
OpenQuake Engine Manual

Release 3.18.0

**M. Pagani, V. Silva, A. Rao, M. Simionato,
K. Johnson**

Oct 25, 2023

CONTENTS

1	Introduction	1
1.1	OpenQuake-engine Background	1
1.1.1	Overview	1
1.1.2	Supplementary resources	2
1.1.3	Launching a calculation	2
2	Hazard	5
2.1	Introduction to the Hazard Module	5
2.1.1	Source typologies	5
2.1.1.1	Source typologies for modelling distributed seismicity	7
2.1.1.2	Fault sources with floating ruptures	12
2.1.1.3	Fault sources without floating ruptures	17
2.1.1.4	Non-Parametric Sources	20
2.1.2	Magnitude-frequency distributions	23
2.1.3	Magnitude-scaling relationships	26
2.1.3.1	Relationships for shallow earthquakes in active tectonic regions .	26
2.1.3.2	Magnitude-scaling relationships for subduction earthquakes .	29
2.1.3.3	Magnitude-scaling relationships stable continental regions .	29
2.1.3.4	Miscellaneous Magnitude-Scaling Relationships	29
2.1.4	Calculation workflows	29
2.1.4.1	Classical Probabilistic Seismic Hazard	30
2.1.4.2	Event-Based Probabilistic Seismic Hazard	30
2.1.4.3	Scenario based Seismic Hazard Analysis	31
2.2	Using the Hazard Module	34
2.2.1	Defining Logic Trees	35
2.2.1.1	Logic trees as described in the nrml schema	37
2.2.2	The Seismic Source System	41
2.2.2.1	The Seismic Source Logic Tree	41
2.2.2.2	The Seismic Source Model	43
2.2.3	The Ground Motion System	44
2.2.3.1	The Ground Motion Logic Tree	44
2.2.4	Configuration file	44

2.2.4.1	Classical PSHA	45
2.2.4.2	Seismic hazard disaggregation	49
2.2.4.3	Event based PSHA	51
2.2.4.4	Scenario hazard	52
2.3	Hazard Calculations and Results	56
2.3.1	Running OpenQuake-engine for hazard calculations	56
2.3.2	Exporting results from a hazard calculation	56
2.3.3	Description of hazard outputs	57
2.3.3.1	Outputs from Classical PSHA	58
2.3.3.2	Outputs from Hazard Disaggregation	60
2.3.3.3	Outputs from Event Based PSHA	60
2.3.3.4	Outputs from Scenario Hazard Analysis	62
2.4	Demonstrative Examples	63
2.4.1	Classical PSHA Demos	64
2.4.1.1	Classical PSHA with different source typologies	64
2.4.1.2	Classical PSHA with non trivial logic trees	73
2.4.2	Hazard Disaggregation Demos	80
2.4.3	Event Based PSHA Demos	81
3 Risk		87
3.1	Introduction to the Risk Module	87
3.1.1	Scenario Damage Assessment	88
3.1.2	Scenario Risk Assessment	90
3.1.3	Classical Probabilistic Seismic Damage Analysis	90
3.1.4	Classical Probabilistic Seismic Risk Analysis	93
3.1.5	Stochastic Event Based Probabilistic Seismic Damage Analysis	93
3.1.6	Stochastic Event Based Probabilistic Seismic Risk Analysis	96
3.1.7	Retrofit Benefit-Cost Ratio Analysis	97
3.1.8	Infrastructure Risk Analysis	100
3.1.8.1	Rationale	100
3.1.8.2	Specification of the Input Model	100
3.1.8.3	Calculation Steps	101
3.1.8.4	Specification of the Outputs Obtained	102
3.1.8.5	References	103
3.1.8.6	Acknowledgements	104
3.2	Risk Input Models	104
3.2.1	Exposure Models	104
3.2.2	Fragility Models	125
3.2.3	Consequence Models	131
3.2.4	Vulnerability Models	133
3.3	Using the Risk Module	139
3.3.1	Scenario Damage Calculator	141
3.3.2	Scenario Risk Calculator	150
3.3.3	Classical Probabilistic Seismic Damage Calculator	153
3.3.4	Classical Probabilistic Seismic Risk Calculator	156

3.3.5	Stochastic Event Based Seismic Damage	160
3.3.6	Stochastic Event Based Seismic Risk Calculator	162
3.3.7	Retrofit Benefit-Cost Ratio Calculator	166
3.3.8	Exporting Risk Results	168
3.4	Risk Results	170
3.4.1	Scenario Damage Outputs	170
3.4.1.1	Scenario damage statistics	171
3.4.1.2	Scenario consequence statistics	174
3.4.2	Scenario Risk Outputs	175
3.4.2.1	Scenario loss statistics	175
3.4.2.2	Scenario losses by event	177
3.4.3	Probabilistic Damage Outputs	177
3.4.3.1	Probabilistic damage distribution	177
3.4.4	Probabilistic Risk Outputs	178
3.4.4.1	Loss exceedance curves	178
3.4.4.2	Probabilistic loss maps	180
3.4.4.3	Stochastic event loss tables	181
3.4.5	Benefit-Cost Ratio Outputs	182
3.4.5.1	Retrofitting benefit/cost ratio maps	182
3.5	Demonstrative Examples	183
3.5.1	Scenario Damage	185
3.5.2	Scenario Risk Demos	185
3.5.3	Classical Probabilistic Seismic Damage Demos	186
3.5.4	Classical Probabilistic Seismic Risk Demos	187
3.5.5	Event Based Probabilistic Seismic Damage Demos	187
3.5.6	Event Based Probabilistic Seismic Risk Demos	188
3.5.7	Retrofit Benefit-Cost Ratio Demos	189
3.6	Bibliography	189
4	Secondary Perils Analysis	191
4.1	Liquefaction and Landslide models	191
4.1.1	Liquefaction models	191
4.1.1.1	HAZUS	192
4.1.1.2	Geospatial models	192
4.1.1.3	Permanent ground displacements due to liquefaction	196
4.1.2	Landslide models	197
4.1.3	Reference	198
4.2	Tutorials for running secondary perils analysis	199
5	Thanks	201
5.1	Public Partners	201
5.2	Private Partners	202
5.2.1	Governors	202
5.2.2	Advisors	203
5.3	Associate Partners	204

