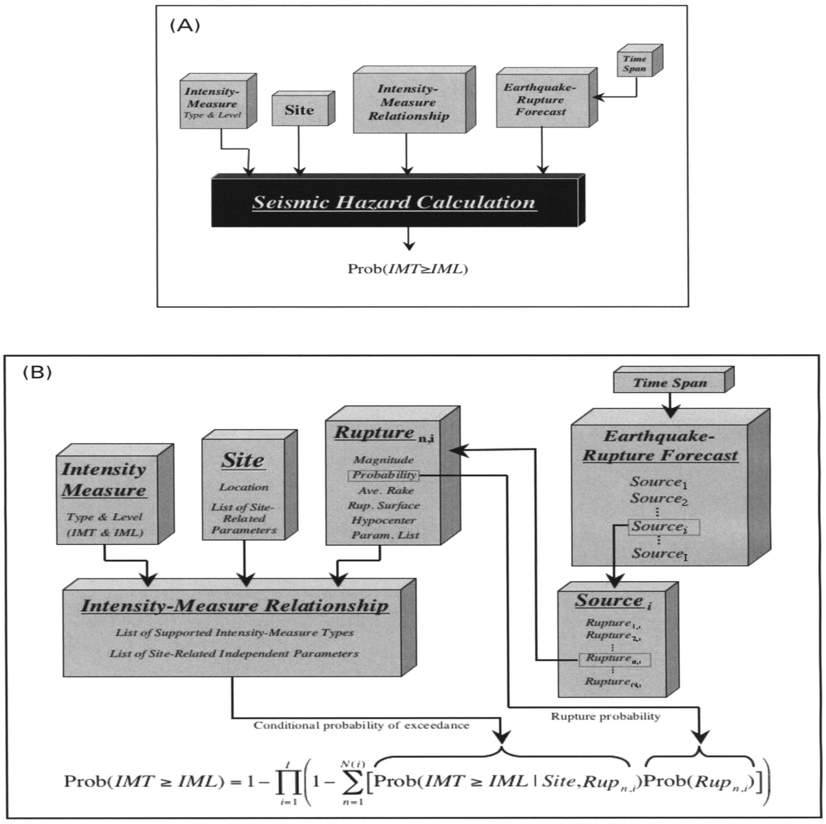

Figure 2.1: (A) The fundamental elements needed to compute the probability that an intensity-measure type (IMT) will exceed a certain intensity-measure level (IML); **(B)** The calculation sequence inside the black box of **(A)**. *Rupture* is short for *Probabilistic Earthquake Rupture*, and *Source* is shorthand for *Earthquake Source.* See Field *et al [*2003] for more details.

`The gemModelData` and `gemModelParsers` packages contain Java classes developed for parsing seismicity source models and returning objects, representing the source model, ready to be used by the calculation classes. For the European Model [Grunthal el at 2010], currently existing in the SHARE database, a Java parser was developed, named `NewEurope2GemSourceData`. The European input model contains seismic sources represented as an area of homogeneous seismicity. Two input files were received, one displaying the geometry of the sources and the other containing the seismic activity parameters associate to each area source type. `NewEurope2GemSourceData` wrap-ups the info contained in two files and creates an instance of the European input model. The source model can be then saved as KML file and therefore rapidly inspected, by plotting and checking the activity parameters, or any other associated information. A KML file displaying the seismic sources available for Europe, showing the information associated to a seismic source in Turkey is presented in Figure 2-3.

`gemLogicTree` package contains the main Java classes for logic tree definition. The logic tree structure, as was specified in D6.1, consists of one or more branching levels, each containing one or more branch sets. The main classes to represent and implement the logic tree structure are: `GemLogicTree`, `GemLogicTreeAPI`, `GemLogicTreeBranch and GemLogicTreeBranchingLevel.` Sub-packages containing classes of default GMPEs can be placed in this package. Currently, there is a subpackage containing the classes used to define the simplified logic tree structure adopted in GEM1.

`gemHazardMaps` package contains two main Java classes, CalcInputGenerator and `GemCalcSetup`. The first one implements the methods to obtain from the hazard curves the seismic hazard maps for a given probability of the exceedance; whereas the former implements the calculation settings. The calculation can be run locally or on remote machines. This is can be setting up on a configuration class file, and when is done remotely, there is need to export a stand-alone JAR file. The run can be either run inside Eclipse or lunched from a command line interface.

`gemOutput` contains several classes (`GEMHazardCurveRepository`, `GEMHazardCurveRepositoryList and GEMHazardResults`) to obtain and organize the hazard results. Hazard data can be written to file using a plain ASCII format.

`gemSourceData` package contains the main Java classes to represent the standardized seismic source typologies, as specified in deliverable D6.1. There is a Java class for each seismic source type: `GEMPointSourceData`(implements a point source type), GEMAreaSourceData(implements a area source type); GEMFaultSourceData (implements a simple fault representation), GEMSubductionFaultSourceData(implements complex fault sources - subduction sources). GEMSourceData represents a generic Java class of all the seismic sources implementations.

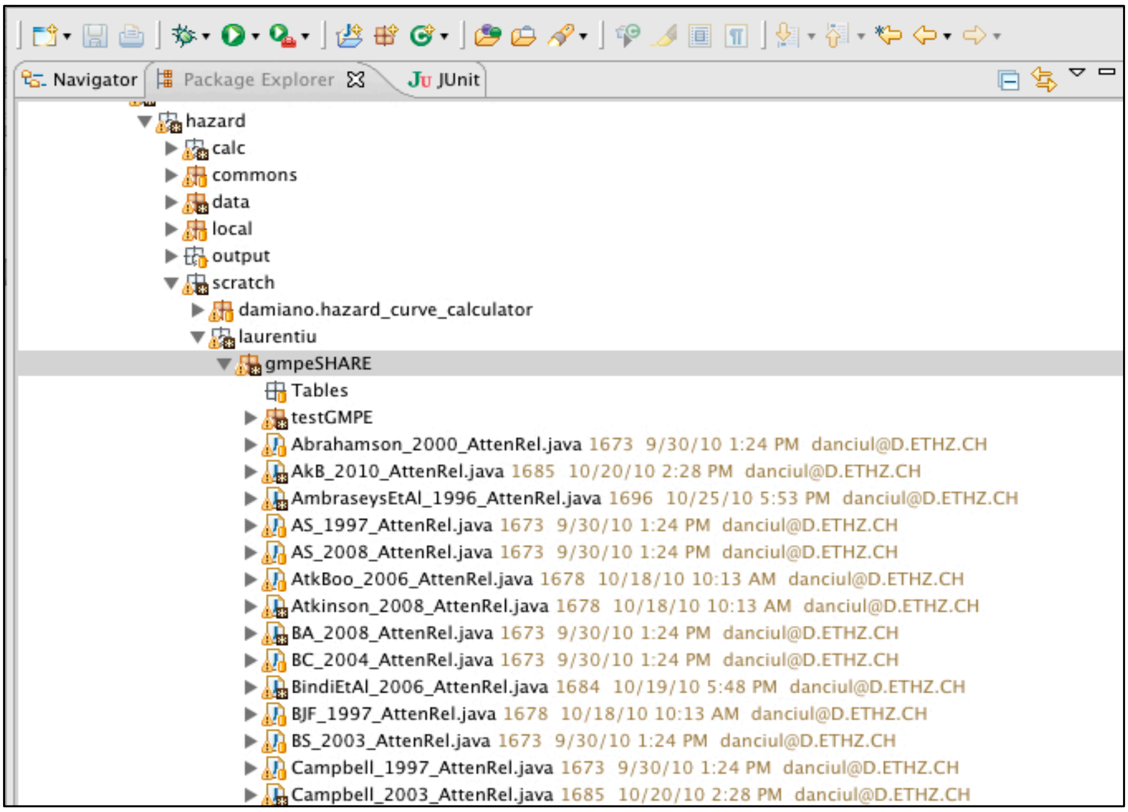

Figure 2.2: Screen capture from Eclipse showing the SHE package structure

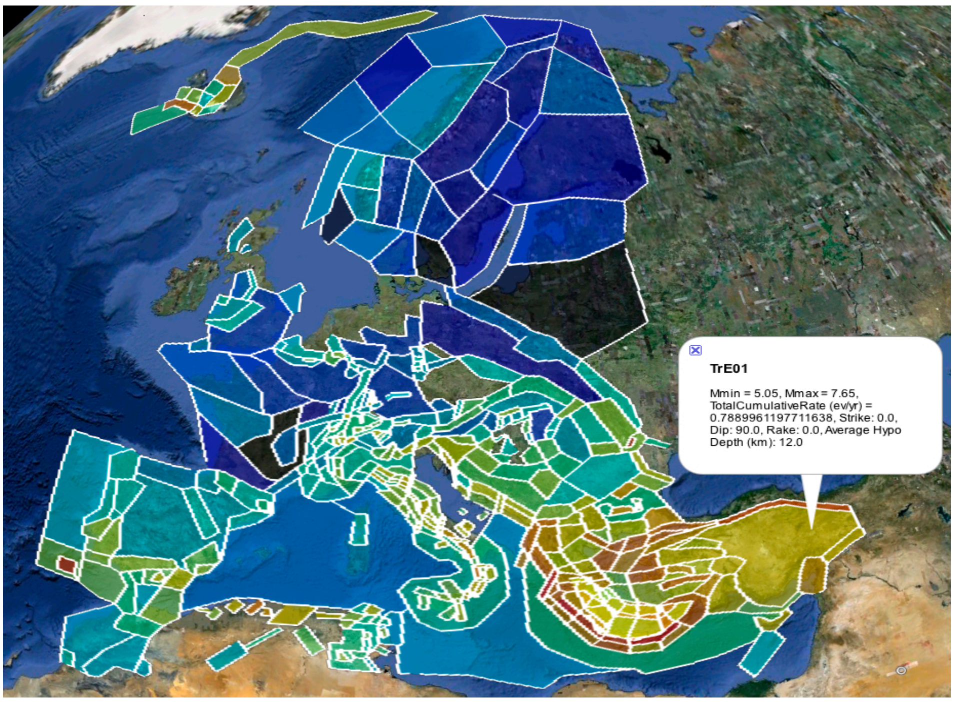

Figure 2-3 – An example of a KML file which shows the European seismic sources together with their associated information

In the current status, the SHE is ready to be fully integrated within the SHARE IT infrastructure as described in deliverables D6.2 and D6.3. A graphical representation of the IT infrastructure is depicted in Figure 2-4. A partial integration has been already achieved: tools for the creation of XML files have been developed and their use allows the input and output data contained in standard java "objects" to be transferred to both the Presentation Tier (Portal) and the Data Tier in an automated fashion.

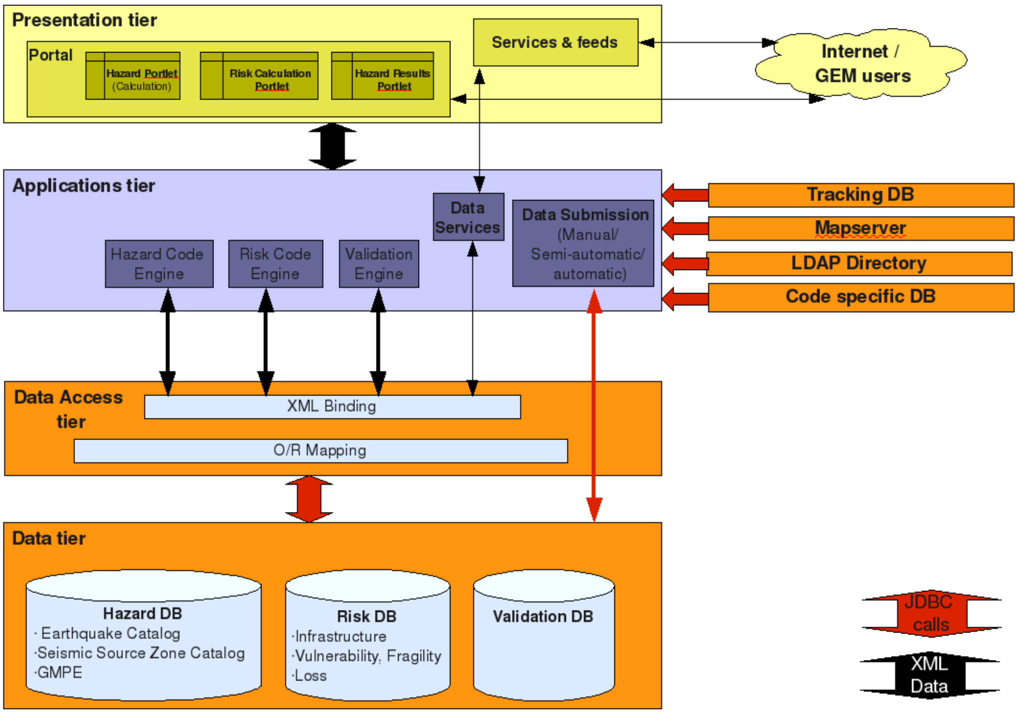

Figure 2-4 - The overall computational infrastructure and the SHE shared by GEM and SHARE.

3 SHE - GMPE implementation

This section describes the status of implementation for the ground motion prediction equations. The SHE prototype as adopted in SHARE, currently contains the following 21 GMPEs:

- Abrahamson and Silva [1997], Abrahamson and Silva [2008], Abrahamson [2000], Atkinson and Boore [2006], Boore and Atkinson [2008], Boore, et al [1997], Campbell [1997], Campbell and Bozorgnia [2003], Campbell and Bozorgnia [2008], Chiou and Youngs [2008], Choi and Steward [2005], Campbell [1997], Dahle et al. [1995], Field [2000], Goulet et al [2006], McVerry et al [2006], Spudich et al [1999], Sadigh et al [1997], Toro et al [1997], Youngs et al [1997], Zhao et al [2006].

All GMPEs specified in deliverable D4.2 will be integrated in the SHE. The selected GMPEs are classified per tectonic regime. GMPEs that remain to be implemented are summarized per tectonic regime:

- Stable Continental Regions:
  - Atkinson [2008], Campbell [2003] , Douglas et al [2006],
- Active Regions with shallow crustal seismicity:
  - Akkar and Boomer [2010], Cauzzi and Faccioli [2008], Pankow and Pechmann [2004], Bindi et al [2009b], Danciu and Tselentis [2007], Douglas et al [2006], Kalkan and Gulkan [2004], Massa et al [2008]
- Subduction Zones:
  - Atkinson and Boore [2003], Lin and Lee [2008], Kanno et al [2006]
- Deep non-subduction Zones:
  - Sokolov [2008]

The **implementation strategy** consists of the following steps:

1. Implementation of the selected GMPEs:

Each GMPE is implemented as an independent Java class, which extends the `AttenuationRelationship` class already existing the SHE.

2. GMPE validation:
   Validation process consists of cross-checking values obtained with the newly developed GMPE Java classes against values obtained from the same GMPE but implemented in different software. The validation process relies on using the JUnit testing framework. JUnit is a simple framework to write repeatable tests [2]. Within the testing framework, the values computed in the Java equations are compared with values obtained with different software. The alternative tables of values are generated using a code developed in Mathematica® and provided by F. Scherbaum. This in ongoing process, and currently only one GMPE was validated – Danciu and Tselentis [2007].
3. GMPE regional adjustment:
   After the validation, an adjustment will be applied. The adjustment, procedure is going to be based on the methodology proposed by Drouet et al [2010].
4. Validation of regionally adjusted GMPEs:
   Validation process would be performed for the adjusted GMPEs, using again the JUnit validation test.

The GMPE Java class `AttenuationRelationship` will in future contain a large quantity of GMPEs. It is essential that the originally published GMPE is available as well as the regionally adjusted GMPEs as a derivation of the original GMPE. A distinguished disclaimer statement has to be written for each Java class that contains a modified GMPE. Adjustements may need to be done for different regional programs in GEM and thus SHARE is laying out the procedure for the adjustment. As an ultimate test for the implementation, all developed Java classes should be submitted for a review by a different IT developer to finally accept the class as part of the core SHE.

Implementation schedule:

GMPE implementation has been foreseen to be completed by the end of November 2010 and later on it will be deployed to the GEM developers for review and integration with the main SHE computational core.

4 SHE – Fault Modeling

Together with area sources, the SHARE model involves seismogenic sources zones as derived by the Database of Individual Seismogenic Sources [DISS, http://diss.rm.ingv.it/dissNet/].

The developed SHE is able to model fault sources as described in Pagani et al. [2010]. Moreover, testing of the fault modelling procedure is reported in Danciu et al [2010], where comparisons are shown between OpenSHA (which provide the fault modelling capability to the SHARE SHE) and the software currently used by the United States Geological Survey (USGS) for calculation of US national seismic hazard maps. The tests done (for simple and complex faults) show high consistency between the results provided by the two compared software. Figure 5-1 and Figure 5-2 from the report by Danciu et al [2010] show the comparison for an area source zone and a fault based hazard calculation. For details please refer to Danciu et al [2010] which is attached as an Appendix.

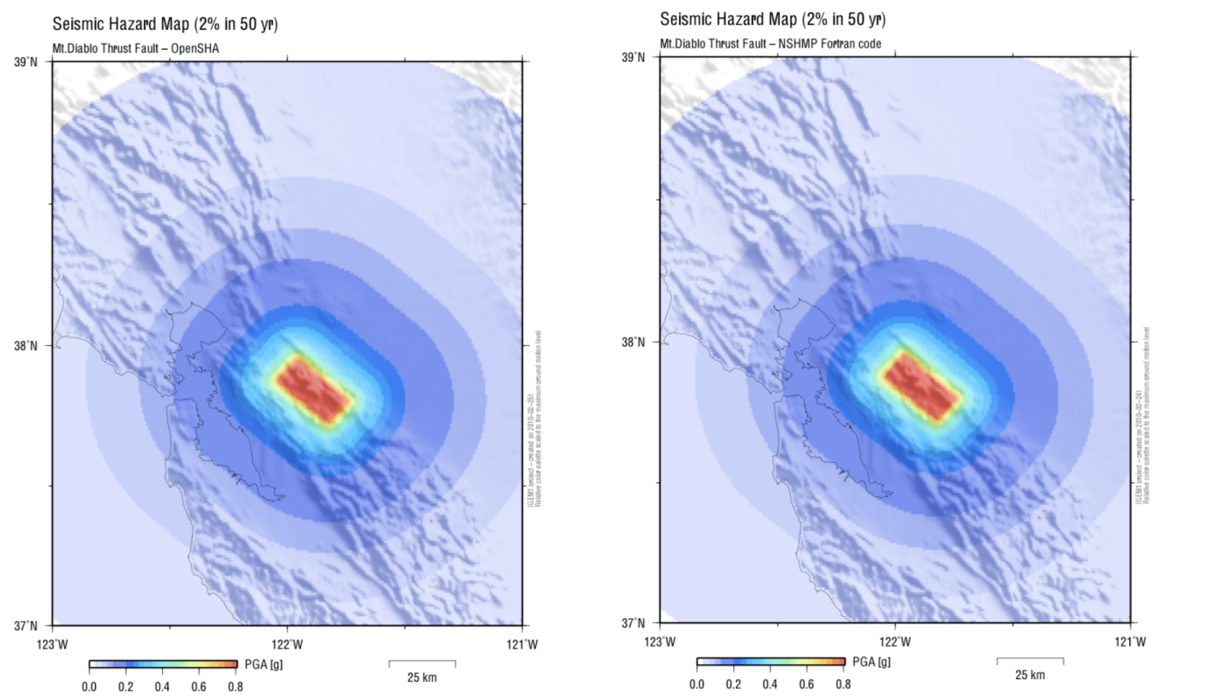

Figure 4-1 - Map of peak ground acceleration for 2-percent probability of exceedance in 50 yr associated with the Mt. Diablo Thrust fault computed by OpenSHA (left), and the NSHMP-USGS code (right) (From Danciu et al. 2010).