5.4	Project Partners	206
5.5	Products Distribution Partners	206
6	Glossary	209
6.1	Area Source	209
6.2	Asset	209
6.3	Branch	209
6.4	Branch Set	210
6.5	Configuration File	210
6.6	Consequence Function	210
6.7	Consequence Model	210
6.8	Characteristic Fault Source	210
6.9	Complex Fault Source	210
6.10	Deductible	210
6.11	Seismic Hazard Disaggregation	211
6.12	Dip	211
6.13	Disaggregation Matrix	211
6.14	Earthquake Rupture Forecast	211
6.15	Earthquake Rupture Forecast Calculator	211
6.16	Epsilon	211
6.17	Exposure Model	212
6.18	Fault Trace	212
6.19	Fragility Function	213
6.20	Fragility Model	213
6.21	Frequency-Magnitude Distribution	213
6.22	Grid Source	213
6.23	Ground-Motion Field (GMF)	213
6.24	Ground-Motion Field Calculator	213
6.25	Ground-Motion Logic Tree	214
6.26	Ground-Motion Model	214
6.27	Ground-Motion Parameter	214
6.28	Ground-Motion Prediction Equation (GMPE)	214
6.29	Ground-Motion System	214
6.30	Initial Seismic Source Input Model	214
6.31	Insured Losses	215
6.32	Integrated Risk Modelling Toolkit	215
6.33	Investigation Time	215
6.34	Limit	215
6.35	Logic Tree	215
6.36	Logic Tree Processor	215
6.37	Magnitude-Scaling Relationship	216
6.38	Magnitude-Frequency Distribution	216
6.39	Non-Parametric Source	216
6.40	Natural Hazards' Risk Markup Language	216
6.41	OpenSHA	216

6.42	Point Source	216
6.43	PSHA Input Model	217
6.44	Probabilistic Seismic Hazard Analysis (PSHA)	217
6.45	Earthquake Rupture	217
6.46	Rupture Model	217
6.47	Rupture Aspect Ratio	217
6.48	Rake	217
6.49	Scenario Based Seismic Hazard Analysis	218
6.50	Seismicity History	218
6.51	Seismicity Rate	218
6.52	Seismic Source Data	218
6.53	Seismic Source Logic Tree	218
6.54	Seismic Source Input Model	218
6.55	Seismic Source	219
6.56	Seismic Source Model (SSM)	219
6.57	Seismic Source System	219
6.58	Simple Fault Source	219
6.59	Stochastic Event Set	219
6.60	Strike	219
6.61	Tag	219
6.62	Taxonomy	220
6.63	Tectonic Region	220
6.64	Temporal Occurrence Model	220
6.65	Vulnerability Function	220
6.66	Vulnerability Model	220
6.67	VS30	220

CHAPTER ONE

INTRODUCTION

The goal of this manual is to provide a comprehensive and transparent description of the features of the OpenQuake Engine. This manual is designed to be readable by someone with basic understanding of Probabilistic Seismic Hazard and Risk Analysis, but no previous knowledge of the OpenQuake engine is assumed.

The OpenQuake engine is an effort promoted and actively developed by the GEM Foundation, a public-private partnership initiated by the Global Science Forum of the Organisation for Economic Co-operation and Development (OECD)¹.

The OpenQuake engine is the result of an effort carried out jointly by the Information Technology and Scientific teams working at the GEM Foundation Secretariat. It is freely distributed under an Afferro GPL license (<http://www.gnu.org/licenses/agpl-3.0.html>).

1.1 OpenQuake-engine Background

1.1.1 Overview

OpenQuake-engine is the seismic hazard and risk calculation software developed by the GEM Foundation. By following current standards in software developments like test-driven development and continuous integration, the OpenQuake engine aims at becoming an open, and community-driven tool for seismic hazard and risk analysis.

The source code of the OpenQuake engine is available on a public web-based repository at the following address: <http://github.com/gem/oq-engine>.

The OpenQuake engine is available for the Linux, macOS, and Windows platforms. It can be installed in several different ways. The following page provides a handy guide for users to choose the most appropriate installation method depending on their intended use cases:

¹

A short description of the process promoted by OECD is available here:
<http://www.oecd.org/science/sci-tech/theglobalearthquakemodelgem.htm>

<https://github.com/gem/oq-engine/blob/engine-3.18/doc/installing/README.md>.

This user manual is for the command line interface for the OpenQuake engine.

1.1.2 Supplementary resources

Guidance instructions for using the OpenQuake engine WebUI are available at <https://github.com/gem/oq-engine/blob/engine-3.18/doc/running/server.md>.

A user manual for the QGIS plugin for the OpenQuake engine is available at <https://docs.openquake.org/oq-irmt-qgis/latest/>. In particular, instructions for using the plugin as an interface for running OpenQuake engine calculations are listed in Chapter 14, and methods for using the plugin for visualization of hazard and risk outputs are listed in Chapter 15.

A manual intended for more advanced users of the OpenQuake engine is available at <https://docs.openquake.org/oq-engine/advanced/OpenQuakeforAdvancedUsers.pdf>.

Interested users are also encouraged to peruse the [OpenQuake Hazard Science](#) and [OpenQuake Risk Science](#) books, which provide explanations of the scientific methodologies adopted in the implementation of the earthquake hazard and risk libraries of the OpenQuake engine.

Subscribe to the OpenQuake users mailing list to keep abreast of the latest announcements from the OpenQuake development team, to ask and answer questions related to the OpenQuake engine and participate in the ongoing discussions: <https://groups.google.com/g/openquake-users>

1.1.3 Launching a calculation

An OpenQuake engine analysis is launched from the command line of a terminal.

A schematic list of the options that can be used for the execution of the OpenQuake engine can be obtained with the following command:

```
user@ubuntu:~$ oq engine --help
```

The result is the following:

```
usage: oq engine [-h] [--log-file LOG_FILE] [--no-distribute] [-y]
                  [-c CONFIG_FILE] [--make-html-report YYYY-MM-DD|today] [-u]
                  [-d] [-w] [--run JOB_INI [JOB_INI ...]]
                  [--list-hazard-calculations] [--list-risk-calculations]
                  [--delete-calculation CALCULATION_ID]
                  [--delete-uncompleted-calculations]
                  [--hazard-calculation-id HAZARD_CALCULATION_ID]
                  [--list-outputs CALCULATION_ID] [--show-log CALCULATION_
(continues on next page)
```