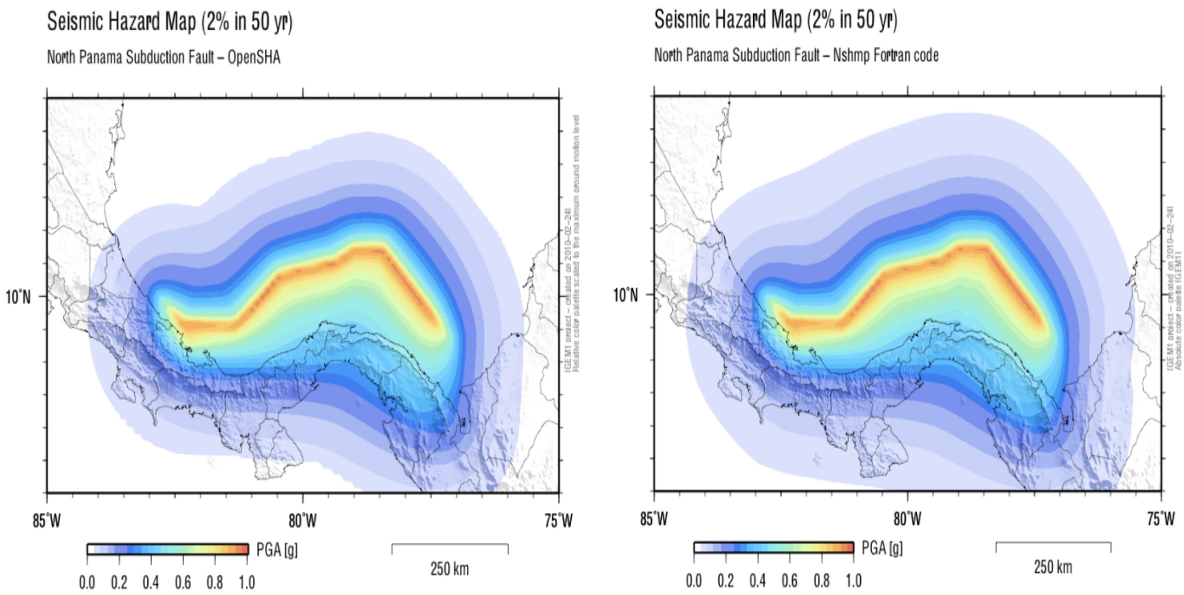

Figure 4-2 - Map of peak ground acceleration for 2-percent probability of exceedance in 50 yr associated with the North Panama Subduction fault computed by OpenSHA (left), and the NSHMP-USGS code (right) (From Danciu et al. 2010).

5 Outlook - SHARE specific requirements

The current SHE version is capable to capture most of the general requirements specified by the SHARE Document of Work (version 15.06.2009), as well as by the Source Model Specification Document [*D5.1*]. In the course of the project, new requirements have been identified. These requirements are partly SHARE specific, however, some of them are also seen as spearheading the needs of other regional programs in the GEM initiative.

The following list is according to the priorities for SHARE and implementation is expected until month 24 of SHARE:

1. **Additions to the core SHE**:
   - Allow for a logic tree for each spectral ordinate (different GMPEs with different weights).
   - Implement and test a solution to generate Uniform Hazard Spectra (UHS), because for each GMPE the spectral ordinates might not be uniformly sampled.
   - Allow for a logic tree GMPE definition for different binning magnitude-distance scheme. The binning scheme has to be defined.
2. Add the new tectonic regime classification as was defined on WP3-WP4-WP5 model building workshop (GFZ Potsdam, October 2010).
3. Implement a logic tree for a fault mechanism distribution associated with a seismic source (for example 30% strike slip, 70% normal)
4. Allow to set-up a depth distribution to each area source type.
5. Implement different magnitude scaling relationships, mostly for the subduction sources.
6. Improve the disaggregation module in order to indentify the controlling earthquake scenario as is defined in Eurocode 8 – decision to be taken – because the scenario is defined in terms of ML and epicentral distance.

SHARE requires to obtain all pieces of software that are used to determine parameters from the hazard input data to be part of the SHARE software collection. SHARE WP6 coordinates the efforts for pooling codes that are used at the model building facility for transparency and reproducibility reasons. The software pool shall be filled by the end of the project. Important software pieces will be:

1. Implement the EPRI method for estimating the maximum magnitude (WP3) as outlined in deliverable D3.3.
2. Implement the software for computing the activity rates parameters (WP3, Task 3.6)

In the long-term, the model building facilities EFEHR will:

1. Provide a user manual to enhance usability of the SHE.

2. A “suite” of basic tools such as software for input file generation, logic tree visualization, sanity check of input files, etc.

6 REFERENCES

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6.1.2 Website references

1. OpenSHA

A community-modeling environment for seismic hazard analysis.

[Available at http://www.opensha.org]

2. **Eclipse**

An open development platform comprised of extensible frameworks , tools and runtimes for building, deploying and managing software across the lifecycle

[Available at http://www.eclipse.org]

3. JUnit Test

Resources for Test Driven Development

[Available at http://www.junit.org]

APPENDIX A GEM1 Hazard: Overview of PSHA software

This appendix contains the report by Danciu et al. [2010] written during the GEM1 pilot project comparing different PSHA software.

GEM Technical Report 2010-2

GEM1 Hazard: Overview of PSHA Software

L. Danciu, M. Pagani, D. Monelli, S. Wiemer

OpenSHA
SEISHAZ
CRISIS2007
PROGRAM FOR COMPUTING SEISMIC HAZARD
SEISRISK III
USGS-NSHMP
MoCaHAZ

GEM1 Hazard: Review of PSHA software

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ABSTRACT

The present report reviews a set of probabilistic seismic hazard analysis (PSHA) computer programs (CRISIS, EQRM, NSHMP, OpenSHA, and SEISHAZ) proposed as possible platforms for the development of the GEM1's hazard engine. The analysis is supplemented by including a number of additional software (FRISK88M, MoCaHAZ, MRS, OHAZ, and SEISRISK IIIM) considered important to obtain a more comprehensive understanding of the current state-of-the-art in PSHA.

The report is organized into two sections. The first describes the main properties of each PSHA program on the technical (e.g. the programming language) and scientific level (e.g. the PSHA source typologies supported). The second illustrates, for a subset of the selected software, a simple benchmarking exercise aimed at understanding the behaviour of the programs, and to compare the results provided for very simple cases.

The review of the selected PSHA software proved to be a very useful exercise to delineate the desirable properties for the GEM1 seismic hazard engine and shows that OpenSHA can accommodate the GEM1 IT and hazard specifications better than the other evaluated software.

Keywords: seismic hazard software, test bed, CRISIS2007, EQRM, FRISK 88M, MoCaHAZ, MRS, NSHMP, OHAZ, OpenSHA, SEISHAZ, SEISRISK IIIM, GEM, GEM1.

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1 Introduction

One important goal of the GEM1 project was the identification of a probabilistic seismic hazard analysis (PSHA) computer program capable to accommodate the hazard analysis requirements as well as the IT specifications peculiar to the GEM project. Role of the selected software was to serve as platform for the development of the GEM1 seismic hazard engine.

This report describes the process and the results arising from the review and evaluation of a set of predominantly non-commercial/freely-available/open-source PSHA software. The evaluation process consisted of two phases: in the first one we reviewed the main features and functionalities of each program, while in the second we compared the results of some of the software using a set of simple test beds.

This report is organized as follows: In Section 2 we describe the envisioned requirements for the PSHA software coming from the IT system design and hazard calculation specifications. In Section 3 we briefly illustrate the main properties of the PSHA software considered for evaluation. In section 4 we present one example of the results for one seismic hazard calculation test. Finally, in section 5, we present the main conclusions. In Appendix A we document the results provided by the NSHMP and OpenSHA software considering three different source typologies.

We believe it is important to stress that the present report is neither an exhaustive review of the PSHA software currently available nor a solid validation exercise. The time constraints within which the GEM1 hazard team had to operate did not allow for the completion of a comprehensive evaluation and testing study

2 The GEM1 Seismic Hazard Engine – Specifications

The envisioned properties and functionalities of the GEM1 seismic hazard engine can be categorized into two parts: IT specifications and seismic hazard specifications.

From an IT perspective, the ideal PSHA software should be:

- Based on Open source/Open standards
- Programmed following an Object-oriented paradigm
- Portable (platform independent)
- Capable of high-end computations

From a seismic hazard perspective, the ideal PSHA code should be:

- Capable of computing hazard using a classical probabilistic seismic hazard approach and producing a full spectrum of outputs, including site specific hazard curves and spectra, seismic hazard maps, and disaggregation of seismic hazard results;
- Extensible (i.e. having the flexibility to cope with current and future seismic hazard input models and with new calculation kernels)
- Able to incorporate complex ground motion prediction models
- Capable to account for epistemic uncertainties of the input model (e.g. through the use of logic trees) and able to perform sensitivity analyses
- Compute stochastic event sets and scenario shake maps (or “ground-motion fields”)

Regarding the IT specifications, the requirement related to open source/open standards is in agreement with the nature of the GEM initiative. The object-oriented requirement is especially important for code flexibility, maintenance and testing, and for allowing an easier implementation of new features. Portability reduces the dependency from specific platforms and allows for an easier distribution of the software; note that this property is tightly connected with the programming language and platform originally adopted to develop the software. Complex seismic hazard models require high-end computation.

In terms of seismic hazard specifications, all the requirements can be summarized by saying that the GEM hazard engine must perform state-of-the-art hazard calculations and therefore be able to process the current most-complex (regional/national) hazard models, which may involve different seismic source typologies and logic trees both in the source and ground motion models.

3 Overview of Seismic Hazard Software

3.1 IT Specific Functionalities

Table 3.1 summarizes some general information regarding the evaluated PSHA software. The highlighted programs (see yellow cells in the table), were recommended during the Canberra kick-off meeting as possible candidates for the GEM1 computational engine, whereas the others were subsequently added to cover a broader spectrum of the currently available PSHA software.

In terms of licensing status, the PSHA software can be separated into: proprietary (FRISK88M and SEISHAZ), free-upon-request (CRISIS, MOCAHAZ, MRS and OHAZ), free downloadable (SEISRISK III and NSHMP), and open-source (EQRM and OpenSHA). Most of the selected PSHA software including CRISIS, EQRM, FRISK88M, MRS, OHAZ, and SEISRISK IIIM provide documentation in the form of a user manual. For software like MoCaHAZ, OpenSHA, NSHMP, and SeisHaz the only documentation comes from the comments in the source code. Among the selected PSHA software, only CRISIS and OHAZ offer a graphic user interface (GUI). OpenSHA offers customizable GUIs for several pre- and post-processing modules (e.g. attenuation relationship plotter, hazard curve calculator/plotter). The rest of the PSHA programs interact with the user through a command line interface. The evaluated programs are written in different programming languages, including Fortran, Python, C, Java, and Visual Basics and have different programming paradigms, such as purely procedural (NSHMP and SEISRISK III), or purely object-oriented (OpenSHA and OHAZ).

Table 3.1 General information of the selected PSHA software

Software Name	Version	Developer	Availability	Documentation	GUI	Program Language
CRISIS	6.0 (2007)	Ordaz, M., et al	Free upon Request	User Manual	Yes	Visual Basic
EQRM	3.2 (2009)	Robinson, D. et al.	Open Source	User Manual	No	Python
FRISK88M	1.8	R. McGuire	Proprietary	User Manual	No	Fortran
MoCaHAZ	2004	S. Wiemer	Free upon Request	Self-Explained	No	MATLAB
MRS	3.0	R. Laforge	Free upon Request	User Manual	No	C
NSHMP	2008	Frankel et al.	Free-Download	Self-Explained	No	Fortran, C
OHAZ	2.1	B. Zabikovic	Free upon Request	User Manual	Yes	Java
OpenSHA	2009	E. H. Field et al.	Open Source	Self-Explained	No	Java
SEISRISK IIIM	1996	Bender , B Perkins, D.M, R. LaForge	Free-Download	User Manual	No	Fortran
SeisHaz	2005	M. Stirling et al	Proprietary	Self-Explained	No	Fortran

3.2 PSHA Specific Functionalities

A summary of the functionalities and the modelling capabilities of each PSHA software is presented in Table 3.2. The majority of the PSHA software implements the classical PSHA approach [Cornell 1968], whereas two programs (EQRM and MoCaHAZ) use a Monte Carlo based approach.

3.2.1 Seismic Sources

Almost all of the PSHA software can model area-type seismic sources, with the exception of NSHMP and SeisHaz. Seismic faults represented as line segments are implemented in CRISIS, FRISK88M, NSHMP, OHAZ, OpenSHA, SEISRISK IIIM and SeisHaz. Three dimensional (3D) fault sources can be implemented only in CRISIS, FRISK88M, NSHMP, OpenSHA and SeisHaz. EQRM simulates events on virtual 3D faults, but has limited capabilities on modelling real seismic fault sources. CRISIS, MoCaHAZ, NSHMP, OHAZ, OpenSHA and SEISHAZ can model single point sources.

Assignment of depth distribution and predominant fault mechanism to each seismic source is possible – with some variations – in almost all the selected PSHA software. Some programs such as EQRM, NSHMP, OHAZ, OpenSHA and SEISHAZ can explicitly incorporate the focal mechanism parameters. MRS allows declaring the predominant faulting style (namely “strike-slip”, “thrust” or “normal”). CRISIS does not explicitly allow assigning a specific fault mechanism to a seismic source. SEISRISK IIIM places all the seismic sources at the surface and there are not explicit parameters to declare the predominant style-of faulting. However, for programs like CRISIS, MoCaHAZ and SEISRISK IIIM, the predominant fault mechanism can be incorporated in the calculation by assigning to each source a unique ground motion model that considers the style-of faulting (i.e. one source with a ground motion model for normal fault mechanism, another source with a ground motion model for strike-slip).

All the programs that model finite ruptures use a magnitude-length/area scaling relationship. Usually, when the rupture is assigned to a specific fault surface, the rupture is not allowed to extend outside. Different rupture size-magnitude relationships are implemented in each program; the most common relationship is the one of Wells and Coppersmith [1993].

3.2.2 Seismicity Occurrence Model

Earthquake occurrence in time is modelled as a Poisson process in all the selected PSHA software; CRISIS, NSHMP and OpenSHA include also time-dependent occurrence models.

Regarding the magnitude-frequency distribution (MFD), all the computer programs incorporate a Gutenberg-Richter [1944] magnitude distribution, whereas a few (CRISIS, FRISK88M, NSHMP, OpenSHA and SeisHaz) additionally support a characteristic (or Gaussian) magnitude distribution. Some software (NSHMP and OpenSHA) allow the user to choose the discretization interval of the MFD, while the rest of the programs have a default value, generally equal to 0.1 magnitude units. MoCaHAZ does not require a MFD discretization, because the stochastic events are generated continuously between the minimum and maximum magnitudes.

3.2.3 Ground Motion Prediction Equations (GMPE)

Almost all the PSHA software offer a set of built-in ground motion prediction equations (GMPEs), and some also allow the user to add new GMPEs as tables (CRISIS, MoCaHAZ, and SEISRISK IIIM) or as stand-alone functions (NSHMP, OpenSHA and SeisHaz). Ground motion truncation is supported by all the evaluated software. Certain PSHA programs offer the capability to truncate the ground motion distribution at a maximum value (CRISIS, FRISK88M and SEISRISK IIIM) and/or at a certain number of standard deviations (all the software, with the exception of SEISRISK IIIM).

3.2.4 Logic Trees

Logic trees represent a standard procedure for a formal and quantitative treatment of epistemic uncertainties in seismic hazard models. The logic trees approach is implemented differently among the selected software. A logic tree structure can be found in EQRM, FRISK88M, NSHMP, OpenSHA and SeisHaz. For instance, the NSHMP programs allow the definition of epistemic uncertainties for maximum magnitude (for Gutenberg-Richter sources), for mean magnitude (for characteristic/Gaussian sources), and for GMPEs. Programs such as CRISIS, MRS and SEISRISK IIIM do not provide specific data structures able to define a logic tree object but permit sequential execution (batch run) of various individual models (end-branches), and separate post-processing is required to obtain aggregated results (i.e. mean, median, fractiles).

3.2.5 Output

In terms of generated output, all the programs provide hazard curves, maps and/or disaggregation results. The majority of the software present a hazard curve as annual frequency of exceedance versus ground motion intensity values. MRS and OpenSHA output a hazard curve as annual probability of exceedance versus ground motion intensity values. MRS reports site specific seismic hazard curves and uniform hazard spectra (UHS) but not hazard maps. On the other hand, OHAZ outputs only seismic hazard maps but not site-specific hazard curves. Supplemental post-processing programs allow the user to derive the desired output for these programs.

Disaggregation of the seismic hazard, nowadays, is a required feature of any PSHA code and in fact almost all the PSHA computer programs reviewed (except OHAZ) implement a disaggregation technique. SEISRISK IIIM and SeisHaz implement a disaggregation technique that outputs the contribution of magnitude and distance pair whereas the rest of the software implement disaggregation techniques that quantifies the contribution to the final hazard results in terms of magnitude-distance-epsilon. MRS is the only code that implements a geographical disaggregation technique (Bazzurro and Cornell [1999]). Additionally, OpenSHA and CRISIS offer the possibility to generate single or multiple scenarios as input for seismic risk assessment. EQRM is the only program that covers the complete spectrum from hazard to risk.