(continued from previous page)

```

↪ID]
    [--export-output OUTPUT_ID TARGET_DIR]
    [--export-outputs CALCULATION_ID TARGET_DIR] [-e]
    [-l {debug, info, warn, error, critical}] [-r]
    [--param PARAM]

Run a calculation using the traditional command line API

optional arguments:
  -h, --help            show this help message and exit
  --log-file LOG_FILE, -L LOG_FILE
                        Location where to store log messages; if not
                        specified, log messages will be printed to the ↪
↪console
                        (to stderr)
  --no-distribute, --nd
                        Disable calculation task distribution and run the
                        computation in a single process. This is intended ↪
↪for
                        use in debugging and profiling.
  -y, --yes             Automatically answer "yes" when asked to confirm ↪
↪an
                        action
  -c CONFIG_FILE, --config-file CONFIG_FILE
                        Custom openquake.cfg file, to override default
                        configurations
  --make-html-report YYYY-MM-DD|today, --r YYYY-MM-DD|today
                        Build an HTML report of the computation at the ↪
↪given
                        date
  -u, --upgrade-db      Upgrade the openquake database
  -d, --db-version      Show the current version of the openquake database
  -w, --what-if-I-upgrade
                        Show what will happen to the openquake database ↪
↪if you
                        upgrade
  --run JOB_INI [JOB_INI ...]
                        Run a job with the specified config file
  --list-hazard-calculations, --lh
                        List hazard calculation information
  --list-risk-calculations, --lr
                        List risk calculation information
  --delete-calculation CALCULATION_ID, --dc CALCULATION_ID

```

(continues on next page)

(continued from previous page)

```
          Delete a calculation and all associated outputs
--delete-uncompleted-calculations, --duc
          Delete all the uncompleted calculations
--hazard-calculation-id HAZARD_CALCULATION_ID, --hc HAZARD_CALCULATION_
ID
          Use the given job as input for the next job
--list-outputs CALCULATION_ID, --lo CALCULATION_ID
          List outputs for the specified calculation
--show-log CALCULATION_ID, --sl CALCULATION_ID
          Show the log of the specified calculation
--export-output OUTPUT_ID TARGET_DIR, --eo OUTPUT_ID TARGET_DIR
          Export the desired output to the specifiedDIR
→directory
--export-outputs CALCULATION_ID TARGET_DIR, --eos CALCULATION_ID TARGET_
→DIR
          Export all of the calculation outputs to theDIR
→specified
          directory
-e, --exports
          Comma-separated string specifying the exportformats,
→formats,
          in order of priority
-l, --log-level {debug, info, warn, error, critical}
          Defaults to "info"
-r, --reuse-input
          Read the sources|exposures from the cache (if any)
--param PARAM, -p PARAM
          Override parameters specified with the syntax
          NAME1=VALUE1,NAME2=VALUE2,...
```

CHAPTER TWO

HAZARD

2.1 Introduction to the Hazard Module

The hazard component of the OpenQuake engine builds on top of the OpenQuake hazard library (oq-hazardlib), a Python-based library containing tools for PSHA calculations.

The web repository of this library is available at the following address:

<https://github.com/gem/oq-engine/tree/master/openquake/hazardlib>.

In this section we briefly illustrate the main properties of the hazard component of the OpenQuake engine. In particular, we will describe the main typologies of sources supported and the main calculation workflows available.

2.1.1 Source typologies

An OpenQuake engine seismic source input model contains a list of sources belonging to a finite set of possible typologies. Each source type is defined by a set of parameters - called source data - which are used to specify the source geometry and the properties of seismicity occurrence.

Currently the OpenQuake engine supports the following source types:

- Sources for modelling distributed seismicity:
 - *Point Source* - The elemental source type used to model distributed seismicity. Grid and area sources (described below) are different containers of point sources.
 - *Area Source* - So far, the most frequently adopted source type in national and regional PSHA models.
 - *Grid Source* - A replacement for area sources admitting spatially variable seismicity occurrence properties.
- Fault sources with floating ruptures:

- *Simple Fault Source* - The simplest fault model in the OpenQuake engine. This source is habitually used to describe shallow seismogenic faults.
- *Complex Fault Source* - Often used to model subduction interface sources with a complex geometry.
- Fault sources with ruptures always covering the entire fault surface:
 - *Characteristic Fault Source* - A typology of source where ruptures always fill the entire fault surface.
 - *Non-Parametric Source* - A typology of source representing a collection of ruptures, each with their associated probabilities of 0, 1, 2 ... occurrences in the investigation time
- Sources for representing individual earthquake ruptures
 - Planar fault rupture - an individual fault rupture represented as a single rectangular plane
 - Multi-planar fault rupture - an individual rupture represented as a collection of rectangular planes
 - Simple fault rupture - an individual fault rupture represented as a simple fault surface
 - Complex fault rupture - an individual fault rupture represented as a complex fault surface

The OpenQuake engine contains some basic assumptions for the definition of these source typologies:

- In the case of area and fault sources, the seismicity is homogeneously distributed over the source;
- Seismicity temporal occurrence follows a Poissonian model.

The above sets of sources may be referred to as “parametric” sources, that is to say that the generation of the *Earthquake Rupture Forecast* is done by the OpenQuake engine based on the parameters of the sources set by the user. In some cases, particularly if the user wishes for the temporal occurrence model to be non-Poissonian (such as the lognormal or Brownian Passage Time models) a different type of behaviour is needed. For this OpenQuake-engine supports a *Non-Parametric Source* in which the *Earthquake Rupture Forecast* is provided explicitly by the user as a set of ruptures and their corresponding probabilities of occurrence.

2.1.1.1 Source typologies for modelling distributed seismicity

Point sources

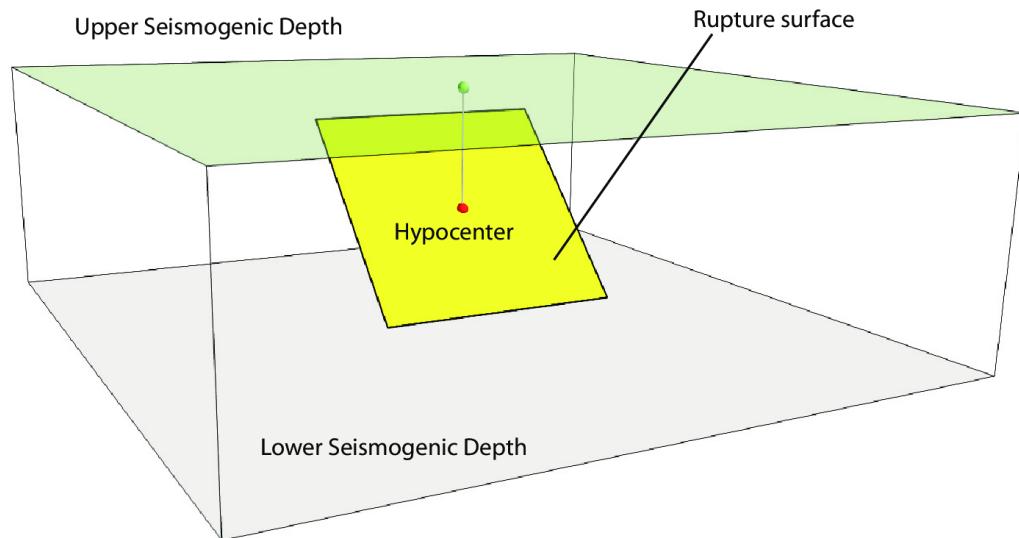


Fig. 2.1: Single rupture

The point source is the elemental source type adopted in the OpenQuake-engine for modelling distributed seismicity. The OpenQuake engine always performs calculations considering finite ruptures, even in the case of point sources.

These are the basic assumptions used to generate ruptures with point sources:

- Ruptures have a rectangular shape
- Rupture hypocenter is located in the middle of the rupture
- Ruptures are limited at the top and at the bottom by two planes parallel to the sea level and placed at two characteristic depths named upper and lower seismogenic depths, respectively (see Fig. 2.1)

Source data

For the definition of a point source the following parameters are required (Fig. 2.1 shows some of the parameters described below, together with an example of the surface of a generated rupture):

- The coordinates of the point (i.e. longitude and latitude) [decimal degrees]
- The upper and lower seismogenic depths [km]
- One *Magnitude-Frequency Distribution*
- One magnitude-scaling relationship
- The rupture aspect ratio
- A distribution of nodal planes i.e. one (or several) instances of the following set of parameters:
 - strike [degrees]
 - dip [degrees]
 - rake [degrees]
- A magnitude independent depth distribution of hypocenters [km].

Fig. 2.2 shows ruptures generated by a point source for a range of magnitudes. Each rupture is centered on the single hypocentral position admitted by this point source. Ruptures are created by conserving the area computed using the specified magnitude-area scaling relationship and the corresponding value of magnitude.

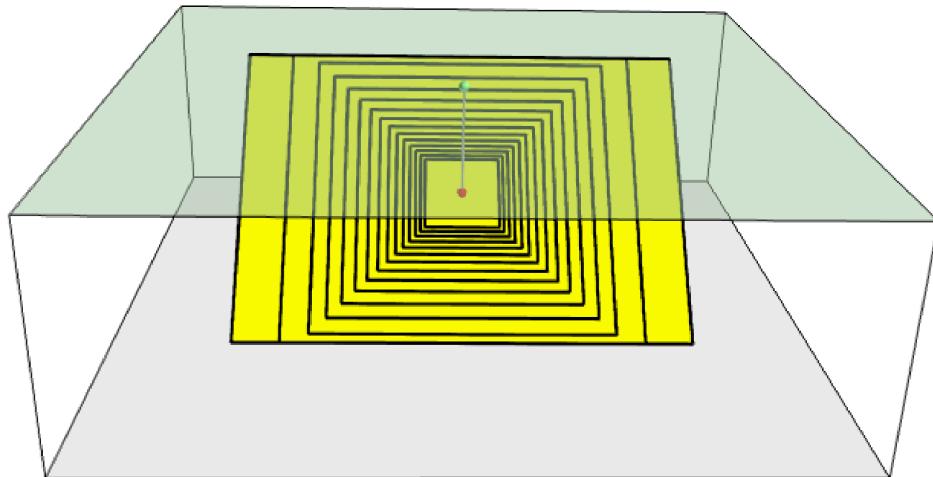


Fig. 2.2: Point source with multiple ruptures. Note the change in the aspect ratio once the rupture width fills the entire seismogenic layer.

Below we provide the excerpt of an .xml file used to describe the properties of a point source. Note that in this example, ruptures occur on two possible nodal planes and two hypocentral depths. Fig. 2.3 shows the ruptures generated by the point source.

```

1 <pointSource id="1" name="point" tectonicRegion="Stable Continental Crust
2   >
3     <pointGeometry>
4       <gml:Point>
5         <gml:pos>-122.0 38.0</gml:pos>
6       </gml:Point>
7       <upperSeismoDepth>0.0</upperSeismoDepth>
8       <lowerSeismoDepth>10.0</lowerSeismoDepth>
9     </pointGeometry>
10    <magScaleRel>WC1994</magScaleRel>
11    <ruptAspectRatio>0.5</ruptAspectRatio>
12    <truncGutenbergRichterMFD aValue="-3.5" bValue="1.0" minMag="5.0"
13      maxMag="6.5" />
14    <nodalPlaneDist>
15      <nodalPlane probability="0.3" strike="0.0" dip="90.0" rake="0.0" />
16    </nodalPlaneDist>
17    <hypoDepthDist>
18      <hypoDepth probability="0.5" depth="4.0" />
19      <hypoDepth probability="0.5" depth="8.0" />
20    </hypoDepthDist>
21  </pointSource>
```

Grid sources

A *Grid Source* is simply a collection of point sources distributed over a regular grid (usually equally spaced in longitude and latitude). In *Probabilistic Seismic Hazard Analysis* a grid source can be considered a model alternative to area sources, since they both model distributed seismicity. Grid sources are generally used to reproduce more faithfully the spatial pattern of seismicity depicted by the earthquakes occurred in the past; in some models (e.g. Petersen et al. (2008)) only events of low and intermediate magnitudes are considered. They are frequently, though not always, computed using seismicity smoothing algorithms (Frankel 1995; Woo 1996, amongst many others).

The use of smoothing algorithms to produce grid sources brings some advantages compared to area sources, since (1) it removes most of the unavoidable degree of subjectivity due to the definition of the geometries of the area sources and (2) it produces a spatial pattern of seismicity that is usually closer to what observed in the reality. Nevertheless, in many cases smoothing algorithms require an a-priori definition of some setup parameters that expose the calculation to a certain degree of

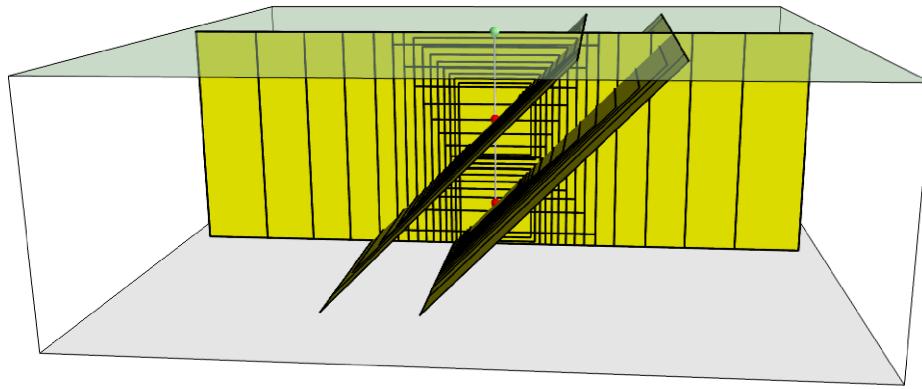


Fig. 2.3: Ruptures produced by the source created using the information in the example .xml file described on page .

partiality.

Grid sources are modeled in OpenQuake engine simply as a set of point sources; in other words, a grid source is just a long list of point sources specified as described in the previous section.