Table 3.2 Functionalities and features of the selected PSHA software

<table>
<tr><th colspan="2">Features</th><th>CRISIS</th><th>EQRM</th><th>FRISK 88M</th><th>MoCaHAZ</th><th>MRS</th><th>NSHMP</th><th>OHAZ</th><th>OpenSHA</th><th>SEISRISK</th><th>SEISHAZ</th></tr>
<tr><td colspan="2">PSHA approach</td><td>classic</td><td>Monte Carlo</td><td>classic</td><td>Monte Carlo</td><td>classic</td><td>classic</td><td>classic</td><td>classic</td><td>classic</td><td>classic</td></tr>
<tr><td colspan="12">Seismic Source Types</td></tr>
<tr><td colspan="2">Area</td><td colspan="5">Yes</td><td>No</td><td colspan="3">Yes</td><td>No</td></tr>
<tr><td rowspan="2">Fault</td><td>Line [2D]</td><td>Yes</td><td rowspan="2">Limited</td><td rowspan="2">Yes</td><td rowspan="2">No</td><td rowspan="2">No</td><td rowspan="2">Yes</td><td>Yes</td><td rowspan="3">Yes</td><td>Yes</td><td rowspan="3">Yes</td></tr>
<tr><td>Volume [3D]</td><td>Yes</td><td>No</td><td rowspan="2">No</td></tr>
<tr><td colspan="2">Point</td><td>Yes</td><td>No</td><td>Yes</td><td>Yes</td><td>No</td><td>Yes</td><td>Yes</td></tr>
<tr><td colspan="2">Allow to assign a depth distribution to each source</td><td colspan="8">Yes</td><td>No</td><td>Yes</td></tr>
<tr><td colspan="2">Allow to assign a style-of faulting to each source</td><td>Limited</td><td colspan="2">Yes</td><td>No</td><td colspan="4">Yes</td><td>No</td><td>Yes</td></tr>
<tr><td colspan="2">Rupture length & width Modelling</td><td colspan="3">Yes</td><td>No</td><td colspan="6">Yes</td></tr>
<tr><td colspan="12">Magnitude Frequency Distribution [MFD]</td></tr>
<tr><td colspan="2">Gutenberg-Richter</td><td colspan="10">Yes</td></tr>
<tr><td colspan="2">Gaussian</td><td>Yes</td><td>No</td><td>Yes</td><td>No</td><td>No</td><td>Yes</td><td>No</td><td>Yes</td><td>No</td><td>Yes</td></tr>
<tr><td colspan="2">Customize MFD intervals</td><td>No</td><td>Yes</td><td>No</td><td>No</td><td>No</td><td>Yes</td><td>No</td><td>Yes</td><td>Yes</td><td>No</td></tr>
<tr><td colspan="12">Ground Motion Prediction Equations [GMPE]</td></tr>
<tr><td colspan="2">Built-in</td><td colspan="8">Yes</td><td>No</td><td>Yes</td></tr>
<tr><td colspan="2">User Defined</td><td>Yes</td><td>No</td><td>Limited</td><td>Yes</td><td>No</td><td>No</td><td>Limited</td><td>No</td><td>Yes</td><td>No</td></tr>
<tr><td colspan="2">Allow to assign different GMPEs per seismic source type</td><td colspan="3">Yes</td><td>No</td><td colspan="4">Yes</td><td>No</td><td>Yes</td></tr>
<tr><td rowspan="2">Truncation</td><td>Max Ground Motion Value</td><td colspan="3">Yes</td><td colspan="4">No</td><td colspan="2">Yes</td><td>No</td></tr>
<tr><td>No. of Sigma</td><td colspan="10">Yes</td></tr>
<tr><td colspan="2">Variability</td><td colspan="10">Yes</td></tr>
<tr><td colspan="2">Customizable units</td><td colspan="4">Yes</td><td>No</td><td>Yes</td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="12">LOGIC TREE</td></tr>
<tr><td colspan="2">Allows to define a logic tree</td><td colspan="3">Yes</td><td>No</td><td>No</td><td>Yes</td><td>No</td><td>Yes</td><td>No</td><td>YEs</td></tr>
<tr><td colspan="12">OUTPUT</td></tr>
<tr><td colspan="2">Hazard Curves</td><td colspan="6">Yes</td><td>No</td><td colspan="3">Yes</td></tr>
<tr><td colspan="2">Hazard Maps</td><td colspan="4">Yes</td><td>No</td><td colspan="5">Yes</td></tr>
<tr><td colspan="2">Uniform Hazard Spectra</td><td>Yes</td><td>No</td><td colspan="4">Yes</td><td>No</td><td>Yes</td><td>No</td><td>Yes</td></tr>
<tr><td rowspan="3">Dis-aggregation</td><td>M-R</td><td colspan="4" rowspan="2">Yes</td><td rowspan="3">Yes</td><td rowspan="2">Yes</td><td rowspan="3">No</td><td rowspan="2">Yes</td><td>Yes</td><td>Yes</td></tr>
<tr><td>M-R-epsilon</td><td rowspan="2">No</td><td>No</td></tr>
<tr><td>Geographic</td><td colspan="4">No</td><td>Yes</td><td>No</td><td>No</td></tr>
<tr><td colspan="2">Eq. Scenario /Shake Maps</td><td>Yes</td><td>Yes</td><td colspan="5">No</td><td>Yes</td><td colspan="2">No</td></tr>
</table>

3.3 CRISIS 2007

CRISIS: a computer program to compute seismic hazard

3.3.1 Developers

Ordaz, M., Aguilar, A., and Arboleda, J., Instituto de Ingeniería, UNAM, Mexico

3.3.2 Overview

CRISIS 2007 provides a user-friendly environment to compute seismic hazard. The software runs on Microsoft Windows

OS, and has an intuitive GUI to data input and output.

CRISIS implements a classical probabilistic seismic hazard methodology where seismic sources can be modelled as points, lines and areas. In the case of area sources, the software offers an integration procedure that takes advantage of a triangulation algorithm used for seismic source discretization. This solution improves calculation efficiency while maintaining a reliable description of source geometry and seismicity. Additionally, supplementary filters (e.g. fix a site-source distance that excludes from calculation sources at great distance) allow the program to balance precision and efficiency during hazard calculation.

Earthquake temporal occurrence is assumed to follow a Poisson process, and the code facilitates two types of MFDs: a truncated exponential Gutenberg-Richter [1944] magnitude distribution and a characteristic magnitude distribution [Youngs and Coppersmith, 1985]. Notably, the software can deal with uncertainty in the seismicity input parameters such as maximum magnitude value. CRISIS offers a set of built-in GMPEs, as well as the possibility of defining new ones by providing information in a tabular format.

According to the user, CRISIS can produce several outputs such as, hazard maps, hazard curves, UHS, disaggregation data, source-by-source results, and additional information related to the computation model. This software can generate single or multiple ground-motion fields to be used in applications such as seismic risk assessment. CRISIS has the graphical capability to plot seismic hazard maps together with additional information such as: the grid used for the computation, seismic sources, and a map of the region.

3.3.3 Seismic source description

Seismic Sources - Geometry

CRISIS models the following types of seismic sources:

Point sources

The following parameters are required to specify a point source:

- Geographical coordinates (latitude, longitude and depth)

Area sources

Represented as polygons. Area sources can be two- (2D) or three-dimensional (3D) and are defined by the following parameters (vertex coordinates of the polygons in the case of area sources must be ordered clock-wise):

- Geographical coordinates (latitudes, longitudes and depths) of the vertexes

Fault sources

Represented as polylines and defined by

- Geographical coordinates (latitude, longitude and depth)

The predominant fault mechanism cannot be explicitly specified for each seismic source, however, the user can associate to each source a specific GMPE that takes into account the style-of-faulting (i.e. normal strike-slip, or normal or reverse fault mechanism).

Seismic Sources - Seismicity

Two alternative magnitude-frequency distributions are currently implemented in CRISIS: a truncated exponential Gutenberg-Richter (GR) magnitude-frequency distribution and a doubly truncated Gaussian distribution that reproduces a characteristic earthquake model. The parameters required to specify the truncated GR distribution are: the minimum magnitude m_{min}, the rate of occurrence for earthquakes of magnitude equal or greater than m_{min}, the GR beta value β_{GR}, and the maximum magnitude, m_{max}. To account for epistemic uncertainties, the coefficient of variation for β_{GR} and m_{max} can be also specified.

The definition of the characteristic earthquake model in CRISIS2007 requires: (i) the median value of the inter-occurrence time between characteristic earthquakes with magnitude $m \geq m_{min}$ (this is the inverse of the rate of occurrence for earthquakes of $m \geq m_{min}$.); (ii) minimum possible magnitude of a characteristic earthquake; (iii) maximum magnitude of the characteristic earthquake; (iv) standard deviation of the characteristic earthquake magnitude (it is assumed independent of time). There is an additional option to describe the expected characteristic magnitude as a function of time as in the slip-predictable model [Lay and Wallace, 1995]; in this case the expected characteristic magnitude increases with time.

In both cases (GR and Characteristic) the seismicity temporal occurrence model corresponds to a Poisson model.

Rupture Area/Length vs. Magnitude Relationship

CRISIS computes source-site distances considering extended ruptures; the geometry of each rupture is defined using a specified magnitude-area (in case of area sources) or magnitude-length (in case of faults) relationship. The user can provide the parameters that relate the rupture area/length to magnitude or use the built in set of constants. The following relationships are built-in Brune [1970], Singh et al. [1980] and Wells and Coppersmith [1994].

In the case of area sources, CRISIS will assume that the rupture realizes on the area surface; the shape of the rupture area is assumed to be a circle. In the case of fault sources CRISIS will assume that the earthquake takes place along a line defined by the source geometry. For the case of point sources, rupture finiteness is not modelled.

3.3.4 Ground Motion Prediction Equations

CRISIS accommodates GMPEs in two different ways, built-in and user-defined. The following models are built-in:

- Abrahamson and Silva [1997], Garcia et al. [2005], Spudich et al. [1997], and Youngs et al. [1997].

In general, only one GMPE will be assigned to a source. However, there is the possibility to assign one ore more special GMPEs to a source, which will be effective only for sites located inside corresponding polygons, called “special attenuation regions”. CRISIS accounts for the ground motion variability and provides an option to truncate the ground motion distribution at a certain number of sigmas (standard deviations) as well to cap the ground motion at a user-defined upper threshold. The user-defined GMPEs can be implemented in a tabular form, depicting median values of the ground motion intensity measures as a function of magnitude, distance, depth and standard deviation. Truncation options and the units have to be specified also. In CRISIS various ground motion intensity measures can be setup as long as the units are correct.

Distance Measures

CRISIS accommodates the following source-to-site distance types:

- Epicentral distance, hypocentral distance, Joyner and Boore distance, closest distance to the fault rupture,

The user must indicate to CRISIS what type of distance he wishes to use, depending on the characteristics of the GMPE being used.

3.3.5 Output

CRISIS generates several output files in a ASCII or binary format: results (.res), graphic (*.gra), map (*.map), source by source results (*.fue), M-R disaggregation results (*.des), maximum earthquake (*.smx), epsilon disaggregation file (*.eps).

The .res file contains a summary of the calculation, including the geometry and seismicity description of the sources, characteristics of the selected GMPEs, description of the computational parameters, and details of the computational grid. The mmary is provided for each site, indicating the considered sources and the ones excluded. Customizable seismic hazard curves are one type of output generated with CRISIS. The level of discretization of each hazard curve is controlled by an upper limit parameter and a number of discretization levels. The hazard curve is defined as the annual rate of exceedance (y-axis) versus the ground motion intensity measure (x-axis) and the hazard curve information resides in the *.gra file. The *.map file contains the intensity levels associated to selected return periods, for each grid point and for each intensity measure. The seismic hazard map can be exported in various formats, including bitmap, XYZ-ASCII file and Surfer DSAA file format. Upon the user’s decision, UHS can be computed, if a suitable intensity measure is selected (spectral acceleration/velocity/displacement) as well as a proper set of spectral ordinates. Two types of disaggregation results are presented by CRISIS. The first type contains the results of seismic hazard disaggregation in terms of magnitude and distance; in this case the information is written in *.des file. The second type of disaggregation results, given a site, provides the exceedance rates conditioned by discrete values of epsilon, intensity measure and intensity levels (the information is contained in a *.eps file). Single or multiple earthquake scenarios can be generated. For a given site, these scenarios are computed using the worst combination of closest distance to a source and expected value of maximum magnitude. The highest intensity computed for all sources is printout in .smx file, for different values of epsilon.

3.3.6 Possible Restrictions and Limitations

The current version of CRISIS has the following constraints (note that these limits that come from older versions can be easily extended):

- Maximum number of GMPEs: 50
- Maximum number of spectral ordinates: 40
- Maximum number of seismic sources: 400

For the rest of the variables, the size of the corresponding arrays is only limited by the Microsoft Windows OS memory

3.3.7 Software Requirements, Version, Content of Software Package, Input/Output Format, User Manual, Code Availability

Three versions of CRISIS were released during the last decade: version CRISIS99, CRISIS2003 and CRISIS. CRISIS99 was written in Fortran whereas the CRISIS 2003 and 2007 were written in Visual Basic; they all have a GUI. The package requires a Microsoft Windows OS and an installation file is provided. The code supports several import/export formats, such as ESRI file format (import source geometries), bitmap format (to export hazard maps), binary files (to export hazard maps), DSSA-Surfer ASCII format (to export hazard maps), simple ASCII text (export hazard curves or UHS). There is not a dedicated user manual, but the help section is well structured. The code is available upon request.

3.4 EQRM

EQRM: Geoscience Australia's Earthquake Risk Model

3.4.1 Developers

Robinson, D., Gray, D., Row, P., Wilson, R., Newey, V., Horspool, N., Fulford, G., and Dhu, T., Geoscience Australia, Australia.

3.4.2 Overview

EQRM is a software for estimating earthquake hazard and earthquake risk, developed at Geoscience Australia, an Australian Government Agency.

EQRM performs probabilistic seismic hazard analysis (PSHA) and probabilistic seismic risk analysis (PSRA) using an event based approach. The event-based approach is based on the creation of a catalogue of synthetic events where, ground motions – and losses – are computed for each event individually. This information is successively aggregated to obtain probabilistic results.

The following steps describe the procedure followed by EQRM to compute the hazard:

- Generation of a synthetic catalogue of earthquakes. Note that EQRM works with area sources whose magnitude-frequency-distribution corresponds to a truncated Gutenberg-Richter distribution. The parameters that describe a simulated event are its location, geometry, magnitude and activity (likelihood of occurrence).
- For each event in the synthetic catalogue, calculation of the ground motion at each investigated site using a specified GMPE; eventually, site effects can be taken into account using amplification factors that depend on magnitude, RSA period and soil-category.

The features relative to risk implemented in EQRM are summarized in the report prepared for GEM1 by the GEM1 risk team [Crowley et al., 2010].

3.4.3 Seismic Source Description

Seismic Sources - Geometry

EQRM models diffused seismicity using area source. One particularity of this software stands on the idea of creating virtual faults inside area sources. EQRM indeed computes hazard by generating sets of stochastic events where each event is represented in terms of a 3D rupture surface. For each event, the program initializes a virtual fault and then places a rupture on the virtual fault. The fault is described in terms of length, width, dip and the depth to the seismogenic layer (identified as the depth to the top of rupture – this is an area-specific and user-defined parameter). The location of each simulated event is assigned randomly within the area source; note that the rupture is not forced to fall completely within it. The originating area source is only used to constrain the position of the centre of rupture. The azimuth of the fault can be constrained within a user defined range or be completely random; the fault dip can be completely random or a user-specified value.

EQRM can accommodate overlapping area sources, i.e. where two seismic zones share a common geographical region. Two different techniques are used to solve this problem (a) cutting out a doughnut and (b) splitting the outer polygon.

The user can decide on the number of desired events in each seismic zone. The number of desired events within a seismic zone should be the value that, when increased, hazard results remain stable. A sensitivity analysis is usually recommended to establish the optimal number of simulated events.

Seismic Sources - Seismicity

EQRM utilizes area sources whose seismicity temporal occurrence model is assumed to follow a homogeneous Poisson process. For each source the MFD is described by a truncated exponential GR magnitude distribution.

Interestingly, EQRM implements a stratified Monte-Carlo technique to optimize the number of event necessary to reliably sample the whole MFD. For a detailed description of this interesting technique we refer the reader to the EQRM user-manual [Robinson et al., 2006].

Rupture Area/Length vs. Magnitude Relationship

The width and length of the rupture are computed using empirical relationships based on the moment magnitude of the event. The relationship between rupture area/length and moment magnitude implemented in EQRM is a modified version of the relationships proposed by Wells and Coppersmith (1994).

3.4.4 Ground Motion Prediction Equations

EQRM incorporates five GMPEs for spectral acceleration (SA) and earthquake intensity (MMI) (Gaull et al., 1990) mostly recommended for stable continental regions. The user has no options to add a new GMPE, unless by modifying the source code.

These are GMPEs implemented:

- Atkinson and Boore [1997], Gaull et al. [1990], Sadigh et al. [1997], Somerville et al. [2001], and Toro et al. [1997].

EQRM encompasses the following techniques to account for GMPEs variability: random sampling of the ground motion Probability Density Function (PDF); sampling the ground motion PDF using spawning techniques; adding or subtracting one or two standard deviations from median ground motion measure (i.e PGA, SA). Moreover, EQRM allows the user to use one or many alternative GMPEs in order to incorporate epistemic uncertainty in the ground motion distribution.

Distance Measures

EQRM considers the following source-site distances:

- Epicentral distance, hypocentral distance, Joyner and Boore distance, closest distance to the rupture.

The software includes also an approximation technique that computes the epicentral and hypocentral distances using Joyner and Boore distance and rupture distance respectively.

3.4.5 Output

The EQRM output is represented in terms of:

- Values of ground motion with a specified probability of exceedance in time t at each node of a grid (i.e. a classical format used to represents seismic hazard maps)
- Hazard curves - given a site, an intensity measure type and a set of intensity measure levels
- A UHS - given a site an intensity measure type (spectral acceleration/velocity/displacement) and a suitable number of spectral ordinates.

In some cases post-processing operations have to be performed in order to customize the hazard results. A set of MATLAB routines is provided to process and/or plot the data.

3.4.6 Possible Restrictions and Limitations

The software models only with area sources and supports a single MFD. EQRM currently offers GMPEs mostly focused on a single tectonic region. The information related to a possible limitation on the maximum number of sources, or maximum number of GMPEs used is not available. The current version has no graphic user interface (GUI)

3.4.7 Software Requirements, Version, Content of Software Package, Input/Output Format, User Manual, Code Availability

EQRM is written in Python, and can be installed on any operating system. The installation of EQRM requests various libraries including: scipy, numpy, numeric, libgeos, ctypes, minGW (only for Microsoft Windows OS). Through a configuration file the user controls the input and output of the hazard or risk analysis. The data input files are in an eXtensible Markup Language (XML) format, whereas the output files can be saved as ASCII text files (*.txt), comma separated values (*.csv) tables or gzip compressed text files. EQRM has a dedicated user manual. The EQRM version tested is 1.972 and the source code is freely available on SourceForge: http://sourceforge.net/projects/eqrm/

3.5 FRISK88M

FRISK88M: Fortran Computer Program for Seismic Risk Analysis

3.5.1 Developers

McGuire, R. K., Risk Engineering Inc., U.S.A.

3.5.2 General overview

FRISK88M is perhaps one of the most used software for probabilistic seismic hazard assessment. FRISK88M calculates hazard using the classical PSHA approach; it can be used to estimate the seismic hazard at a site or for a region. FRISK88M accounts for both randomness and epistemic uncertainty by allowing multiple-weighted assumptions represented as branches in a logic tree structure. The program produces a complete list of hazard results for each branch of the logic tree.

The main types of result generated are: hazard maps, hazard curves, UHS, disaggregation of hazard by magnitude, distance and epsilon. No plotting functions are provided with the program. FRISK88M is proprietary software and the license belongs to Risk Engineering, Inc.

3.5.3 Seismic Source Representation

FRISK88M accommodates seismic sources described as area sources, faults and points.

Seismic Sources - Geometry

FRISK88M represents the seismic sources as following:

Point sources correspond to points of active seismicity. The following parameters are required to specify a point source:

- Geographical coordinates (latitudes and longitudes) of the point source
- Hypocentral depth;

Area sources are represented as polygons parallel to the surface of the Earth. In the input file, the user defines each area source using the following parameters:

- Geographical coordinates (latitudes and longitudes) of the vertexes of the polygon
- Average hypocentral depth.

Vertex coordinates of the polygons can be either ordered clock- or counter-clock-wise.

Fault sources: characterized by a surface trace and subsurface geometry. A fault source can be defined by the following parameters:

- Geographical coordinates (latitude and longitude) of their surface trace
- Subsurface geometry parameters:
    - Three depth values
    - Two dip angles

The first depth value specifies the upper seismogenic depth of the fault (or the minimum depth of energy release); the second depth defines the depth where the fault surface dip angle changes and the third depth delineates the lower seismogenic depth. The first dip angle - with respect to the earth's surface - is the angle of the top section of the fault surface; the second dip angle is the angle of the lower section of the fault.

Seismic Sources - Seismicity Models

FRISK88M supports the following MFDs:

- Characteristic Earthquake (only for fault sources) The model implemented follows the one proposed by Youngs and Coppersmith [1985];
- Truncated exponential GR

Rupture Area/Length vs. Magnitude Relationship

The software explicitly accounts the finite dimension of the earthquake rupture and the dependence of rupture size on earthquake magnitude. In the case of area sources, FRISK88M uses a variable number of azimuths depending on the rupture length and the distance between the site and the grid point.

FRISK88M includes empirical relationships relating rupture size to magnitude. The user can customize these relationships by specifying the parameters characterizing the relationship. FRISK88M incorporates the equations provided by Wells and Coppersmith [1994].

3.5.4 Ground Motion Prediction Equations

The following GMPEs are built-in the FRISK88M package:

- Campbell [1993, 1994], Idriss [1993], Sadigh et al [1993, 1994], and Joyner and Boore [1993, 1994]. Recent versions of the code include recently published GMPEs, including the NGA equations for active tectonic regions, Akkar and Bommer [2010] for Europe, Zhao et al. [2006] for Japan, and Atkinson and Boore [2006] for stable continental regions.

Additional GMPEs can be added by means of tables. FRISK88M takes into account the variability of ground motion in the computation of hazard. The code supports the truncation of the ground motion probability distribution; the user controls the truncation values by defining a fixed value of ground motion or by specifying a multiple of sigma.

Distance Measures

The following distance metrics are supported in FRISK88M:

- Epicentral distance; hypocentral distance; closest distance to the rupture; closest distance to the surface projection of the rupture

3.5.5 Output

FRISK88M generates the following output:

- Seismic hazard curves defined as annual probability of exceedance versus ground motion values;
- Uniform Hazard Spectra
- Disaggregation of the hazard in terms of magnitude, distance, and epsilon;
- Hazard curves for each end branch of a logic tree
- Sensitivities of the hazard to different assumptions in the input parameters

3.5.6 Possible Restrictions and Limitations

There are some limitations related to the version of FRISK88M considered, including the maximum number of gross sources (200), a maximum of 50 sub-sources in each gross source. Array size (maximum magnitude*number of source rate parameters*number of depth assumptions*total number of sources) must be less than 50000. The maximum number of GMPEs to be adopted in a hazard analysis is limited to nine.

3.5.7 Software Requirements, Version, Content of Software Package, Input/Output Format, User Manual, Code Availability

FRISK88M runs from command line on almost all operative systems. The executions require a minimal temporary disk space unless you choose to save hazard curve values for each hypothesis. In this case the disk space requirements can increase substantially. The input and output files are in ASCII text file format. The package has a dedicated user manual. FRISK88M reviewed version is 1.8. The software is proprietary software and the license belongs to Risk Engineering, Inc (http://www.riskeng.com/SoftwareHTML/software_frisk.html).

3.6 MoCaHAZ

MoCaHAZ: Monte Carlo based Seismic Hazard Assessment

3.6.1 Developers

Stefan Wiemer, ETH Zurich, Switzerland

3.6.2 Overview

MoCaHAZ is a Monte Carlo based seismic hazard calculator implemented in MATLAB; the software is a collection of functions and scripts. MoCaHAZ was used to calculate the seismic hazard maps for Switzerland in 2004 [Giardini et al., 2004]. The package contains two modules: one for synthetic catalog generation, and one for computing the hazard curves. The package accommodates only area sources. The temporal occurrence of earthquakes within an area source follow a Poisson process and the MFD is described in terms of a truncated exponential GR magnitude distribution. The software can handle different seismicity models, such as characteristic, non-Poissonian, or Markov model. Logic tree definition, as well as a sensitivity analysis can be set-up. The package contains a set of functions for plotting hazard curves, UHS, maps and disaggregation of the hazard. By using the latest MATLAB versions (2008/2009) parallel calculations are supported.

3.6.3 Seismic Source Description

Seismic Sources - Geometry

Only area sources are supported and they are represented as polygons parallel to the surface of the Earth. Area sources are modelled by a set of points sources located on an evenly spaced grid and are defined by the following parameters:

- Geographical coordinates (latitudes and longitudes) of the vertexes polygon
- Average hypocentral depth.

Coordinates of the polygons can be either ordered clock-wise or counter-clock.

Seismic Sources - Seismicity Models

The seismicity of each source is characterized by the truncated exponential GR magnitude distribution. The user controls the number of events that can be generated within each seismic source.

3.6.4 Ground Motion Prediction Equations

There is a single GMPE implemented, specific to the region of Switzerland:

- Bay et al. [2003, 2004]

The user has the possibility to build-up any GMPE by adding a new MATLAB function to the package. Various truncation levels are possible, truncation at the minimum distance, at the maximum ground motion amplitude or truncation in terms of sigma. The software is flexible in defining different distance measures, according with the selected GMPE.

Distance Measures

The following standard distance measures can be defined:

- Epicentral distance and hypocentral distance

3.6.5 Output

MoCaHAZ provides the following results typologies: hazard curves, hazard maps, UHS, and disaggregation in terms of magnitude-distance and/or epsilon. Additionally, sensitivity analysis results can be reported. Several plot functions are available for all these results. The results are printed-out in ASCII text files (*.txt) or MATLAB binary files (*.MAT).

3.6.6 Possible Restrictions and Limitations

Faults and gridded seismicity sources are not supported.

3.6.7 Software Requirements, Version, Content of Software Package, Input/Output Format, User Manual, Code Availability

MATLAB is required. The package contains a set of MATLAB routines, and can run on any operating system supported by MATLAB. The input/output files are ASCII text files. The output can be converted in MATLAB binary files (*MAT). User manual is not available. The version under review was the version released in 2004. The software is available upon request following the link:

http://www.earthquake.ethz.ch/research/Swiss_Hazard/downloads/software_downloads

3.7 MRS

MRS: A program for site-specific probabilistic seismic hazard analysis for zones of random seismicity

3.7.1 Developers

Roland Laforge, US Bureau of Reclamation, Technical Service Centre Geophysics, Paleohydrology, and Seismotectonics Group, Denver, Colorado

3.7.2 Overview

MRS is a set of programs developed to compute seismic hazard for a specific site. The program relies on the classical PSHA methodology, and computes the hazard from area sources within which seismicity is assumed to occur randomly in time and space. The MRS suite consists of mrs3.0, mrs3.1, mrs3.2, mrs3.3, mrs3.4 and mrs3.5. These codes differ in respect to whether one (mrs3.1) or all-spectral response period (mrs3.0) are computed, and how seismicity rates and their uncertainty are handled. MRS version 3.0 can model only area sources; the seismicity temporal occurrence model follows a Poisson process. The software implements a large number of GMPEs. Additional GMPEs can be added by modifying the source code. MRS outputs a comprehensive set of hazard results, including hazard curves and UHS (mean, median or fractals) and disaggregation of the hazard. Logic tree models can be implemented by setting up a batch script.

3.7.3 Seismic Source Description

Seismic Sources - Geometry

MRS supports only area sources. They are represented as polygons parallel to the surface of the Earth; area sources are modelled by a set of point sources within each polygon located on an evenly spaced grid. Each area source is defined by the following parameters:

- Geographical coordinates (latitudes and longitudes) of the polygon
- Hypocentral depth distribution defined by the following parameters:
  - Maximum hypocentral depth
  - Stress drop value (up to 100bars)
  - Average dip of faults in the area
- Predominant fault mechanism (i.e. strike slip, fault, thrust, reverse or normal fault)

Coordinates of the polygons must be ordered clock-wise.

Seismic Sources - Seismicity

MRS assumes that earthquake occurrence in time follows a Poisson process. MRS uses a truncated exponential GR magnitude-frequency distribution to represent the frequency of occurrence for different earthquake magnitudes. The user has to specify the lower and upper magnitude bounds, a_{GR}-value normalized per square km, b_{GR}-value. The package offers the option to compute the GR recurrence parameters based on an input earthquake catalogue and a table containing completeness time periods; the maximum likelihood approach proposed by Weichert [1980] is implemented.

Rupture Area/Length vs. Magnitude Relationship

The relationship between rupture area/length and moment magnitude implemented in MRS is a modified version of the one proposed by Wells and Coppersmith [1994].

3.7.4 Ground Motion Prediction Equations

MRS contains a large dataset of built-in GMPEs:

- Abrahamson and Silva [1997], Ambraseys et al [2005], Atkinson and Boore [1990, 1995, 2003], Boore and Atkinson [1987], Campbell [1981, 1990, 1997], Donovan [1973], EPRI [1993], Gregor et al [2002], Idriss [1991], Joyner et al [1994,1997], Joyner and Boore [1981, 1988], Motazedian and Atkinson [2003], Sabetta and Pugliese [1996], Spudich et al [1996, 1999], Pankow and Pechmann [2004], Toro and McGuire [1987], Wong et al [2005], and Youngs et al [1997].

The user can implement new GMPEs by modifying to the source code. Ground motion variability is incorporated in the computations assuming a lognormal distribution of the ground-motion; truncation of the ground motion distribution at a given values sigma value is also possible.

Distance Measures

- *Epicentral distance, hypocentral distance, Joyner and Boore distance, closest distance to the rupture,*

3.7.5 Output

MRS offers a number of hazard output typologies. These include hazard curves, UHS, and disaggregation of the hazard. In addition, other files are available for diagnostic purposes. A file that contains the coordinates of all the grid points and their distance to the site; a second file that contains a table for plotting return periods for all ground motion levels at different fractile; a third file that contains the sorted likelihood distribution of annual exceedance for specific ground levels. Seismic hazard curves are reported in the file *mrs3.x.hazdat*, which can be in text or MS Excel format (*xls). This file contains the hazard curves for ech single source, as well as in a cumulative form. The hazard curve represents the annual probability of exceedance for distinct values of a ground motion parameters. Hazard curves are customizable, and the number of the discretization points can be modified.

MRS computes seismic hazard just for a single site and there's no option available for output of a seismic hazard map. A batch file can be setup in order to output the hazard values for a set of points (eventually organized into a grid). Mean values of UHS are reported in mrs.3.x.rspectra_mean file, whereas the fractile values are reported in *mrs.x.rspectra_fracts*. When multiple GMPEs are used, UHSs are computed using an interpolation procedure that provides values of spectral ordinates (e.g. acceleration) for a standard set of periods.

The disaggregation technique proposed by Bazzurro and Cornell [1999] is implemented in MRS. Disaggregation output comprises: mean and mode values of joint magnitude-distance, and of marginal distributions of magnitude-distance-epsilon. Moreover, disaggregation in terms of latitude-longitude–magnitude-ground motion epsilon, (also called geographic disaggregation) is also supported. Files containing the results of seismic hazard disaggregation can be either in an ASCII or binary format.

3.7.6 Possible Restrictions and Limitations

MRS computes hazard using only area sources. There are also some input parameters that need to be specified in two file headers (mrs3.0.h and mrs3.4.h). The following parameters can be modified to meet the requirements of the analyst:

- Number of acceleration bins at 0.01g intervals: default 800
- Number of magnitude intervals: default 15
- Number of sources: default 50
- Number of periods in a period set of predicting equation: default 50
- Maximum number of points in a polygon: default 20
- Number of discretization points for seismicity rate distributions: default 20
- Number of return periods: default 10
- Number of discretization points for hazard matrix: default 50
- Number of discretization points for depth distribution: default 5
- Number of percentile levels in output: default 5
- Maximum source-to-site distance considered, in km: default 500

3.7.7 Software Requirements, Version, Content of Software Package, Input/Output Format, User Manual, Code Availability

The programs, written in C, can be easily compiled on any platform using freely available C compilers. The MRS suite consists of the following software:

- mrs3.0 computes hazard for a set of response periods. Seismicity rates are computed from an user specified earthquake catalogue and magnitude completeness time;
- mrs3.1 computes hazard for a single response period (or ground motion parameter). Seismicity rates are computed from an user specified earthquake catalogue and magnitude completeness time;
- mrs3.2 collects the magnitude, distance, epsilon and attenuation percentile for a particular ground motion exceedance value, and write these values into a file. It requests the same input file as mrs3.1;
- mrs3.3 collects the magnitude, distance, epsilon and attenuation percentile for a particular ground motion exceedance value, and write these values into a file. It requests the same input file as mrs3.1;
- mrs3.4 computes hazard for all response periods. Seismicity rates are defined from a supplied a_{GR}- and b_{GR}-values;
- mrs3.5 computes hazard for all response periods. Seismicity rates are defined from a supplied a_{GR} - and b_{GR} - values;
- deagg computes all marginal probability density functions for four parameters, plus joint probability mass functions for magnitude-distance, and magnitude-distance-epsilon.
- deagg_lite computes only marginal densities

The package has a dedicated user manual, with a comprehensive description of the package and input data. The package works with ASCII text files for both input and output data. Additional formats, binary or MS Excel format (*xls) are used for storing the results. The code doesn't contain a graphical interface, but instead use command line arguments. The version evaluated is 3.0.

3.8 NSHMP

NSHMP: Software suite for Probabilistic Seismic Hazard Analysis

3.8.1 Developers

Harmsen, S. C., Frankel, A. D., Petersen, M. D. - U.S. Geological Survey, USA

3.8.2 Overview

The NSHMP suite contains computer programs used by the U.S. Geological Survey (USGS) to generate the 2008 version of the U.S. national seismic hazard maps. The NSHMP package handles different source typologies, such as distributed seismicity, shallow and subduction faults. A configurable logic tree structure – specific to the USGS PSHA input models – is embedded in the software. The NSHMP suite allows the user to incorporate the local site conditions through the definition of a $V_{S,30}$ value..

The standard output of the NSHMP package comprises: hazard curves, hazard values on a regular grid of nodes, Uniform Hazard Spectra (UHS), as well as disaggregation of seismic hazard (in terms of magnitude-distance-ground motion epsilon or latitude-longitude-magnitude and epsilon).

3.8.3 Seismic Source Description

The software contained in the NSHMP suite compute the hazard using diverse seismic source typologies. In particular: (a) grid sources and (b) fault sources.

Seismic Sources - Geometry

Grid sources model distributed seismicity by considering a set point sources – with varying seismicity occurrence properties – distributed over a regular grid. To properly model the spatial distribution of ruptures, a number of – magnitude dependent – depth to the top of rupture classes can be defined [see page A-1 of Petersen et al., 2008]. The code dealing with grid sources takes account of the finiteness of (vertical) ruptures though the calculation of a corrected distance that replaces the Joyner and Boore distance [see Appendix C of Petersen et al., 2008].

In general, these are the parameters that specify the geometry of a grid node:

- Geographical coordinates (latitudes and longitudes) of the point source
- The depth to the top of rupture

Fault sources are represented by three-dimensional surfaces, defined by

- Geographical coordinates (latitude and longitude) of their surface trace
- Subsurface geometry parameters:
    - Depth to the top of rupture
    - Dip angle
    - Down-dip width

The NSHMP suite supports also subduction fault sources (usually used to model intra-plate seismicity). Almost the same information as for the shallow fault sources is required to model this source type. Indeed, the main difference between the two fault typologies is that the subduction sources are defined by a top-of-zone and a bottom-of-zone contour, whereas shallow faults are defined by top-of-fault and fixed width.

Seismic Sources - Seismicity

The seismicity occurrence generally is assumed to follow a homogeneous Poisson process; in case of the New Madrid fault system a clustered seismicity time-dependent model was developed on purpose.

The MFD available are: a truncated exponential GR magnitude distribution and a Characteristic Earthquake distribution. For background sources, the GR *a*-value, *b*-value, and *Mmax* are defined on a spatial grid and can vary on that grid.

Rupture Area/Length vs. Magnitude Relationship

Lengths of the finite faults are determined using the Wells and Coppersmith (1994) relations for all faulting styles taken together.

3.8.4 Ground Motion Prediction Equations

The recently proposed GMPEs developed within the Next Generation Attenuation Relation Project (NGA) are available in the NSHMP suite.

Here a comprehensive list of GMPEs included in the NSHMP software:

- Abrahamson and Silva [1997, 2008], Atkinson and Boore [1994, 2003, 2006], Boore and Atkinson [2008], Boore et al. [1997], Campbell and Bozorgnia [2003, 2008], Chiou and Youngs [2008], Youngs et al. [1997], Gregor et al. [2002], Idriss [2008], Kanno et al. [2006], Sadigh et al. [1997], Spudich et al. [2000], Tabakoli and Pezeshk [2005], and Toro et al. [1997].

Median ground motion are capped at 1.5g for PGA. Truncation of the ground motion distribution at a given number of sigmas is also available. The truncation option is hardcoded.

Distance Measures

Four distance measures are implemented:

- Hypocentral distance,
- Joyner and Boore distance,
- Closest distance to the rupture,
- Rx, a signed distance to top-of-fault, negative on footwall side (used in some NGA-W GMPEs)

For non-planar fault models the hazFXnga7c code supports the Joyner-Boore and the closest distance to the fault surface.

3.8.5 Output

The software reads several ASCII text files and binary input files; binary files must be written using the “little endian” convention. The standard output of the NSHMP package comprises: seismic hazard curves, seismic hazard values (i.e. ground motion with a specified probability of exceedance in time t) on a regular grid of points, uniform hazard spectra, as well as disaggregation of seismic hazard in terms of magnitude, distance and ground motion epsilon. Geographical disaggregation is an additional output of the NSHMP package.

Post-processing programs are available for combining and retrieving the desired output.

3.8.6 Possible Restrictions and Limitations

The code in many parts contains options that are hardcoded and cannot be controlled by the user. The software does not offer a GUI or plotting features.

3.8.7 Software Requirements, Version, Content of Software Package, Input/Output Format, User Manual, Code Availability

The NSHMP software consists of FORTRAN, C, and various shell scripts. The C code is just used for input/output (I/O) routines, while the shell scripts controls the sequence of calculations performed by the FORTRAN codes.

The software works with ASCII text and binary files for both input and output data. The following FORTRAN programs are part of the NSHMP software suite:

- agridMLsm.v2: computes smoothed seismicity (10^{aGR}) on a regular grid of points, given an input catalogue and an input file with magnitude completeness times.

- flrate.v2: calculates rates for characteristic earthquakes and incremental a-values, given slip rates and points of faults. The output is a set of parameters for a characteristic and GR model that are input files for hazFXnga7.
- HazgridX: computes hazard based on seismicity rates computed with agridML on a grid points.
- HazFXnga7c: calculates for a set of sites hazard curves using a set of fault sources.
- HazgridXnga2: computes hazard curves using gridded sources. The program defines and analyses virtual dipping faults at all the distances in order to compute the hanging-wall effects.
- HazgridXnga3: computes hazard curves using gridded sources. This program is mainly used for gridded hazard with a normal-slip or reverse slip-component.
- HazgridXnga4, hazgridXnga5: more recent updates of hazgridXnga3. HazgridXnga5 has more attenuation models included in its subroutines than the earlier versions.
- HazSUBXnga: program to compute the hazard from subducting-slab models.
- HazallXL.v2: program that uses a log-log interpolation to combine the output files of the above-mentioned programs.

Additional software are provided with the aim of converting between the ASCII and binary output files (bin2xyzX);

- Gethead.nga: program that allows to read the header information associated with the hazard files.
- hazpoint: program that will output a hazard curve(s) associated with one geographic position, given by its lat/long coordinate pair.
- iosubs: the program provides basic I/O subroutines for writing and reading C binary files. These routines have some machine dependencies.

The NSHMP programs suite can be considered platform independent since it was successfully tested on Sun Solaris with Unix OS, Windows PC and Linux machines. The version reviewed in the present study was released in 2008. The code has a dedicated section on the USGS NSHMP 2008 project web site and it can be downloaded at the following address: http://earthquake.usgs.gov/hazards/products/conterminous/2008/software/

3.9 OHAZ

OHAZ: A Computer Program for Seismic Hazard Computation

3.9.1 Developers

B. Zabukovec, B. Sket-Motnikar, Geophysical Survey of Slovenia, Slovenia.

3.9.2 Overview

OHAZ is a program for computing probabilistic seismic hazard using a smoothed seismicity methodology. The approach on which is based is an extension of the Frankel [1995] methodology and was developed by Geophysical Survey of Slovenia [Lapajne et al., 1997; Lapajne, 2000; Motnikar et al., 2000, Polijak et al., 2000]. The program is structured in three modules: seismic activity module, annual rates module and ground motion module. These modules can be executed independently or can be combined together. In the latter case, the user specifies the input parameters for these modules and for each stage of computation so that the output of the preceding stage becomes the input of the next one.

OHAZ has an intuitive GUI, organized in six panels: program flow, activity, catalogue, smoothing, hazard and files. The user can switch between these tabs; note that not all the parameters are required for each type of computation.

Seismic hazard is either computed for a single location or for a grid of locations. Various output files are generated during a hazard computation with OHAZ, including seismic activity maps, hazard values for specific return periods, computed Gutenberg-Richter b-values from an earthquake catalogue and a combination of hazard maps based on predefined weights.

3.9.3 Seismic Sources Description

Seismic Sources - Geometry

OHAZ has capacity for modelling area or fault sources.

Area sources are represented as polygons parallel to the surface of the Earth. The key elements on defining an area source are:

- Geographical coordinates (latitudes and longitudes) of the polygon vertexes
- Average hypocentral depth
- Predominant fault mechanism (i.e. strike slip, thrust, reverse or normal fault)
- Predominant fault orientations (strike in degrees)
- Corresponding weights associated to each predominant fault orientation

An area seismic source can be characterized by one or more predominant faults systems, with distinct orientations and corresponding weights. It is recommended that the sum of all weights in one seismogenic area is 1. When specifying the polygon coordinates of the area sources the first and the last vertex should not coincide. Coordinates of the polygons can be either clock-wise or counter clock-wise.