Area sources

Area sources are usually adopted to describe the seismicity occurring over wide areas where the identification and characterization - i.e. the unambiguous definition of position, geometry and seismicity occurrence parameters - of single fault structures is difficult.

From a computation standpoint, area sources are comparable to grid sources since they are both represented in the engine by a list of point sources.

The OpenQuake engine using the source data parameters (see below) creates an equally spaced in distance grid of point sources where each point has the same seismicity occurrence properties (i.e. rate of events generated).

Below we provide a brief description of the parameters necessary to completely describe an area source.

Source data

- A polygon defining the external border of the area (i.e. a list of Longitude-Latitude [degrees] tuples) The current version of the OQ-engine doesn't support the definition of internal borders.
- The upper and lower seismogenic depths [km]
- One *Magnitude-Frequency Distribution*
- One *Magnitude-Scaling Relationship*
- The rupture aspect ratio
- A distribution of nodal planes i.e. one (or several) instances of the following set of parameters
 - strike [degrees]
 - dip [degrees]
 - rake [degrees]
- A magnitude independent depth distribution of hypocenters [km].

Below we provide the excerpt of an .xml file used to describe the properties of an area source. The ruptures generated by the area source described in the example are controlled by two nodal planes and have hypocenters at localized at two distinct depths.

```

1 <areaSource id="1" name="Quito" tectonicRegion="Active Shallow Crust">
2   <areaGeometry>
3     <gml:Polygon>
4       <gml:exterior>
5         <gml:LinearRing>
6           <gml:posList>
7             -122.5 37.5
8             -121.5 37.5
9             -121.5 38.5
10            -122.5 38.5
11          </gml:posList>
12        </gml:LinearRing>
13      </gml:exterior>
14    </gml:Polygon>
15    <upperSeismoDepth>0.0</upperSeismoDepth>
16    <lowerSeismoDepth>10.0</lowerSeismoDepth>
17  </areaGeometry>
18  <magScaleRel>PeerMSR</magScaleRel>
19  <ruptAspectRatio>1.5</ruptAspectRatio>
20  <incrementalMFD minMag="6.55" binWidth="0.1">
21    <occurRates>0.0010614989 8.8291627E-4 7.3437777E-4 6.108288E-4

```

(continues on next page)

(continued from previous page)

```

22      5.080653E-4</occurRates>
23  </incrementalMFD>
24  <nodalPlaneDist>
25    <nodalPlane probability="0.3" strike="0.0" dip="90.0" rake="0.0"/>
26    <nodalPlane probability="0.7" strike="90.0" dip="45.0" rake="90.0"
27  </>
28  </nodalPlaneDist>
29  <hypoDepthDist>
30    <hypoDepth probability="0.5" depth="4.0" />
31    <hypoDepth probability="0.5" depth="8.0" />
32  </hypoDepthDist>
</areaSource>
```

2.1.1.2 Fault sources with floating ruptures

Fault sources in the OpenQuake engine are classified according to the method adopted to distribute ruptures over the fault surface. Two options are currently supported:

- With the first option, ruptures with a surface lower than the whole fault surface are floated so as to cover as much as possible homogeneously the fault surface. This model is compatible with all the supported magnitude-frequency distributions.
- With the second option, ruptures always fill the entire fault surface. This model is compatible with magnitude-frequency distributions similar to a characteristic model (à la (Schwartz and Coppersmith 1984)).

In this subsection we discuss the different fault source types that support floating ruptures. In the next subsection we will illustrate the fault typology available to model a characteristic rupturing behaviour.

Simple Faults

Simple Faults are the most common source type used to model shallow faults; the “simple” adjective relates to the geometry description of the source which is obtained by projecting the fault trace (i.e. a polyline) along a characteristic dip direction.

The parameters used to create an instance of this source type are described in the following paragraph.

Source data

- A horizontal *Fault Trace* (usually a polyline). It is a list of longitude-latitude tuples [degrees].
- A *Frequency-Magnitude Distribution*
- A *Magnitude-Scaling Relationship*
- A representative value of the dip angle (specified following the Aki-Richards convention; see Aki and Richards (2002)) [degrees]
- Rake angle (specified following the Aki-Richards convention; see Aki and Richards (2002)) [degrees]
- Upper and lower depth values limiting the seismogenic interval [km]

For near-fault probabilistic seismic hazard analysis, two additional parameters are needed for characterising seismic sources:

- A hypocentre list. It is a list of the possible hypocentral positions, and the corresponding weights, e.g., `alongStrike="0.25" downDip="0.25" weight="0.25"`. Each hypocentral position is defined in relative terms using as a reference the upper left corner of the rupture and by specifying the fraction of rupture length and rupture width.
- A slip list. It is a list of the possible rupture slip directions [degrees], and their corresponding weights. The angle describing each slip direction is measured counterclockwise using the fault strike direction as reference.

In near-fault PSHA calculations, the hypocentre list and the slip list are mandatory. The weights in each list must always sum to one. The available GMPE which currently supports the near-fault directivity PSHA calculation in OQ-engine is the ChiouYoungs2014NearFaultEffect GMPE developed by Brian S.-J. Chiou and Youngs (2014) (associated with an Active Shallow Crust tectonic region type).

We provide two examples of simple fault source files. The first is an excerpt of an xml file used to describe the properties of a simple fault source and the second example shows the excerpt of an xml file used to describe the properties of a simple fault source that can be used to perform a PSHA calculation taking into account directivity effects.

```

1 <simpleFaultSource id="1" name="Mount Diablo Thrust"
2   tectonicRegion="Active Shallow Crust">
3   <simpleFaultGeometry>
4     <gml:LineString>
5       <gml:posList>
6         -121.82290 37.73010
7         -122.03880 37.87710
8       </gml:posList>
9     </gml:LineString>
10    <dip>45.0</dip>
```

(continues on next page)