Fault sources are represented as line segments and are defined by:

- Geographical coordinates (latitude and longitude) of their surface trace
- Subsurface geometry parameters:
    - Predominant style-of faulting (i.e. strike slip, fault, thrust, reverse or normal fault)
    - Orientation of the fault in space: strike and dip angle
    - Corresponding weights associated to each predominant fault

Seismic Sources - Seismicity

Seismicity in OHAZ is specified of computed using the activity module. Three options are available: (i) count the number of earthquake in a given region; (ii) compute the frequency of earthquakes considering the seismic energy released and assuming a MFD; and (iii) take on a uniform seismic activity. The first two options rely on an earthquake catalogue, whereas the last one does not.

Smoothing the seismic activity is performed in two stages and is controlled by a set of smoothing parameters. During the first smoothing stage OHAZ applies a circular smoothing kernel controlled by a correlation distance. Smoothing stage two is based on an elliptical Gaussian smoothing kernel that requires the axes ratio (i.e. the ratio between the primary and secondary axes of the smoothing ellipse). The primary axis is defined as the product between expected rupture length and an axis/rupture ratio.

Earthquake catalogue has to be an ASCII file in five-column format, where the columns are: year of earthquake occurrence, latitude of the epicentre, longitude of the epicentre, depth and magnitude. The forth column is not used. The catalogue has to be filtered to certain maximum and minimum magnitude, and minimum/maximum year. Starting from this catalogue, the parameters characterizing a double truncated Gutenberg-Richter distribution can be computed using the maximum likelihood estimation (MLE) method (eventually, the user has the possibility of customizing the MLE parameters).

Moreover, OHAZ has an option to normalize the seismic activity, controlled by a normalization factor. This factor represents the ratio between average reference activity and the average current activity. Reference activity is defined as the seismic activity to which current activity should be normalized; while, the current activity represents the seismic activity under consideration that is not yet normalized. Normalization can be done automatically using the catalogue data, or using a magnitude-frequency relationship. The normalization technique applies to the first two models (i.e. counted and energy models) of computing the seismic activity. It is important to note that the area where seismic activity is computed has to cover the seismic sources; otherwise any grid point of the activity map located outside the seismic sources will be ignored [Lapajne et al., 2003].

Rupture Area/Length vs. Magnitude Relationship

Two sets of rupture-magnitude relationships are built-in in the OHAZ software. Wells and Coppersmith [1994] equations are available for all four predefined fault mechanisms, while the equations proposed by Vakov [1996] are available for all fault types but thrusts. Alternatively, the user can specify their own relationships as a function of magnitude and faults type.

3.9.4 Ground Motion Prediction Equations

OHAZ contains three built-in equations:

- Ambraseys et al [1996], Sabetta and Pugliese [1996], and Pugliese and Sabetta [1989].

The user can add more GMPEs, but there is a limitation imposed by the built-in functional form, since it is constrained to a very basic equation. Ground motion variability is incorporated assuming a normal distribution of the logarithm of ground-motion with standard deviation (sigma). No truncation option is available within OHAZ.

Distance Measures

OHAZ supports just two source-site distances:

- Epicentral distance; closest distance to the surface projection of the rupture

3.9.5 Output

OHAZ generates various output files, including grid configuration information and seismicity activity description (all in ASCII format). The program tracks the computation process and a log file is generated. By inspecting the log file, a user can detect the possible errors or improperly set parameters. Also, information regarding the computational time for each step is reported.

OHAZ does not report hazard curves, UHS, or disaggregation of the hazard. The software outputs hazard values that can be used to construct hazard maps.

An additional tool can be used to combine hazard maps accordingly to user-defined weights. Up to five hazard maps can be combined, and the maps should cover the same geographical region and have exactly the same internal organization (i.e. locations must be in the same order in all of the map files).

3.9.6 Possible Restrictions and Limitations

Default values for controlling parameters can be modified, according to the needs of the user. In particular, the configuration submenu in the GUI provides access to some environment variables, such as parameters for seismic hazard computation, parameters controlling the integration procedures as well as default paths where saving output files. The main limitation of the software is related to the output files since there is no option for hazard curves, UHS or disaggregation.

Some limitations on the input model:

- No characteristic earthquake model to describe the seismic activity
- Limited source to site measures
- User defined ground motion prediction equations constrained to a basic functional form
- No option to control the ground motion truncation level;

3.9.7 Software Requirements, Version, Content of Software Package, Input/Output Format, User Manual, Code Availability

OHAZ is written in the Java-programming language, therefore is OS independent. The version under review (version 2.1) was tested successfully on Solaris, Windows, MAC OS and Linux platforms. OHAZ provides a well-structured user manual, as well as explicit examples for understanding the capabilities of the software. The input/output file format is ASCII. The source software is available by request at the following address: http://www.esc-web.org/ohaz/ohaz.html

3.10 OpenSHA

OpenSHA: Open Seismic Hazard Assessment

3.10.1 Developers

Field, E. H. and the OpenSHA development team (the components of the team changed during the years)

3.10.2 Overview

OpenSHA, a joint SCEC-USGS initiative, goes beyond the classic PSHA code concept by introducing what has been called a "community-modelling environment" for seismic hazard analysis; indeed, OpenSHA can be considered more a library of Java classes than a rigid PSHA code.

OpenSHA was developed around two fundamental concepts (i.e. components): the Earthquake Rupture Forecast (ERF) and the Intensity Measure Relationship (IMR, also commonly called GMPE). The ERF is an object that collects all the possible ruptures occurring on all the sources being part of a PSHA input model; each rupture in ERF is associated with a probability of occurrence in a given time span (i.e. the investigation period). The IMR is an object that given an Intensity Measure Type (i.e. a ground motion parameter), a rupture, and a site computes the probability that an intensity measure level will be exceeded Note also that OpenSHA has a clear taxonomy to unambiguously specify all the most important objects considered in its development (see also the OpenSHA glossary at http://www.opensha.org/documentation/glossary/index.html).

OpenSHA is based on a modular concept of PSHA that allows the user to create his own ERF using the available tools or, alternatively, to add – without altering any component of the computational kernel – new tools for the creation of customized ERF. For example, the user can add a seismic source typology not already available in the OpenSHA library. The same concept holds in case of new IMRs.

The output of a hazard analysis can be customized and the results represented using different formats. OpenSHA offers a set of GUIs to explore components used in the computation of hazard (e.g. IMRs) or to interactively compute hazard curves using predefined ERFs with the option to customize the calculation by modifying a set of adjustable parameters. The package does not have a single User Manual, but rather a well-documented web page with various manuals and tutorials. An overview of the OpenSHA framework is summarized in Field et al [2003], and several publications since then have exemplified the use of OpenSHA for different problems (see the OpenSHA website for a comprehensive list).

3.10.3 Seismic Source Description

OpenSHA can accommodate several seismic source typologies going from simple point sources to complex 3D fault planes.

Seismic Sources - Geometry

These are the principal seismic sources typologies defined within OpenSHA:

Point sources are represented as points of active seismicity (each node will be a point source). The hypocenter of each event is presumed to be located at the point source. The following parameters are required to specify a point source:

- Geographical coordinates (latitude and longitude) of the point source
- Average hypocentral depth or depth to the top of rupture (in case extended rupture are taken into account);

Area sources are represented as polygons parallel to the surface of the Earth. The main parameters on defining an area source are:

- Geographical coordinates (latitudes and longitudes) of the polygon
- Average hypocentral depth or depth to the top of rupture (in case extended rupture are taken into account);
- Predominant fault mechanism defined by
    - Average dip angle

- Average rake angle
- Average strike angle

Fault sources specified by the following parameters:

- Geographical coordinates (latitude and longitude) of their surface trace
- Subsurface geometry parameters:
    - Depth to the top of rupture
    - Depth to the bottom of rupture
    - Average Dip angle
    - Average Rake angle
    - Floating Rupture Flag

In order to distribute ruptures over the fault sources three floating options are available: (i) float along strike with rupture extending all the way down dip; (ii) float down dip and along fault; and (iii) float along the mid-depth point.

Seismic Sources - Seismicity

Earthquake occurrence in time can be modeled using a homogeneous Poisson model as well as using time-dependent models.

OpenSHA internally it represents magnitude-frequency distributions (MFD) as evenly discretized distributions. These are the main MFDs supported:

- Single-Magnitude distribution
- Truncated exponential GR magnitude distribution
- Tapered GR magnitude distribution
- Gaussian Distribution
- Youngs and Coppersmith Distribution (i.e. the "Characteristic" Distribution)
- Arbitrary (user defined) Distribution
- Summed MFD (the sum of other distributions)

Rupture Area/Length vs. Magnitude Relationship

Finite faults dimensions are determined using one of the magnitude-area or magnitude-length relationships implemented (e.g. Wells and Coppersmith [1994],

3.10.4 Ground Motion Prediction Equations

The following GMPEs are implemented in OpenSHA:

- Abrahamson and Silva [1997], Abrahamson and Silva [2008], Abrahamson [2000], Boore and Atkinson [2008], Boore, et al. [1997], Campbell and Bozorgnia [2003], Campbell and Bozorgnia [2008], Chiou and Youngs [2008]; Campbell [1997], Dahle et al. [1995], Field [2000], Spudich et al. [1999], and Sadigh et al. [1997];

A stand-alone application is available for visualization of the implemented GMPEs.

Distance Measures

The source-to site distances supported by OpenSHA are:

- *Hypocentral distance; Epicentral distance; closest distance to rupture; seismogenic distance; Joyner and Boore distance*

3.10.5 Output

OpenSHA can generate various outputs, including seismic hazard curves, maps, disaggregation results, ground-motion fields. Hazard curves, are defined as curves expressing the probability of exceedance for a set of of *Intensity-Measure levels* (IMLs) at a given *Site* in a specified time span. Seismic hazard maps as well as the disaggregation results can be stored in ASCII formatted file or plotted using the Generic Mapping Tool. Sources and earthquake ruptures can be visualized in 3D using the SCEC-VDO software (http://scec.usc.edu/internships/useit/scec-vdo).

3.10.6 Possible Restrictions and Limitations

The principal shortcoming of the OpenSHA package is that there is no dedicated user manual. The OpenSHA web page provides a description of the framework, a glossary, and updated Java Docs. Some manuals for the stand-alone applications can be also accessed on-line (e.g. Attenuation Relationship Plotter Manual). Due to the high level of complexity associated with this software, the developer should be familiar with the principles of the object-oriented programming.

3.10.7 Software Requirements, Version, Content of Software Package, Input/Output Format, User Manual, Code Availability

OpenSHA is written in Java (the version under review is the latest version released in 2009), although some of the components are legacy code written in other languages and wrapped in Java. Several stand-alone GUIs are available (see the OpenSHA website for a comprehensive list http://www.opensha.org).

The package is available upon request at the OpenSHA website.

3.11 SEISHAZ

SeisHAZ: A program for probabilistic seismic hazard computation

3.11.1 Developers

M. Stirling, G. McVerry, University of Nevada Reno and GNS Science, New Zeeland

3.11.2 Overview

SeisHAZ was developed at GNS Science and has been used to develop the seismic hazard model for New Zeeland [Stirling et al., 2002]. The software, composed of Fortran programs, implements a classical PSHA approach. It supports spatial smoothed seismicity (using an adaptation of the Frankel [1995] approach), as well as fault sources.

SeisHAZ contains several ground motion equations, derived for a variety of tectonic regimes. The software can also support input models organized into a logic tree structure to account for epistemic uncertainties.

SeisHaz computes annual frequencies of exceedance for ground motion at a single site or at a grid of sites. The output consists of hazard maps, hazard curves, uniform hazard spectra, and disaggregation of hazard in terms of magnitude and distance. SeisHAZ does not offer a GUI but offers an interactive command line interface.

3.11.3 Seismic Source Description

Seismic Sources - Geometry

SeisHAZ support the following source typologies:

Point sources. They represent points of active seismicity. This source-type can be used to model an area sources, as well as grid sources resulting from the application of smoothing seismicity algorithms.
The following parameters specify a point source:

- Geographical coordinates (latitudes and longitudes) of the point source
- Hypocentral depth parameters (five values);

Fault sources – can represented as single or multiple segments.

Fault sources are defined by:

- A set of points defined by geographical coordinates (latitude, longitude and depth) and corresponding to the vertexes of the fault trace
- Subsurface geometry parameters:
    - Modelled hypocentral depth
    - Depth to the top of rupture
    - Depth to the bottom of rupture
    - Orientation of the fault in space defined by a strike and a dip angle

Note that ruptures extend to the ends of the fault segment(s), but they are not allowed to extend beyond these ends; ruptures can overlap.

Seismic Sources - Seismicity

The characteristic earthquake model is employed for all fault sources. Truncated exponential GR magnitude distribution applies for all point sources.

Rupture Area/Length vs. Magnitude Relationship

The Aki and Richards, Hanks and Kanamori, and Wells and Coppersmith [1994] relationships are applied to define the moment magnitude from fault rupture parameters describing fault geometry (rupture) is implemented in SeisHAZ. A three tier procedure is adopted depending on the quality and quantity of existing data for the fault source [Stirling et al., 2002]. The epistemic uncertainty on these relationships can be taken into account in the calculations.

3.11.4 Ground Motion Prediction Equations

SeisHAZ includes a large dataset of built-in GMPE's and supports the use of tectonic-region dependent GMPEs. Following a list of available GMPEs:

- Abrahamson and Silva [1997], Atkinson and Boore [1994], Boore et al [1993], Dahle et al [1990], Fukusima and Tanaka [1990], McVerry et al [2000], Sadigh et al [1997], Toro et al [1990], and Young et al [1997].
- Combined Abrahamson and Silva [1997] (crustal) and Youngs et al [1997] (subduction zone)
- Combined Sadigh [1997] (crustal) and Youngs et al [1997] (subduction)
- Combined Fukushima & Tanaka [1990] and Youngs et al [1997] for deeper earthquakes (h>30km) - PGA only
- Combined Molas and Yamazaki [1995] with Sadigh [1997] for large magnitude, close earthquakes – PGA only

The software accounts for ground motion variability and permits the truncation of the ground motion distribution at a user-defined number of standard deviations.

Distance Measures

SeisHAZ accommodates the following source-site distance definitions:

- *Hypocentral distance; Joyner-Boore distance; shortest distance from fault rupture*

3.11.5 Output

SeisHAZ provides hazard curves for a range of spectral periods, uniform hazard spectra for a large number of return periods, spectral values at 50, 84 and 90-percentile levels for a scenario fault; spectral values at 50, 84 and 90-percentile levels for the fault that is dominant at a selected spectral value. The hazard curves are defined as annual frequency of exceedance (y-axis) versus ground motion amplitude (x-axis). Other output includes seismic hazard values for mapping. Disaggregation of the hazard is computed in terms of the magnitude-distance pair.

3.11.6 Possible Restrictions or Limitations

In case of point sources the finiteness of ruptures is not taken into account, but has been implemented in specific applications of the code.

3.11.7 Software Requirements, Version, Content of Software Package, Input/Output Format, User Manual, Code Availability

The software is a collection of Fortran programs and Matlab scripts, therefore Matlab and a Fortran compiler are required. SeisHAZ does not have a GUI, but it offers an interactive command line interface. This interface asks step-by-step details to characterize the PSHA, such as: type of analysis (site specific or regional – in the latter also specification of geographical boundaries of the region of interest most be specified), type of input sources (e.g. fault or point sources), GMPEs, ground motion parameters (peak or spectral acceleration), names of the output files and so on. The program works with ASCII text file formats both for input and output data. SeisHAZ does not have a dedicated user manual. The version under review was produced in 2005. The software is not available for downloading.

3.12 SEISRISK IIIM

SEISRISK III: A computer Program for Seismic Hazard Estimation

3.12.1 Developers

B. Bender and D.M. Perkins, United States Department of the Interior Geological Survey

Roland Laforge, US Bureau of Reclamation, Technical Service Centre Geophysics, Paleohydrology, and Seismotectonics Group, Denver, Colorado

3.12.2 Overview

SEISRISK III is one of the most popular PSHA software to compute seismic hazard; the software uses the classical PSHA approach. The program was designed to compute ground motion levels that have a specified probability of not being exceeded during fixed time periods at each of a set of sites uniformly spaced on a two dimensional grid..

The input requires attenuation relationships in tabular form (ground motion versus magnitude and distance) and the description of each source including the geometry, the uncertainty in earthquake location and the occurrence rates (number of earthquake occurrences at given magnitude intervals normalized to a given number of years). Earthquake occurrences are assumed to follow a Poisson distribution, and rates are not restricted to fit an exponential distribution. SEISRISK III also allows for earthquake location uncertainty by considering locations normally distributed with standard deviation sigma. Ground motion variability is incorporated in the computations assuming a lognormal distribution of the ground-motion parameter with standard deviation. The present version SEISRISK IIIM is a modified version proposed by R. Laforge, in order to (i) make the input file more efficient and user friendly; (ii) provide the hazard disaggregation capabilities. SEISRISK III was used to compute pre-1996 seismic hazard maps in the US.

3.12.3 Seismic Source Description

Seismic Sources - Geometry

SEISRISK III supports the following seismic source typologies:

Area sources: modelled polygons parallel to the surface of the Earth, defined by the geographical coordinates (latitudes and longitudes) of the polygon vertexes. Coordinates of the polygons must be ordered clock-wise always starting from the top left corner. When specifying the vertex coordinates the first and the last vertex should not coincide.

Fault sources: modelled as one or more straight-line segments. If more that one segment is specified, the fault is considered articulated.

The following parameters are required to specify a fault source:

- Geographical coordinates (latitude and longitude) of its surface trace
- Distance between two parallel hypothetical faults

Seismic Sources - Seismicity

SEISRISK IIIM assumes that earthquakes occur randomly within area sources or along faults. Also, the program considers earthquakes within a seismic source to be normally rather than uniformly distributed. Therefore, each point is considered as the mean location of a future earthquake; this 2D Gaussian distribution is controlled by a standard deviation. This is denoted as "earthquake location uncertainty" and permits earthquake rates to vary smoothly across the boundaries of the zone. Earthquake occurrence is assumed to follow a Poissonian process, and the occurrence rates as a function of an evenly- discretized set of magnitudes have to be provided as an input.

Rupture Area/Length vs. Magnitude Relationship

For fault sources, SEISRISK IIIM allows the earthquakes to be modelled as finite-length rupture along linear fault segments. An individual fault may consist of a maximum of 24 straight-line segments and a rupture may span all segments but cannot extend beyond the end of the fault. Rupture length is defined as a function of magnitude and the values of the coefficients have to be provided for the rupture-length relationship. If no values are provided, the default values of the Bonilla and Buchanan [1970] relationships are used. Moreover, the program does a distance and a magnitude smoothing in order to remove the spikes that may occur on the calculated ground motion densities. The program cannot do both distance and magnitude smoothing. Details related to the smoothed approaches are presented in SEISRISK IIIM user manual.

3.12.4 Ground Motion Prediction Equations

The input for SEISRISK III requires user-defined GMPEs implemented in tabular form (i.e. a table specifying: values of a ground motion parameters, for discrete values of magnitude and distance). Variability on the ground motion is taken into account during calculation; and the ground motion distribution can be tapered at a user-provided value. There is no option for truncation based on the ground motion variability [standard deviation]. The units of the GMPEs are customizable.

Distance Measures

SeisHaz accommodates the following distance definitions:

- Epicentral distance, hypocentral distance, Joyner-Boore distance.

3.12.5 Output

SEISRISK IIIM generates several output files in an ASCII or binary format. The main hazard results are contained in a file, denoted riskx.out; a disaggregation file called risk.table, and two additional output files that contain the table of relative contributions to specified values of hazard.