(continued from previous page)

```

11      <upperSeismoDepth>10.0</upperSeismoDepth>
12      <lowerSeismoDepth>20.0</lowerSeismoDepth>
13  </simpleFaultGeometry>
14  <magScaleRel>WC1994</magScaleRel>
15  <ruptAspectRatio>1.5</ruptAspectRatio>
16  <incrementalMFD minMag="5.0" binWidth="0.1">
17      <occurRates>0.0010614989 8.8291627E-4 7.3437777E-4 6.108288E-4
18          5.080653E-4</occurRates>
19  </incrementalMFD>
20  <rake>30.0</rake>
21  <hypoList>
22      <hypo alongStrike="0.25" downDip="0.25" weight="0.25"/>
23      <hypo alongStrike="0.25" downDip="0.75" weight="0.25"/>
24      <hypo alongStrike="0.75" downDip="0.25" weight="0.25"/>
25      <hypo alongStrike="0.75" downDip="0.75" weight="0.25"/>
26  </hypoList>
27  <slipList>
28      <slip weight="0.333">0.0</slip>
29      <slip weight="0.333">45.0</slip>
30      <slip weight="0.334">90.0</slip>
31  </slipList>
32</simpleFaultSource>
```

```

1 <simpleFaultSource id="1" name="Mount Diablo Thrust"
2     tectonicRegion="Active Shallow Crust">
3     <simpleFaultGeometry>
4         <gml:LineString>
5             <gml:posList>
6                 -121.82290 37.73010
7                 -122.03880 37.87710
8             </gml:posList>
9         </gml:LineString>
10        <dip>45.0</dip>
11        <upperSeismoDepth>10.0</upperSeismoDepth>
12        <lowerSeismoDepth>20.0</lowerSeismoDepth>
13    </simpleFaultGeometry>
14    <magScaleRel>WC1994</magScaleRel>
15    <ruptAspectRatio>1.5</ruptAspectRatio>
16    <incrementalMFD minMag="5.0" binWidth="0.1">
17        <occurRates>0.0010614989 8.8291627E-4 7.3437777E-4 6.108288E-4
18            5.080653E-4</occurRates>
19  </incrementalMFD>
```

(continues on next page)

(continued from previous page)

```

20 <rake>30.0</rake>
21 <hypoList>
22   <hypo alongStrike="0.25" downDip="0.25" weight="0.25"/>
23   <hypo alongStrike="0.25" downDip="0.75" weight="0.25"/>
24   <hypo alongStrike="0.75" downDip="0.25" weight="0.25"/>
25   <hypo alongStrike="0.75" downDip="0.75" weight="0.25"/>
26 </hypoList>
27 <slipList>
28   <slip weight="0.333">0.0</slip>
29   <slip weight="0.333">45.0</slip>
30   <slip weight="0.334">90.0</slip>
31 </slipList>
32 </simpleFaultSource>

```

Complex Faults

A complex fault differs from simple fault just by the way the geometry of the fault surface is defined and the fault surface is later created. The input parameters used to describe complex faults are, for the most part, the same used to describe the simple fault typology.

In the case of complex faults, the dip angle is not requested while the fault trace is substituted by two fault edges limiting the top and bottom of the fault surface. Additional curves lying over the fault surface can be specified to complement and refine the description of the fault surface geometry. Unlike the simple fault these edges are not required to be horizontal and may vary in elevation, i.e. the upper edge may represent the intersection between the exposed fault trace and the topographic surface, where positive values indicate below sea level, and negative values indicate above sea level.

Usually, we use complex faults to model intraplate megathrust faults such as the big subduction structures active in the Pacific (Sumatra, South America, Japan) but this source typology can be used also to create - for example - listric fault sources with a realistic geometry.

```

1 <complexFaultSource id="1" name="Cascadia Megathrust"
2   tectonicRegion="Subduction Interface">
3   <complexFaultGeometry>
4     <faultTopEdge>
5       <gml:LineString>
6         <gml:posList>
7           -124.704  40.363  0.5493260E+01
8           -124.977  41.214  0.4988560E+01
9           -125.140  42.096  0.4897340E+01
10      </gml:posList>
11    </gml:LineString>

```

(continues on next page)

(continued from previous page)

```

12   </faultTopEdge>
13   <intermediateEdge>
14     <gml:LineString>
15       <gml:posList>
16         -124.704  40.363  0.5593260E+01
17         -124.977  41.214  0.5088560E+01
18         -125.140  42.096  0.4997340E+01
19       </gml:posList>
20     </gml:LineString>
21   </intermediateEdge>
22   <intermediateEdge>
23     <gml:LineString>
24       <gml:posList>
25         -124.704  40.363  0.5693260E+01
26         -124.977  41.214  0.5188560E+01
27         -125.140  42.096  0.5097340E+01
28       </gml:posList>
29     </gml:LineString>
30   </intermediateEdge>
31   <faultBottomEdge>
32     <gml:LineString>
33       <gml:posList>
34         -123.829  40.347  0.2038490E+02
35         -124.137  41.218  0.1741390E+02
36         -124.252  42.115  0.1752740E+02
37       </gml:posList>
38     </gml:LineString>
39   </faultBottomEdge>
40 </complexFaultGeometry>
41 <magScaleRel>WC1994</magScaleRel>
42 <ruptAspectRatio>1.5</ruptAspectRatio>
43 <truncGutenbergRichterMFD aValue="-3.5" bValue="1.0" minMag="5.0"
44                               maxMag="6.5" />
45 <rake>30.0</rake>
46 </complexFaultSource>
```

As with the previous examples, the red text highlights the parameters used to specify the source geometry, the parameters in green describe the rupture mechanism, the text in blue describes the magnitude-frequency distribution and the gray text describes the rupture properties.

2.1.1.3 Fault sources without floating ruptures

Characteristic faults

The characteristic fault source is a particular typology of fault created with the assumption that its ruptures will always cover the entire fault surface. As such, no floating is necessary on the surface. The characteristic fault may still take as input a magnitude frequency distribution. In this case, the fault surface can be represented either as a *Simple Fault Source* surface or as a *Complex Fault Source* surface or as a combination of rectangular ruptures as represented in Fig. 2.4. Multiple surfaces containing mixed geometry types are also supported.

Source data

- The characteristic rupture surface is defined through one of the following options:
 - A list of rectangular ruptures (“planar surfaces”)
 - A *Simple Fault Source* geometry
 - A *Complex Fault Source* geometry
- A *Frequency-Magnitude Distribution*.
- Rake angle (specified following the Aki-Richards convention; see Aki and Richards (2002)).
- Upper and lower depth values limiting the seismogenic interval.

A comprehensive example enumerating the possible rupture surface configurations is shown below.

```

1 <characteristicFaultSource id="5" name="characteristic source, simple_
2   ↵fault"
3     tectonicRegion="Volcanic">
4       <truncGutenbergRichterMFD aValue="-3.5" bValue="1.0"
5         minMag="5.0" maxMag="6.5" />
6       <rake>30.0</rake>
7       <surface>
8         <!-- Characteristic Fault with a simple fault surface -->
9           <simpleFaultGeometry>
10             <gml:LineString>
11               <gml:posList>
12                 -121.82290 37.73010
13                 -122.03880 37.87710
14               </gml:posList>
15             </gml:LineString>
16             <dip>45.0</dip>
17             <upperSeismoDepth>10.0</upperSeismoDepth>

```

(continues on next page)

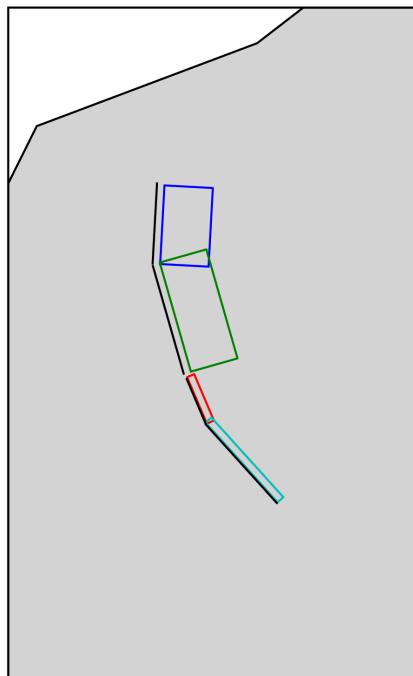


Fig. 2.4: Geometry of a multi-segmented characteristic fault composed of four rectangular ruptures as modelled in OpenQuake.

(continued from previous page)

```

17      <lowerSeismoDepth>20.0</lowerSeismoDepth>
18    </simpleFaultGeometry>
19  </surface>
20</characteristicFaultSource>
```

```

1<characteristicFaultSource id="6" name="characteristic source, complex_
2  ↳fault"
3          tectonicRegion="Volcanic">
4    <incrementalMFD minMag="5.0" binWidth="0.1">
5      <occurRates>0.0010614989 8.8291627E-4 7.3437777E-4</occurRates>
6    </incrementalMFD>
7    <rake>60.0</rake>
8    <surface>
9      <!-- Characteristic source with a complex fault surface -->
10     <complexFaultGeometry>
11       <faultTopEdge>
12         <gml:LineString>
13           <gml:posList>
14             -124.704 40.363 0.5493260E+01
15             -124.977 41.214 0.4988560E+01
16             -125.140 42.096 0.4897340E+01
17           </gml:posList>
18         </gml:LineString>
19       </faultTopEdge>
20       <faultBottomEdge>
21         <gml:LineString>
22           <gml:posList>
23             -123.829 40.347 0.2038490E+02
24             -124.137 41.218 0.1741390E+02
25             -124.252 42.115 0.1752740E+02
26           </gml:posList>
27         </gml:LineString>
28       </faultBottomEdge>
29     </complexFaultGeometry>
30   </surface>
</characteristicFaultSource>
```

```

1<characteristicFaultSource id="7" name="characteristic source, multi_
2  ↳surface"
3          tectonicRegion="Volcanic">
4    <truncGutenbergRichterMFD aValue="-3.6" bValue="1.0"
5      minMag="5.2" maxMag="6.4" />
```

(continues on next page)

(continued from previous page)

```

5   <rake>90.0</rake>
6   <surface>
7     <!-- Characteristic source with a collection of planar surfaces --
8   <!-->
9     <planarSurface>
10    <topLeft lon="-1.0" lat="1.0" depth="21.0" />
11    <topRight lon="1.0" lat="1.0" depth="21.0" />
12    <bottomLeft lon="-1.0" lat="-1.0" depth="59.0" />
13    <bottomRight lon="1.0" lat="-1.0" depth="59.0" />
14  </planarSurface>
15  <planarSurface strike="20.0" dip="45.0">
16    <topLeft lon="1.0" lat="1.0" depth="20.0" />
17    <topRight lon="3.0" lat="1.0" depth="20.0" />
18    <bottomLeft lon="1.0" lat="-1.0" depth="80.0" />
19    <bottomRight lon="3.0" lat="-1.0" depth="80.0" />
20  </planarSurface>
21  </surface>
</characteristicFaultSource>
```

2.1.1.4 Non-Parametric Sources

Non-Parametric Fault

The non-parametric fault typology requires that the user indicates the rupture properties (rupture surface, magnitude, rake and hypocentre) and the corresponding probabilities of the rupture. The probabilities are given as a list of floating point values that correspond to the probabilities of 0, 1, 2,N occurrences of the rupture within the specified investigation time. Note that there is not, at present, any internal check to ensure that the investigation time to which the probabilities refer corresponds to that specified in the configuration file. As the surface of the rupture is set explicitly, no rupture floating occurs, and, as in the case of the characteristic fault source, the rupture surface can be defined as either a single planar rupture, a list of planar ruptures, a *Simple Fault Source* geometry, a *Complex Fault Source* geometry, or a combination of different geometries.

Comprehensive examples enumerating the possible configurations are shown below:

```

1  <nonParametricSeismicSource id="1" name="A Non Parametric Planar Source"
2    tectonicRegion="Some TRT">
3    <singlePlaneRupture probs_occur="0.544 0.456">
4      <magnitude>8.3</magnitude>
5      <rake>90.0</rake>
6      <hypocenter depth="26.101" lat="40.726" lon="143.0"/>
7      <planarSurface>
```

(continues on next page)

(continued from previous page)

```

8   <topLeft depth="9.0" lat="41.6" lon="143.1"/>
9   <topRight depth="9.0" lat="40.2" lon="143.91"/>
10  <bottomLeft depth="43.202" lat="41.252" lon="142.07"/>
11  <bottomRight depth="43.202" lat="39.852" lon="142.91"/>
12  </planarSurface>
13 </singlePlaneRupture>
14 <multiPlanesRupture probs_occur="0.9244 0.0756">
15   <magnitude>6.9</magnitude>
16   <rake>0.0</rake>
17   <hypocenter depth="7.1423" lat="35.296" lon="139.31"/>
18   <planarSurface>
19     <topLeft depth="2.0" lat="35.363" lon="139.16"/>
20     <topRight depth="2.0" lat="35.394" lon="138.99"/>
21     <bottomLeft depth="14.728" lat="35.475" lon="139.19"/>
22     <bottomRight depth="14.728" lat="35.505" lon="139.02"/>
23   </planarSurface>
24   <planarSurface>
25     <topLeft depth="2.0" lat="35.169" lon="139.34"/>
26     <topRight depth="2.0" lat="35.358" lon="139.17"/>
27     <bottomLeft depth="12.285" lat="35.234" lon="139.45"/>
28     <bottomRight depth="12.285" lat="35.423" lon="139.28"/>
29   </planarSurface>
30 </multiPlanesRupture>
31 </nonParametricSeismicSource>
```

```

1 <nonParametricSeismicSource id="2" name="A Non Parametric (Simple) Source"
2   tectonicRegion="Some TRT">
3   <simpleFaultRupture probs_occur="0.157 0.843">
4     <magnitude>7.8</magnitude>
5     <rake>90.0</rake>
6     <hypocenter depth="22.341" lat="43.624" lon="147.94"/>
7     <simpleFaultGeometry>
8       <gml:LineString>
9         <gml:posList>
10        147.96 43.202
11        148.38 43.438
12        148.51 43.507
13        148.68 43.603
14        148.76 43.640
15       </gml:posList>
16     </gml:LineString>
17     <dip>30.0</dip>
```