Seismic hazard curves are reported as a standard output. The level of discretization of each hazard curve is controlled by a parameter in the input file. Mean or median values can be reported, with considering ground motion variability or not during computation. The hazard curve represents the rate of annual exceedance for a discrete set of ground motion values. Seismic hazard values calculated at the specified probability level for the defined investigation time are reported in a binary file format. Uniform hazard spectra can be obtained with a batch file, which computes the hazard for each spectral period and then extracts the hazard values corresponding to a unique return period.

The disaggregation option – successively added – outputs the relative contributions (as percentage) to the probability of exceedance of a specified ground motion value in a specified investigation time. The relative contribution is specified for discrete values of magnitude and distance.

3.12.6 Possible Restrictions or Limitations

SEISRISK IIIM shows the following limitations:

- Depth can not be assigned to the fault sources
- The Seismic hazard curve is limited to 50 levels of acceleration.

3.12.7 Software Requirements, Version, Content of Software Package, Input/Output Format, User Manual, Code Availability

SEISRISK IIIM is a package written in Fortran. Two additional programs in C, relconm and relconv, add the disaggregation capabilities. The version under review was the modified SEISRISK IIIM version by R. LaForge. SEISRISK IIIM default works with ASCII text files. The user's manual and is the source software of the program are available at the following web address:

http://earthquake.usgs.gov/hazards/apps/seisrisk/

4 Evaluation of PSHA Software

The second phase of the PSHA software appraisal process, was the evaluation of the PSHA software. From the perspective of a hazard analyst, the tests performed were rather simple exercises, however, they gave to the GEM1 hazard team insights into the calculation algorithms and software functionalities. In particular, the evaluation process helped us to:

- Understand the features and functions of each software,
- Analyze and compare the features of candidate PSHA software,
- Understand the information requested for a correct implementation of software features.

Our evaluation exercise consisted on performing simple tests aimed at understanding specific software features or at comparing results from simple test cases. In particular, our concern was to investigate the basic features of the PSHA software including (i) the way the seismic sources are modelled, and (ii) how the truncation of the ground motion influences the results of distinct codes.

We describe here an example of the tests performed. This test consisted of an adaptation of one test case originally proposed within the PSHA software validation study performed during the PEER Lifeline Program [Wong et al. 2004]. The PEER PSHA software validation process was the first attempt to benchmark PSHA software for validation. At the time of the present study the results of the PEER validation exercise were not available yet. However, these results have become recently available [Thomas et al., 2010]. Luckily, some of the software we considered such as MRS, NSHMP, and OpenSHA were successfully benchmarked within the PEER study.

In particular, the test here described consisted in calculating hazard curves using a single area source zone. Despite its simplicity, this source typology is the commonest one in the seismic hazard models collected within GEM1 [Pagani et al., 2010] and the only one supported by almost all the reviewed PSHA software. A summary of the parameters characterizing this test is given in Table 4.1, while Figure 4.1 shows the geometry of the area source and the positions of calculation sites. Additional conditions and assumptions are the following:

- Cell size used to discretize area sources (when applicable): 0.1 decimal degrees.
- Magnitude interval width used to discretize the magnitude-frequency distributions: 0.1 units
- Maximum integration distance: 200 km
- Local site condition: rock ($V_{S,30}$ > 850 m/s)
- The GMPE used is Abrahamson and Silva [1997]
- The results are computed in terms of PGA hazard curves for an investigation time of 50 years.

A special attention was given to identify the parameters that might affect the final results. These parameters differ from code to code and their calibration was done iteratively during the tests. An example of such calibration of the input parameters is presented in Appendix C, for CRISIS.

The benchmarking exercises were conducted considering the following software: OpenSHA, MoCaHAZ, CRISIS 2007, FRISK88M, MRS, SEISRISK IIM; these are the PSHA software that implement by default area sources. OHAZ, EQRM, NSHMP and SeisHaz were withdrawn because neither the used GMPE (OHAZ and EQRM) nor area sources are implemented by default (NSHMP and SeisHaz). NSHMP and SeisHAZ can handle area sources as multiple point sources, but we did not consider this option in the current benchmarking.

In Figure 4.2 we present hazard curves obtained for distinct sites using the selected PSHA software. Although we find a general consistency between the results provided by the different software, we observe SEISRISK to provide lower probability of exceedance values than the other programs. The discrepancy is higher inside the source and decreases when moving outside the source. We observe also that OpenSHA gives slightly higher probabilities of exceedance in two locations along the polygon boundary (sites 3 and 4).

In Figure 4.2 we present hazard curves for site 1 generated by the same software set but with a truncation of the GMPE distribution of two sigmas. In this case the agreement is very good (the same level of consistency is obtained also for the other considered sites) but in this case SEISRISK IIIM was excluded because it didn't support this calculation feature.

Table 4.1 Input parameters and details of the area source-based test case

Source typology	Area		
Source Area [km^2]	22470		
Predominant Fault Type	Normal		
Depth	0 Km		
Polygon vertexes	Point Nr.	Latitude [dd]	Longitude [dd]
	1	34.65	70.00
	2	34.65	71.65
	3	36.00	71.65
	4	36.00	70.00
Calculation Sites	Site 1	35.30	70.82
	Site 2	35.00	70.80
	Site 3	34.65	70.00
	Site 4	34.65	70.80
	Site 5	34.65	71.65
	Site 6	34.30	70.80
	Site 7	34.00	70.80
Magnitude-Freq. Distribution	Double truncated Gutenberg-Richter distribution:		
GMPE:	Abrahamson and Silva [1997] [Fault type: Other ; No-Hanging Wall]		

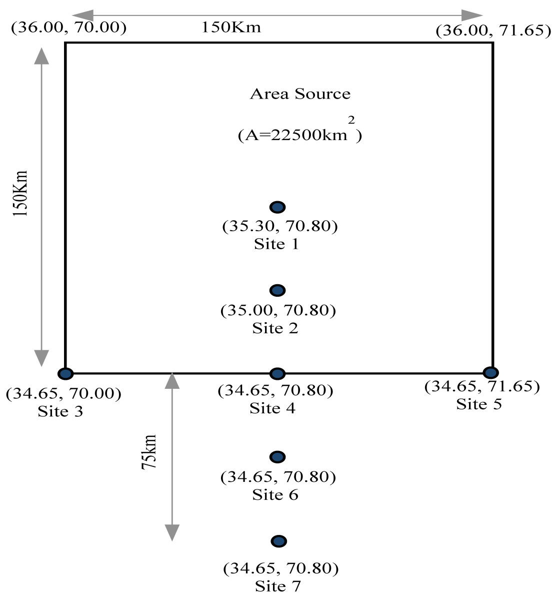

Figure 4.1 Source geometry and calculation sites for area-source test bed.

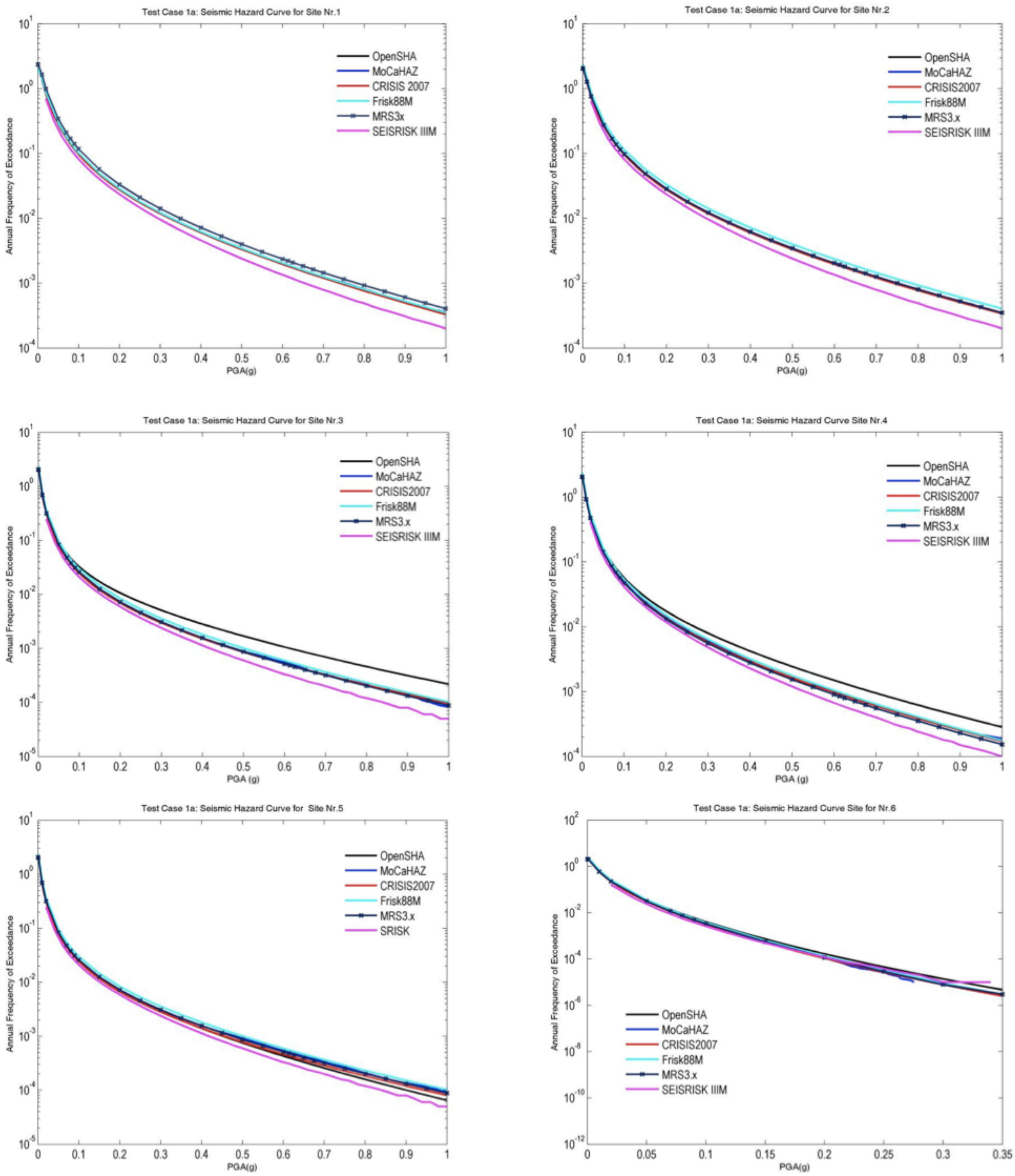

Figure 4.2 Hazard curves for area source-based test case without considering the truncation of the ground motion

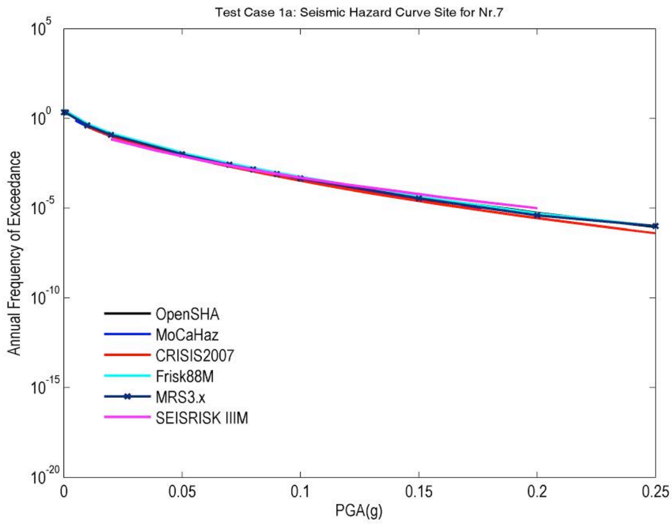

Figure 4.2 (Cont) Hazard curves for area source-based test case without considering the truncation of the ground motion

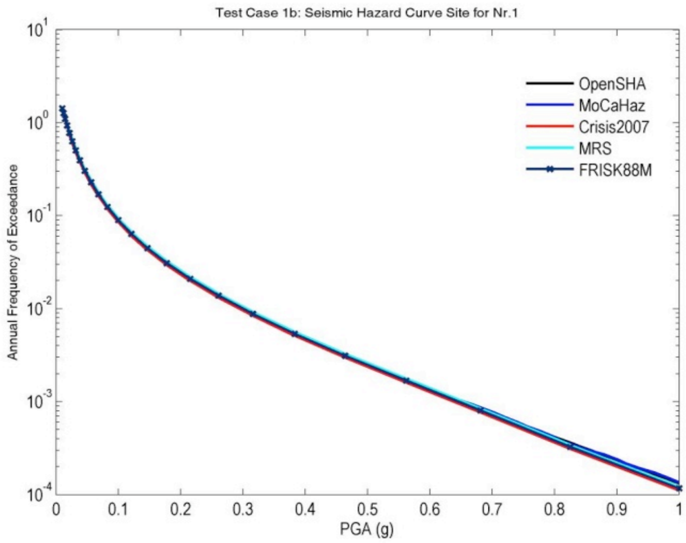

Figure 4.3 Hazard curves computed considering a single area source and truncating at two sigmas the GMPE distribution.

5 Discussion and Conclusions

5.1 Discussion

The review and evaluation of the PSHA software was a self-education exercise that helped to figure out the main characteristics of an ideal PSHA computer program. Several characteristics were integrated in the GEM1 hazard engine specifications presented in the Section 2.

From an IT perspective the main characteristics that were acknowledged are summarized as follows:

Free/Open Source. In the strict sense of *Open Source* definition [2] this is a characteristic of two codes: OpenSHA and EQRM. Note that open source characteristic have to apply to both access and distribution of the source code.

Flexible. The software should be extensible, that is allow for an easy addition of new functionalities or modification of pre-existing ones. OpenSHA, EQRM and CRISIS offer the ability to change easily in response to different user and system requirements. This is due to their programming languages that support the object-oriented paradigm. However, we think that the OpenSHA code structure better supports the option to implement different PSHA calculations kernels (e.g. one kernel based on classic PSHA and a second one based on the generation of stochastic event sets) as well as the definition of additional seismic sources typologies and, more generally, to versatility extend the code. These properties speed up the development process and reduce the possibility of introducing errors.

Efficient. Given the large computations envisioned, the code should be computationally efficient and able to take advantage of large computational facilities. Regarding efficiency, the triangulation-based integration algorithm implemented in CRISIS is particularly powerful in case of area sources. OpenSHA is the only example of PSHA software used with large scale computing facilities.

Graphical User Interface (GUI). This is certainly a desirable feature for the end-user. In this respect, CRISIS and OHAZ are the most user-friendly, due to their intuitive GUI. Also, the stand-alone calculation tools of OpenSHA are worth mentioning [1]. However, this is not a critical feature of the hazard engine, since the user interface within GEM will be developed independently from the hazard engine.

Portable. Almost all the software revised, but CRISIS, can be considered platform independent.

Input/Output standardized format. Most of the PSHA codes define input and output data through plain ASCII files; the only exception is EQRM, which uses a XML file for the input definition. Options to save and/or export the output in different formats, including (ESRI shape-file, Surfer DSAA, KML, and/or binary) as implemented in CRISIS, NSHMP and OpenSHA are also important.

Documentation. The availability of a user manual is important for the understanding and correct usage of software. The minimum documentation should describe how to set up the software, present an overview of the calculation algorithm, and provide calculation examples. In this respect, we appreciate the documentation of EQRM, FRISK88M, MRS, OHAZ and SEISRISK IIIM and OpenSHA javadocs.

From the perspective of purely seismic hazard features, the PSHA software characteristics that were appreciated are the following:

- The triangulation algorithm for area source discretization as implemented in CRISIS,
- Ability to model finite ruptures in area sources (EQRM, FRISK IIIM and OpenSHA)
- The capability of modelling “doughnut” sources (area sources which contain a region of no seismicity) as implemented in EQRM;
- The capability to model floating ruptures on fault sources as implemented in NSHMP, OpenSHA and SEISHAZ.

- The way subduction interface events are modelled in NSHMP (as finite rupture over 3D arbitrarily shaped fault surfaces) and SeisHaz
- The calculation of the activity rate for a source based on a user-supplied earthquake catalogue and a completeness time table as provided in MRS, NSHMP and OHAZ
- The flexibility to discretize the MFD according to a user defined bin width, as presented in NSHMP and OpenSHA
- The methods adopted in EQRM to generate set of stochastic events starting from a MFD
- The flexibility of adding new GMPEs in CRISIS (although only if the GMPE is represented in a table format)
- The ground motion truncation options in CRISIS, FRISK88M, OpenSHA and EQRM
- The customization of the hazard curves and UHS as implemented in CRISIS
- The possibility to define multiple tectonic trends in an area source as supported by OHAZ
- The capability to generate scenario ground-motion fields as implemented in CRISIS and OpenSHA
- The geographical disaggregation of seismic hazard as implemented in MRS and NSHMP

5.2 Conclusions

A review process of a set of PSHA software was performed in two distinct phases. During the first phase, the set of PSHA software was reviewed focussing on the IT aspects and hazard specific features. On the second phase, some exercises were conducted to compare results and – most of all – to understand functionalities peculiar to the different codes. The tested PSHA software generated results whose consistency in most of the cases was considered reasonable. Nevertheless, this consistency was achieved after a deep understanding of the input parameters specific to each PSHA program (not trivial because of missing documentation and/or lack of transparency of the code).

Among the evaluated software, OpenSHA is identified as the most suitable PSHA program to form the basis of the GEM1 hazard engine. OpenSHA is preferred because best suits the IT development strategy and also fulfils most of the hazard analysis requirements. The most appreciated features of OpenSHA are reported below:

- *Open Source* - the software is accessible and has a copyright license that is consistent with the open source philosophy adopted by the GEM project.
- *Flexible,* due to its modular object-oriented structure, it is relatively straightforward to implement new and different types of seismic hazard input models, and introduce new features. For example, OpenSHA is the PSHA code that implements the full UCERF2 time-dependent model for California [Field et al. 2009], which is perhaps one of the most advanced earthquake forecast model ever developed. Object orientation also makes it easy implement and/or share resources with other code developments.
- *Community Development* – OpenSHA has a group of participants developing different components, which accelerates innovation as people can add new capabilities rather than reinventing what's already been done (as well as efficiently test what others have implemented).
- *Portable.* OpenSHA is written i*n Java,* and is therefore platform independent and easily portable to different environments. Non-Java components can also be easily wrapped as exemplified in Field et al. [2005a].
- *Peer Reviewed & Published* – The overall framework was formally reviewed by an expert panel including Norm Abrahamson, Allin C. Cornell, Paul Somerville, Thomas Jordan, and Philip Maechling. The framework was then published in *SRL* [Field et al., 2003].
- *High-Performance Computing* - OpenSHA has been successfully tested on high performance computing facilities [Field et al. 2005b]
- *Distributed Computing* - OpenSHA enables the various computational components to exist anywhere over the Internet as exemplified in Field et al. [2005a]. This could be important for enabling, for example, interoperability with regional model developments or data centres. This also enables applications to be very lightweight. Of course components don't have to be distributed if a closed system is desired.
- *Taxonomy* - OpenSHA has a clear and fixed vocabulary, which was formally reviewed, as described above, and is well documented in an on-line glossary [1]

- *Verified* – The code has been formally verified against both the NSHMP Fortran code [Field et al., 2005a] and by virtue of participating in the PEER PSHA verification exercises. Most GMPEs have also been verified against independent calculations conducted by Kenneth Campbell. Most of these verifications have been implemented as formal Junit tests that get run in the main repository on a nightly basis.
- *Extensible* - The object-oriented nature of OpenSHA means that any of the code can easily be extended for other purposes. This will also enable implementing more computationally efficient calculations (e.g., the adaptive grid spacing used by CRISIS).
- *Well Documented* – See the public web site [1]

Moreover OpenSHA fulfils all the basic seismic hazard requirements, as were specified or identified by the GEM1 hazard team:

- Implements a probabilistic seismic hazard approach.
- Can model various types of seismic sources: area, grid, fault.
- Can incorporate complex GMPE for different ground motion parameters, considering several source-to-site distance measures and styles of faulting. In fact, OpenSHA can implement ground-motion models based on full 3D waveform modelling (e.g., SCEC's CyberShake initiative).
- Accounts for local site effects using whatever regional datasets are available
- Produces customizable outputs including site specific hazard curves and UHS, seismic hazard maps, and disaggregation of seismic hazard;
- Can handle epistemic uncertainty in the input models (e.g. logic trees as exemplified in Field et al. [2005a])
- Generates output for risk, including stochastic event sets and scenario ground-motion fields.

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Website references

1. OpenSHA
The official website of OpenSHA.
[Available at http://www.opensha.org/]

2. OpenSource
The official website of the Open Source initiative.
[Available at http://www.opensource.org/].

APPENDIX A Comparison between OpenSHA and NSHMP Software

We compare herein, for some specific cases, the results obtained using OpenSHA and some of the computer programs in the NSHMP package. This is an exercise performed in the course of the second part of the GEM1 project when the hazard team was actively involved in the implementation of the USGS 2008 model.

A.1 Shallow Crustal Fault Source

As an example of a shallow crustal fault source we considered the Mt. Diablo Thrust fault. This fault is included in the fault model for the State of California and used in the latest NSHMP hazard model for United States [Petersen et al., 2008]. Seismicity parameters and fault trace coordinates are given in Table A.1. The fault is discretized using a grid with 1 km spacing, and the rupture offset (the distance used to float ruptures over the fault surface) is also set to 1 km. Ruptures are allowed to float both along the strike and dip directions. Rupture dimensions are derived using the Wells and Coppersmith 1994 magnitude-area scaling relationship. The rupture aspect ratio is set to 1.

We compute the hazard using the Boore and Atkinson [2008] GMPE for active shallow tectonic regions. OpenSHA was compared with the dedicated code for modelling shallow crustal faults of the NSHMP package. The code is named HazFXnga7c.

The hazard is represented in terms of hazard curves calculated considering the average horizontal component (GMRotI50) of PGA, and assuming a Vs30 equal to 760 m/s. Ground motion is truncated at three values of sigma. We calculate hazard curves on a regular grid of points within a rectangular region including the fault surface and extending from 37.0N to 39.0N in latitude and from 121W to 123W in longitude, with a grid spacing of 0.01 degrees.

Table A.1 Seismicity and geometry parameters for the Mt. Diablo (California) Thrust fault.

Recurrence Model	Gutenberg-Richter		
Incremental a_{GR} value (bin width = 0.1)	2.27		
b_{GR} value	0.8		
Minimum magnitude	6.5		
Maximum magnitude	6.7		
Dip (degree)	38		
Down Dip Width (km)	13		
Top of Fault Depth (km)	8		
Faulting Style	Reverse		
Fault Trace	Point	Latitude	Longitude
	1	37.73010	-121.82290
	2	37.87710	-122.03880

Results obtained using the two software are compared in terms of maps in PGA for 2-percent probability of exceedance in 50 years (Figure A-1). The two maps show a very good agreement both in terms of values (with a maximum value of 0.8 g on top of the fault) and in terms of spatial pattern (lines of equal ground motion are almost coincident).

A.2 Subduction Fault Source

As an example of a subduction fault we considered the North Panama subduction fault included in the NSHMP South America hazard model. Seismicity parameters and geometry parameters for this source are provided in Table A.2. HazSUBXnga was used for comparison with OpenSHA. HazSUBXnga is the dedicated code to model subduction fault sources in the NSHMP suite. Differently to a crustal fault, the geometry of a subduction fault is defined in terms of top and bottom edges; note that in case of this source typology the depths of the top and bottom edges can vary along the traces. A subduction fault may results therefore in a more complex surface than the one representing a crustal fault.

To compute the ground motion associated with a subduction fault we used the Zhao et al. [2006] ground motion prediction equation for subduction interface events. Hazard curves were calculated for the average horizontal component of PGA and the site type was set to rock (corresponding to Vs30 values in between 600 and 1100 m/s). The hypocentral depth was assumed equal to 20 km. The ground motion probability distribution was truncated at three values of sigma. We modelled the fault surface using a grid whose spacing corresponds to 2 km; the rupture offset is also fixed to 2 km. Ruptures were allowed to float only along strike (with the ruptures extending fully in the down-dip direction). Rupture length were computed using the Wells and Coppersmith [1994] magnitude-area scaling relationship assuming a rupture aspect ratio equal to 1.

Hazard curves were calculated on a regular grid of nodes within a rectangular region including the fault surface and extending from 7.0N to 13.0N in latitude and from 75W to 85W in longitude, with a grid spacing of 0.1 degrees.

Results from the two PSHA programs were compared in terms of maps for 2-percent probability of exceedance (Figure A.2). Also in this case the results showed a very good agreement. Note that the subduction source typology was added to OpenSHA during the GEM1 project.

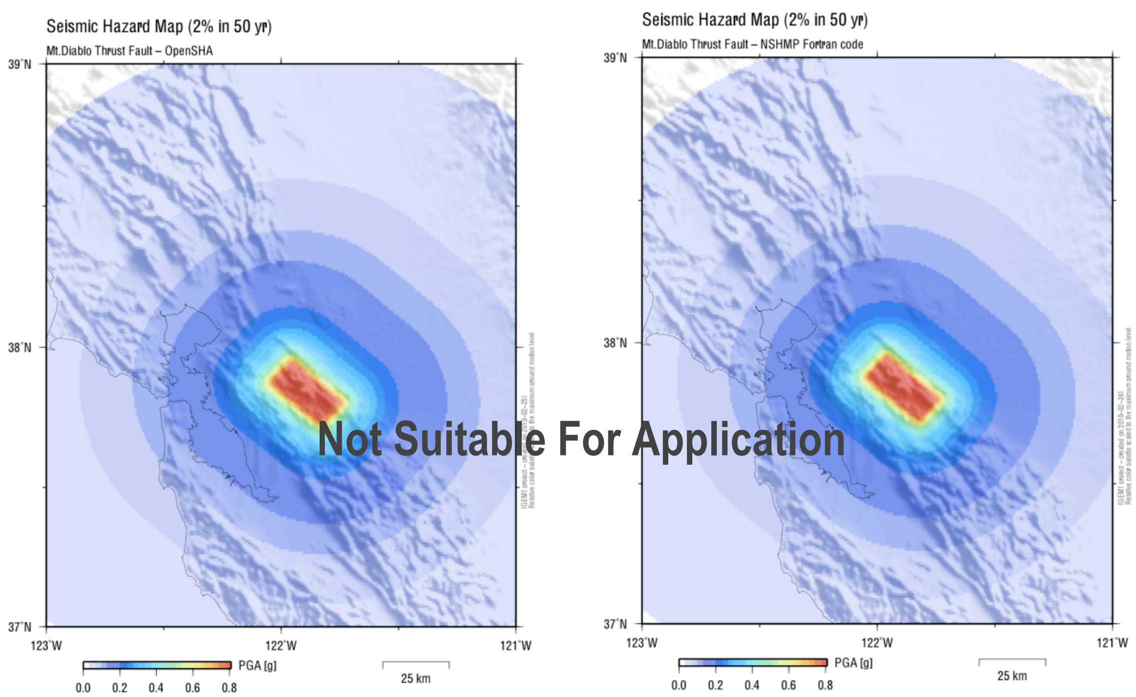


Figure A.1 Map of peak ground acceleration for 2-percent probability of exceedance in 50 yr associated with the Mt. Diablo Thrust fault computed by OpenSHA (left), and by HazFXnga7c (right).

A.3 Point Sources

To test the results derived by the use of a grid source we considered the grid model for the San Gorgonio Pass region (South of California) included in the latest PSHA hazard model for United States [Petersen et al., 2008]. In our calculation, each grid point is treated as a point source with an associated GR magnitude-frequency distribution. The code of the NSHMP suite used was the HazgridXnga2.

For each point source the b_{GR}-value is assumed equal to 0.8, the minimum magnitude is 6.5 and the maximum magnitude is 7.6; the a_{GR}-value is spatially variable. The source belongs to an active shallow crust region and therefore the ground motion is calculated by using the Boore and Atkinson [2008] ground motion prediction equation. Hazard curves were calculated for the average horizontal component (GMRotI50) of PGA, and assuming a Vs30 equal to 760 m/s. Ground motion was truncated at 3σ. Hazard curves were calculated on a regular grid of nodes within a rectangular region extending from 32.0N to 36.0N in latitude and from 114.5W to 118.5W in longitude, with a grid spacing of 0.01 degrees. Results from the two PSHA programs were compared in terms of maps for 2-percent probability of exceedance (Figure A.3). Also in this case the results showed a very good agreement.

Table A.2 Seismicity and geometry parameters for the North Panama Subduction fault.

<table>
<tr><td>Recurrence Model</td><td colspan="4">Gutenberg-Richter</td></tr>
<tr><td>Incremental a_{GR} value (bin width = 0.1)</td><td colspan="4">5.7</td></tr>
<tr><td>b_{GR} value</td><td colspan="4">1.0</td></tr>
<tr><td>Minimum magnitude</td><td colspan="4">7.7</td></tr>
<tr><td>Maximum magnitude</td><td colspan="4">7.7</td></tr>
<tr><td>Faulting Style</td><td colspan="4">Reverse</td></tr>
<tr><td rowspan="9">Top Fault Trace</td><td>Point Nr.</td><td>Latitude</td><td>Longitude</td><td>Depth (km)</td></tr>
<tr><td>1</td><td>10.09</td><td>-82.91</td><td>0</td></tr>
<tr><td>2</td><td>9.59</td><td>-82.32</td><td>0</td></tr>
<tr><td>3</td><td>9.56</td><td>-81.31</td><td>0</td></tr>
<tr><td>4</td><td>10.33</td><td>-80.45</td><td>0</td></tr>
<tr><td>5</td><td>10.53</td><td>-79.36</td><td>0</td></tr>
<tr><td>6</td><td>10.72</td><td>-78.99</td><td>0</td></tr>
<tr><td>7</td><td>10.73</td><td>-78.45</td><td>0</td></tr>
<tr><td>8</td><td>9.24</td><td>-77.00</td><td>0</td></tr>
<tr><td rowspan="6">Bottom Fault Trace</td><td>1</td><td>9.75</td><td>-82.91</td><td>10</td></tr>
<tr><td>2</td><td>9.66</td><td>-82.79</td><td>10</td></tr>
<tr><td>3</td><td>9.33</td><td>-82.25</td><td>7</td></tr>
<tr><td>4</td><td>9.24</td><td>-80.05</td><td>35</td></tr>
<tr><td>5</td><td>9.09</td><td>-79.10</td><td>48</td></tr>
<tr><td>6</td><td>8.00</td><td>-77.00</td><td>37</td></tr>
</table>

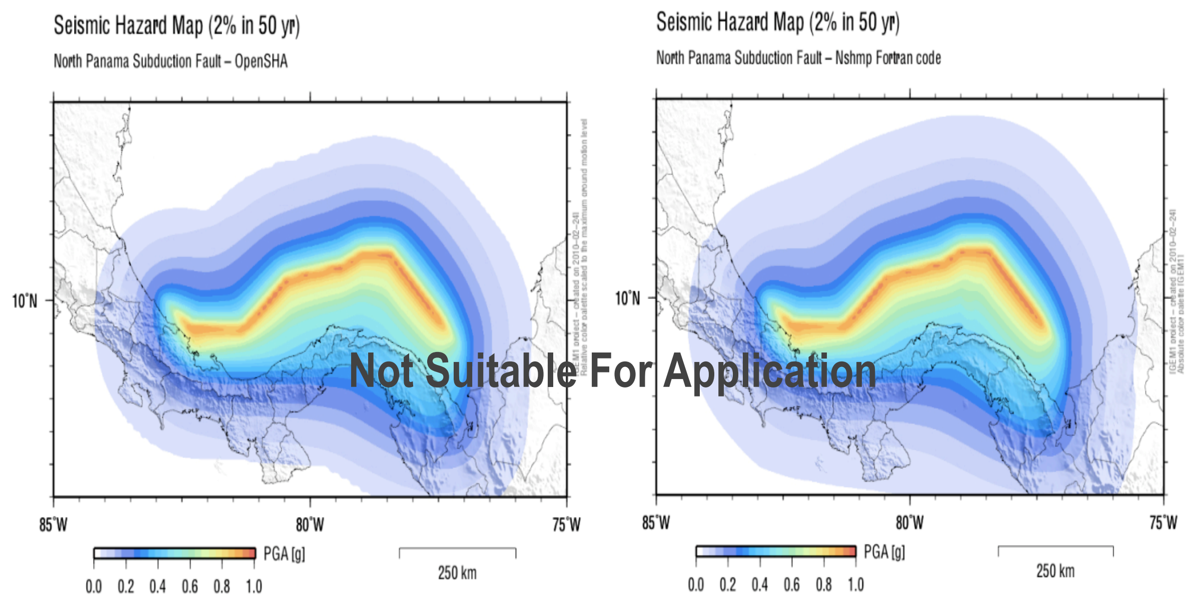


Figure A.2 Map of peak ground acceleration for 2-percent probability of exceedance in 50 yr associated with the North Panama Subduction fault computed by OpenSHA (left), and by HazSUBXnga (right).

A.4 Conclusions

Although limited in number, the above tests show a very good agreement between OpenSHA and the NSHMP software in modelling three main types of sources: crustal faults, subduction faults, and grid sources. It must be noted that even if in all the three cases the results match very well, for subduction faults the original HazSUBXnga source code was modified in order to reproduce the calculations done with OpenSHA. In particular, the original Fortran code for subduction faults did not implement the Wells and Coppersmith magnitude scaling relationship. To reproduce the correct results the rupture length was manually set at the same value calculated by the OpenSHA hazard calculator. Additionally, the Zhao et al. [2006] GMPE requires the hypocentral depth to be defined. NSHMP assumes a fixed value of 20 km for interface events. In the OpenSHA implementation of the Zhao et al. [2006] the hypocentral depth is assumed at the centre of each rupture. Again, in order to obtain consistent results, the hypocentral depth was manually set to 20 km in the OpenSHA implementation. Another factor influencing the results is the rupture-floating algorithm. Currently the NSHMP code for subduction fault supports only floating along the strike direction, while OpenSHA supports additional floating algorithms (like floating along both strike and dip directions, and floating along strike but with the ruptures centred down dip). The choice of the floating algorithm may also produce a change in the results.

The above tests show therefore that the results provided by OpenSHA and the NSHMP software are consistent, despite a careful analysis is necessary to assure that the calculations are done under exactly the same conditions.

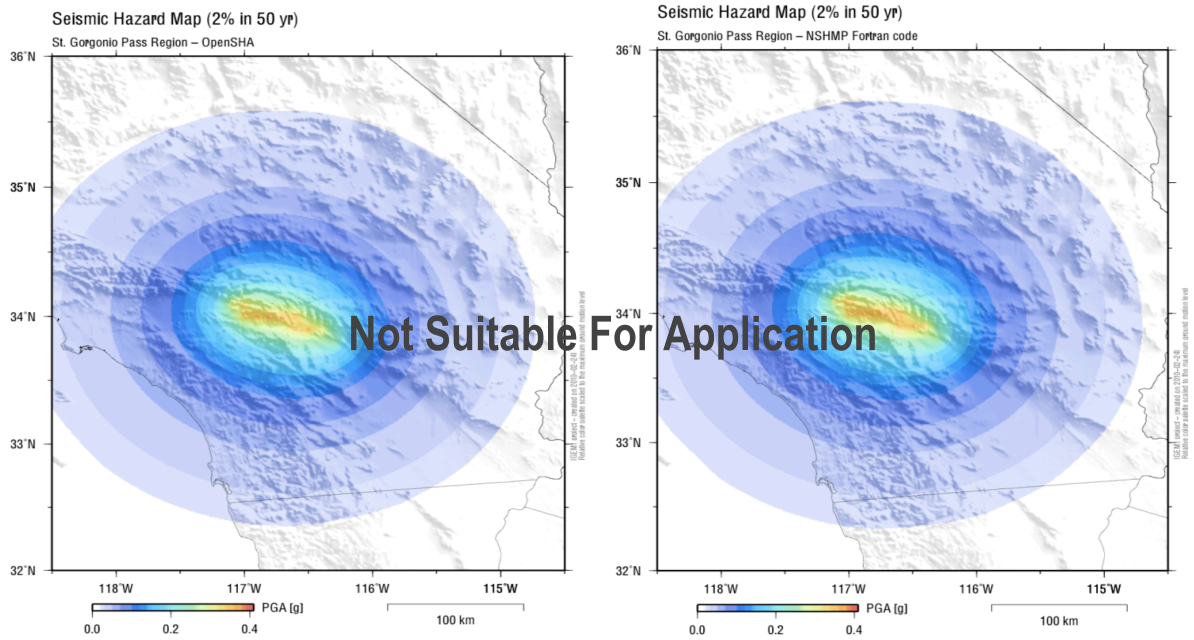


Figure A.3 Map of peak ground acceleration for 2-percent probability of exceedance in 50 yr associated with the San Gorgonio Pass grid model computed by OpenSHA (left), and by HazgridXnga2 (right).

APPENDIX B Regional Seismic Hazard Application

The exercise here illustrated is an example of a regional-scale seismic hazard calculation performed using OpenSHA MoCaHAZ and CRISIS. The aim of this exercise was to get a first order estimation of the computation time and resources needed without any specific validation intent. The model selected, the South-East Asia GSHAP model [Zhang et al., 1999] consists of 132 area sources. To compute the hazard a relatively simple and common GMPE was adopted, the Abrahamson and Silva [1997].

The input parameters for this test case are summarized in Table B.1 while the details of the input parameters for each source are presented in Table B.2

The computation times obtained in this exercise rely only on a single run based on a specific set-up of the configuration parameters, as required by each code; note that - when possible - default values were adopted. We also want to stress that changes of some of the control parameters (e.g. number of ground motion values in the hazard curve calculation, discretization level of the area sources) can probably alter, even sensibly, the results here illustrated. Moreover, the three programs considered implement different PSHA approaches and different numerical algorithms, which may play an important role in the overall performances.

B.1 Results

Running time represents here the total time needed for the entire computational process; this may comprise the reading of input files, actual computation and saving files. These characteristics are difficult to separate in distinct parts, therefore difficult to be quantified/measured. The running times obtained within the current exercise should be examinated under the following conditions:

- Codes were not run in machines with identical hardware characteristics;
- Codes were not run on the same operative system;
- Codes were written in different programming languages, therefore compile/interpreted and/or optimized differently;
- Different output formats were generated that require different computational time.

Without full control of these characteristics the running times cannot be accurately compared. However, the results presented here can constitute a starting point, and a guide to foresee probable computational requirements in terms of both hardware and software. The preliminary running time for each code together with the characteristics of the runs is summarised in Table B-3.

The computed seismic hazard maps in terms of PGA, for a probability of exceedance of 10% in 50 years are represented in the Figures from B-1 to B-3. The maps show an overall agreement in terms of pattern and values even if some differences can be noticed (CRISIS predicts a maximum value of about 0.7g while both OpenSHA and MoCaHAZ predict a maximum value of 0.6g).

Table B.1 Description of the input parameters for regional seismic hazard assessment

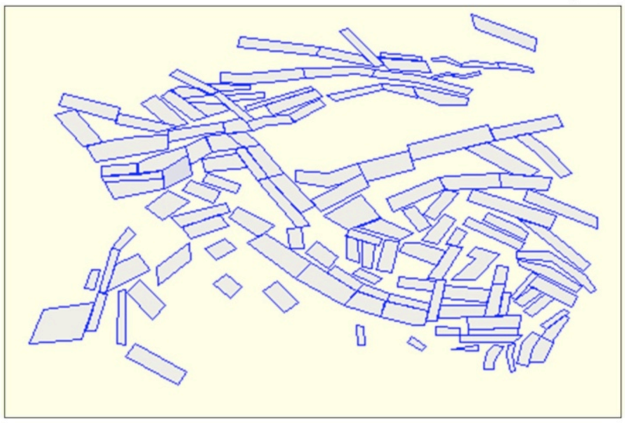
<table>
<tr><td>Number of sources</td><td colspan="3">132</td></tr>
<tr><td>Source typology</td><td colspan="3">Area</td></tr>
<tr><td rowspan="6">Computational region:
South-East Asia</td><td>Point Nr.</td><td>Latitude</td><td>Longitude</td></tr>
<tr><td>1</td><td>25</td><td>65</td></tr>
<tr><td>2</td><td>45</td><td>65</td></tr>
<tr><td>3</td><td>45</td><td>95</td></tr>
<tr><td>4</td><td>25</td><td>95</td></tr>
<tr><td colspan="3">(45.00°,95.00°)

(25.00°, 65.00°)</td></tr>
<tr><td>GMPE:</td><td colspan="3">Abrahamson and Silva (1997) (Fault type: Other ; No-Hanging Wall)</td></tr>
<tr><td>GMPE: Variability</td><td colspan="3">Yes</td></tr>
<tr><td>GMPE: Truncation</td><td colspan="3">2σ</td></tr>
<tr><td>Probability of Exceedence</td><td colspan="3">10%50yr</td></tr>
<tr><td>Seismic Hazard Codes</td><td colspan="3">CRISIS, MoCaHAZ and OpenSHA</td></tr>
</table>

Table B.2 Details of the running time evaluation for CRISIS, OpenSHA and MoCaHAZ

Code	Running Time	Programming Language / OS	Hardware	Nr of Grid Points
CRISIS	4h 30”	Visual Basic / Windows	1CPU 2.66Ghz 2.00Gb DDRAM	70000
OpenSHA	3h 45”	Java/ Linux	24 CPUs 2.66Ghz 8.00Gb DDRAM	70000
MoCaHAZ	14h 00”	MATLAB/ Linux	8 CPUs 2.66Ghz 8.00Gb DDRAM	70000 (11e6 events generated)

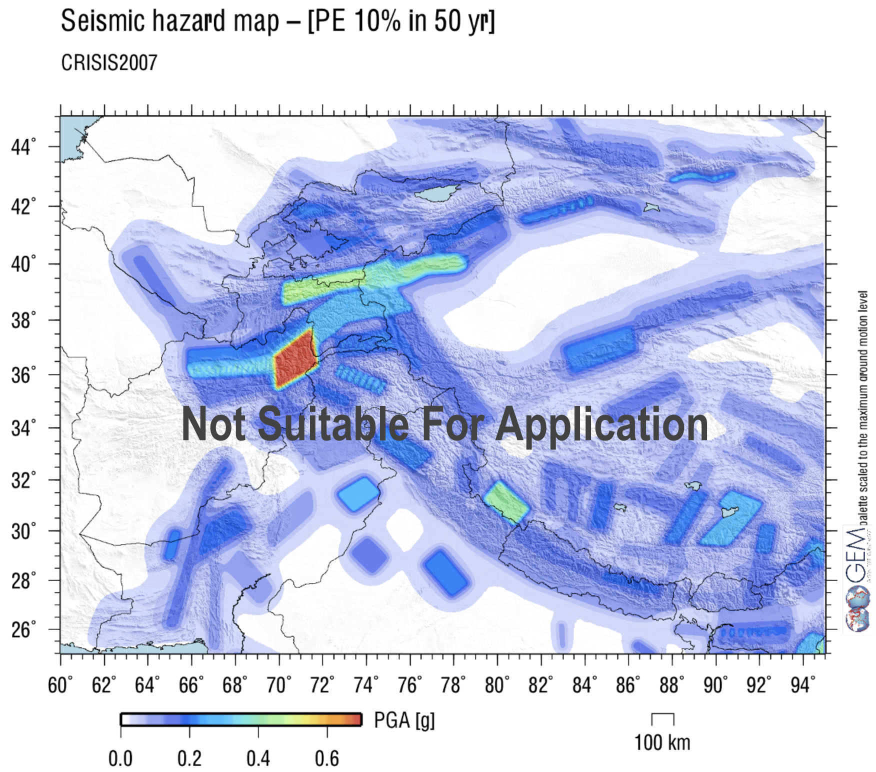


Figure B.1 Seismic Hazard Map for SE Asia computed with CRISIS

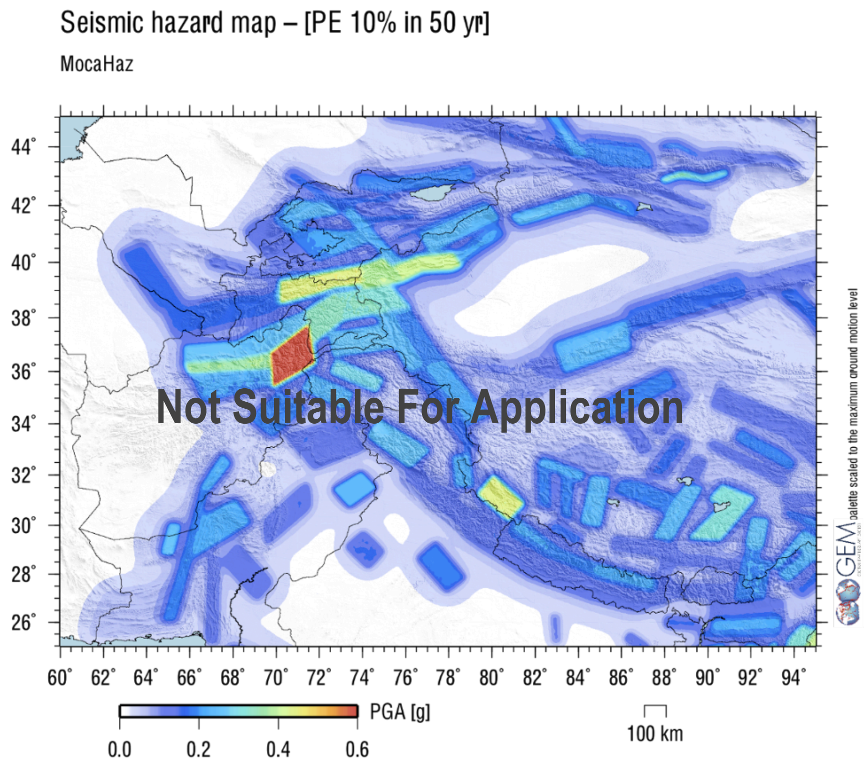


Figure B.2 Seismic Hazard Map for SE Asia computed with MoCaHAZ

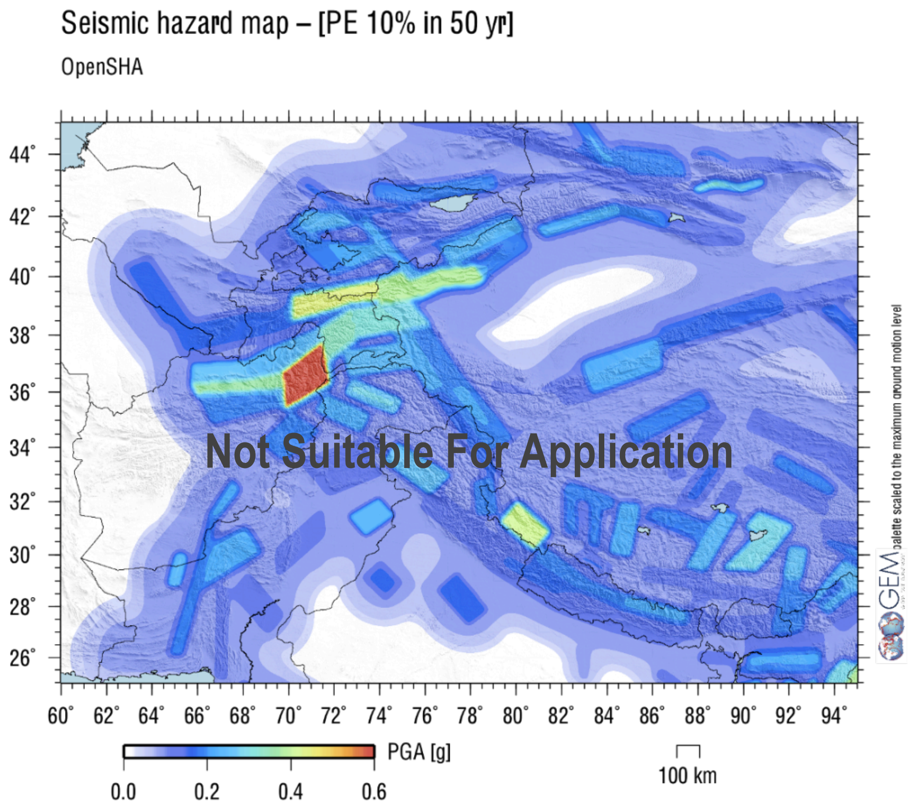


Figure B.3 Seismic Hazard Map for SE Asia computed with OpenSHA

Table B.3 Details of the selected seismic sources for the regional seismic hazard computation

Source Name	Guttenberg-Richter a-value	Guttenberg-Richter b-value	N(M>M_{min})	M_{min}	M_{max}
8.CH.143	5.72	1.16	0.081	5.5	7.1
8.CH.144	4.455	1.16	0.004	5.5	6.8
8.CH.145	4.615	1.16	0.006	5.5	7
8.CH.146	5.156	1.16	0.022	5.5	7
8.CH.147	5.849	1.16	0.109	5.5	7.5
8.CH.148	4.901	1.16	0.012	5.5	6.8
8.CH.149	2.433	0.658	0.041	5.5	7.5
8.CH.150	2.803	0.658	0.098	5.5	7.8
8.CH.151	2.955	0.658	0.138	5.5	7.7
8.CH.152	2.308	0.658	0.028	5.5	6.8
8.CH.153	2.339	0.658	0.03	5.5	6.8
8.CH.154	5.711	1.249	0.023	5.5	6.5
8.CH.155	5.723	1.249	0.023	5.5	6.5
8.CH.156	5.839	1.249	0.031	5.5	6.5
8.CH.157	6.035	1.249	0.05	5.5	6.8
8.CH.158	5.641	1.249	0.02	5.5	7
8.CH.159	6.369	1.249	0.108	5.5	7
8.CH.160	6.173	1.249	0.069	5.5	7
8.CH.161	5.929	1.249	0.039	5.5	6.8
8.CH.162	5.65	1.249	0.02	5.5	6.8
8.CH.163	6.124	1.249	0.061	5.5	6.8
8.CH.164	6.105	1.249	0.059	5.5	7.2
8.CH.165	6.256	1.249	0.083	5.5	7
8.CH.227	4.176	0.9	0.08	5.5	7.8
8.CH.228	3.955	0.9	0.046	5.5	7
8.CH.229	4.439	0.9	0.147	5.5	7.8
8.CH.230	4.7	0.9	0.268	5.5	7.8
8.CH.233	4.378	0.9	0.127	5.5	7.5
8.CH.234	3.955	0.9	0.046	5.5	7
8.CH.236	3.426	0.752	0.112	5.5	8.6
8.CH.237	2.897	0.752	0.033	5.5	7.8
8.CH.238	3.017	0.752	0.039	5.5	6.8
8.CH.239	2.841	0.752	0.026	5.5	6.8
8.CH.240	2.952	0.752	0.031	5.5	6.5
8.CH.241	3.141	0.752	0.056	5.5	7.5
8.CH.242	3.056	0.752	0.044	5.5	7
8.CH.243	3.089	0.752	0.052	5.5	8.7
8.CH.244	2.939	0.752	0.036	5.5	7.8
8.CH.245	2.718	0.752	0.018	5.5	6.5
8.CH.246	2.745	0.752	0.023	5.5	7.6
8.CH.248	2.878	0.752	0.029	5.5	7
8.CH.249	2.857	0.752	0.027	5.5	6.8
8.CH.250	2.885	0.752	0.029	5.5	6.8
8.CH.251	2.874	0.752	0.026	5.5	6.5
8.CH.252	3.141	0.752	0.058	5.5	8
8.CH.253	2.994	0.752	0.041	5.5	8.5
8.CH.254	2.922	0.752	0.035	5.5	8
8.CH.255	2.891	0.752	0.032	5.5	7.5
8.CH.256	2.803	0.752	0.022	5.5	6.5
8.CH.257	3.053	0.752	0.046	5.5	7.5
8.CH.258	3.254	0.752	0.075	5.5	8
8.CH.259	3.022	0.752	0.044	5.5	8
8.CH.260	3.089	0.752	0.048	5.5	7

8.CH.261	3.902	0.752	0.311	5.5	7
8.CH.262	4.292	0.975	0.037	5.5	7
8.CH.263	4.295	0.975	0.037	5.5	7
8.CH.264	4.413	0.975	0.047	5.5	6.8
8.CH.265	4.736	0.975	0.101	5.5	7
8.CH.266	4.624	0.975	0.077	5.5	6.8
8.CH.267	4.797	0.975	0.119	5.5	7.3
8.CH.268	5.15	0.975	0.272	5.5	8.5
8.CH.269	4.529	0.975	0.064	5.5	7.2
8.CH.270	5.343	1.103	0.073	5.5	7.5
8.CH.271	5.568	1.103	0.123	5.5	7.3
8.CH.272	5.369	1.103	0.077	5.5	7
8.CH.273	5.392	1.103	0.082	5.5	7.5
8.CH.274	5.513	1.103	0.107	5.5	7
8.CH.275	5.728	1.103	0.177	5.5	7.2
8.CH.276	5.797	1.103	0.208	5.5	7.2
8.CH.277	5.661	1.103	0.15	5.5	7
8.CH.278	6.475	1.103	1	5.5	7.8
8.CH.2785	5.939	1.103	1.038	5	7.8
8.CH.279	5.688	1.103	0.162	5.5	7.2
8.CH.280	5.496	1.103	0.105	5.5	7.5
8.CH.281	5.85	1.103	0.237	5.5	8
8.CH.282	5.584	1.103	0.128	5.5	7.4
8.CH.283	5.465	1.103	0.096	5.5	7
8.CH.284	5.421	1.103	0.088	5.5	7.5
8.CH.285	5.527	1.103	0.11	5.5	7
8.CH.286	5.28	1.103	0.059	5.5	6.5
8.CH.287	5.168	1.103	0.046	5.5	6.5
8.CH.288	5.69	1.103	0.164	5.5	7.5
8.CH.289	2.979	0.748	0.038	5.5	6.8
8.CH.290	3.026	0.748	0.044	5.5	7
8.CH.291	3.008	0.748	0.042	5.5	7
8.CH.292	3.422	0.748	0.115	5.5	7.6
8.CH.293	3.048	0.748	0.046	5.5	7
8.CH.294	3.027	0.748	0.044	5.5	7
8.CH.295	2.966	0.748	0.038	5.5	7
8.CH.296	3.086	0.748	0.051	5.5	7.2
8.CH.297	2.895	0.748	0.032	5.5	7
8.CH.298	3.208	0.748	0.071	5.5	8.3
8.CH.299	4.598	1.07	0.072	5	7.1
8.CH.300	4.917	1.07	0.149	5	7.4
8.CH.404	4.144	1.07	0.018	5	5.5
8.CH.405	4.166	1.07	0.026	5	6.5
8.CH.407	4.995	1.07	0.178	5	7
8.CH.308	4.543	0.931	0.121	5.5	7.5
8.CH.309	5.128	0.931	0.47	5.5	8
8.CH.310	4.741	0.931	0.191	5.5	7.5
8.CH.311	4.86	0.931	0.254	5.5	8.3
8.CH.312	4.235	0.931	0.058	5.5	7
8.CH.313	3.982	0.931	0.032	5.5	7
8.CH.314	4.533	0.931	0.115	5.5	7
8.CH.315	4.12	0.931	0.045	5.5	7.3
8.CH.316	4.375	0.931	0.082	5.5	7.4
8.CH.317	4.03	0.931	0.036	5.5	7
8.CH.318	4.069	0.931	0.04	5.5	7
8.CH.319	4.03	0.931	0.036	5.5	7
8.CH.320	3.865	0.931	0.024	5.5	6.8

8.CH.321	3.926	0.931	0.028	5.5	6.8
8.CH.322	3.121	0.869	0.011	5.5	7.2
8.CH.323	3.26	0.869	0.015	5.5	7.5
8.CH.324	3.25	0.869	0.014	5.5	7
8.CH.325	3.83	0.869	0.056	5.5	7.8
8.CH.326	3.277	0.869	0.015	5.5	7
8.CH.329	3.841	0.869	0.056	5.5	7.3
8.CH.330	3.613	0.869	0.034	5.5	8
8.CH.331	3.7	0.869	0.039	5.5	6.8
8.CH.332	3.482	0.869	0.024	5.5	7
8.CH.333	4.032	0.869	0.089	5.5	8.3
8.CH.334	3.33	0.869	0.017	5.5	7.5
8.CH.335	3.485	0.869	0.022	5.5	6.5
8.CH.336	3.555	0.869	0.029	5.5	7.5
8.CH.337	3.79	0.869	0.05	5.5	7.5
8.CH.338	3.868	0.869	0.058	5.5	7
8.CH.339	3.91	0.869	0.065	5.5	7.2
8.CH.340	3.734	0.869	0.042	5.5	6.8
8.CH.341	3.471	0.869	0.023	5.5	7
8.CH.342	3.129	0.869	0.011	5.5	7
8.CH.343	3.94	0.869	0.07	5.5	7.3
8.CH.352	2.793	0.731	0.032	5.5	7

APPENDIX C Area Source Discretization in CRISIS

CRISIS uses a triangulation procedure to discretize area-type seismic sources. The procedure is controlled by two parameters: the minimum absolute size of a triangle (Ts) and the ratio triangle-to-site distance/triangle size. In this appendix we study the effect of these control parameters in the hazard curve calculation. Six combinations of parameter values are used:

- Case 1: Ts=11 and Ratio=3;
- Case 2: Ts=5 and Ratio = 3;
- Case 3: Ts=5 and Ratio=4;
- Case 4: Ts=0.5 and Ratio = 3;
- Case 5: Ts=11 and Ratio=1;
- Case 6; Ts=11 and Ratio = 11;

The sensitivity of the results due to these alternative combinations of parameters is presented in Figure C.1. It can be observed that the ratio triangle-to-site distance/triangle size well calibrated and the influence on the final results is not critical. Also, it can be observed that the computational time increases with the increase of the triangle size or ratio triangle-to-site distance/triangle size.

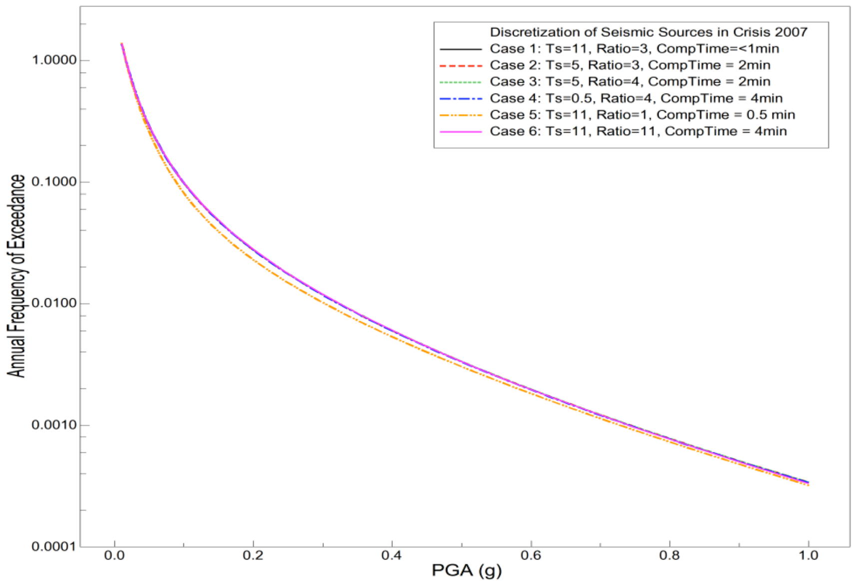


Figure C.1 Influence of the control parameters - Ts and Ratio- on a hazard curve computed with CRISIS