(continues on next page)

(continued from previous page)

```

18      <upperSeismoDepth>14.5</upperSeismoDepth>
19      <lowerSeismoDepth>35.5</lowerSeismoDepth>
20    </simpleFaultGeometry>
21  </simpleFaultRupture>
22</nonParametricSeismicSource>
```

```

1<nonParametricSeismicSource id="3" name="A Non Parametric (Complex) Source
2  "tectonicRegion="Some TRT">
3  <complexFaultRupture probs_occur="0.157 0.843">
4    <magnitude>7.8</magnitude>
5    <rake>90.0</rake>
6    <hypocenter depth="22.341" lat="43.624" lon="147.94"/>
7    <complexFaultGeometry>
8      <faultTopEdge>
9        <gml:LineString>
10       <gml:posList>
11         148.76 43.64 5.0
12         148.68 43.603 5.0
13         148.51 43.507 5.0
14         148.38 43.438 5.0
15         147.96 43.202 5.0
16       </gml:posList>
17     </gml:LineString>
18   </faultTopEdge>
19   <faultBottomEdge>
20     <gml:LineString>
21     <gml:posList>
22       147.92 44.002 35.5
23       147.81 43.946 35.5
24       147.71 43.897 35.5
25       147.5 43.803 35.5
26       147.36 43.727 35.5
27     </gml:posList>
28   </gml:LineString>
29   </faultBottomEdge>
30 </complexFaultGeometry>
31 </complexFaultRupture>
32</nonParametricSeismicSource>
```

2.1.2 Magnitude-frequency distributions

The magnitude-frequency distributions currently supported by the OpenQuake engine are the following:

A discrete incremental magnitude-frequency distribution

It is the simplest distribution supported. It is defined by the minimum value of magnitude (representing the mid point of the first bin) and the bin width. The distribution itself is simply a sequence of floats describing the annual number of events for different bins. The maximum magnitude admitted by this magnitude-frequency distribution is just the sum of the minimum magnitude and the product of the bin width by the number annual rate values. Below we provide an example of the xml that should be incorporated in a seismic source description in order to define this Magnitude-Frequency Distribution.

```

1 <incrementalMFD minMag="5.05" binWidth="0.1">
2   <occurRates>0.15 0.08 0.05 0.03 0.015</occurRates>
3 </incrementalMFD>
```

The magnitude-frequency distribution obtained with the above parameters is represented in Fig. 2.5.

A double truncated Gutenberg-Richter distribution

This distribution is described by means of a minimum `minMag` and maximum magnitude `maxMag` and by the a and b values of the Gutenberg-Richter relationship.

The syntax of the xml used to describe this magnitude-frequency distribution is rather compact as demonstrated in the following example:

```

1 <truncGutenbergRichterMFD aValue="5.0" bValue="1.0" minMag="5.0"
2   maxMag="6.0"/>
```

Fig. 2.6 shows the magnitude-frequency distribution obtained using the parameters of the considered example.

Hybrid Characteristic earthquake model (à la (Youngs and Coppersmith 1985))

The hybrid characteristic earthquake model, presented by (Youngs and Coppersmith 1985), distributes seismic moment proportionally between a characteristic model (for larger magnitudes) and an exponential model. The rate of events is dependent on the magnitude of the characteristic earthquake, the b -value and the total moment rate of the system (Fig. 2.7). However, the total moment rate may be defined in one of two ways. If the total moment rate of the source is known, as may be the case for a fault surface with known area and slip rate, then the distribution can be defined from the total moment rate (in N-m) of the source directly. Alternatively, the distribution can be defined from the rate of earthquakes in the characteristic bin, which may be preferable if the distribution is determined from observed seismicity behaviour. The option to define the distribution according to the total moment rate is input as:

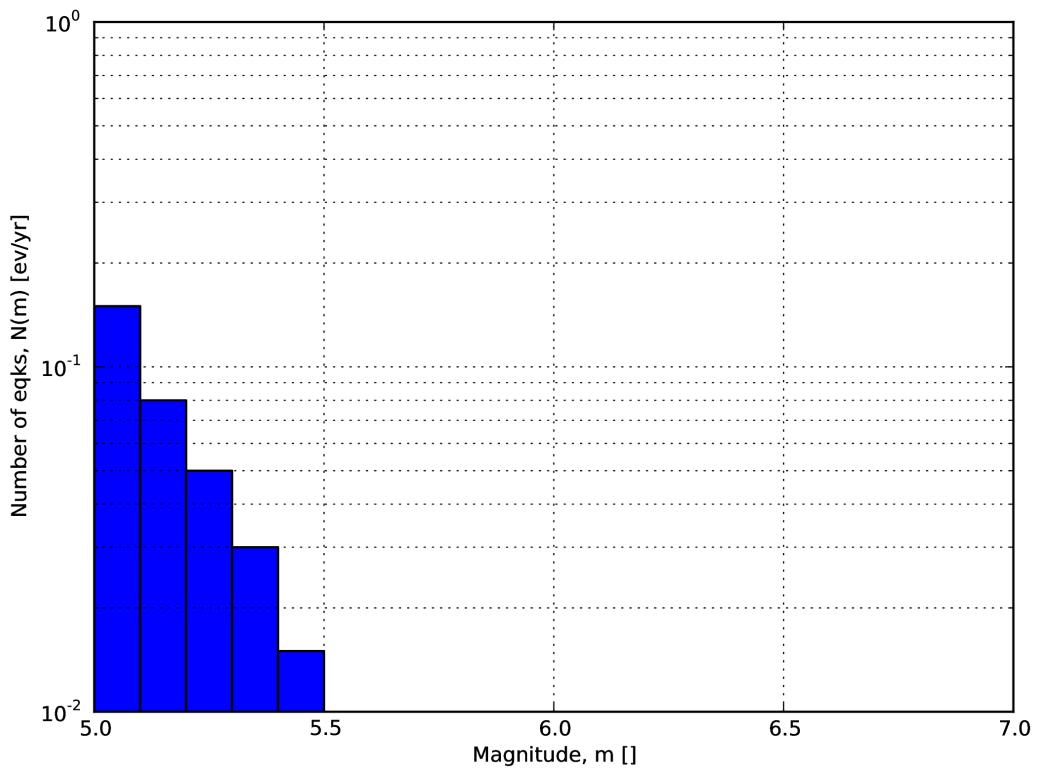


Fig. 2.5: Example of an incremental magnitude-frequency distribution.

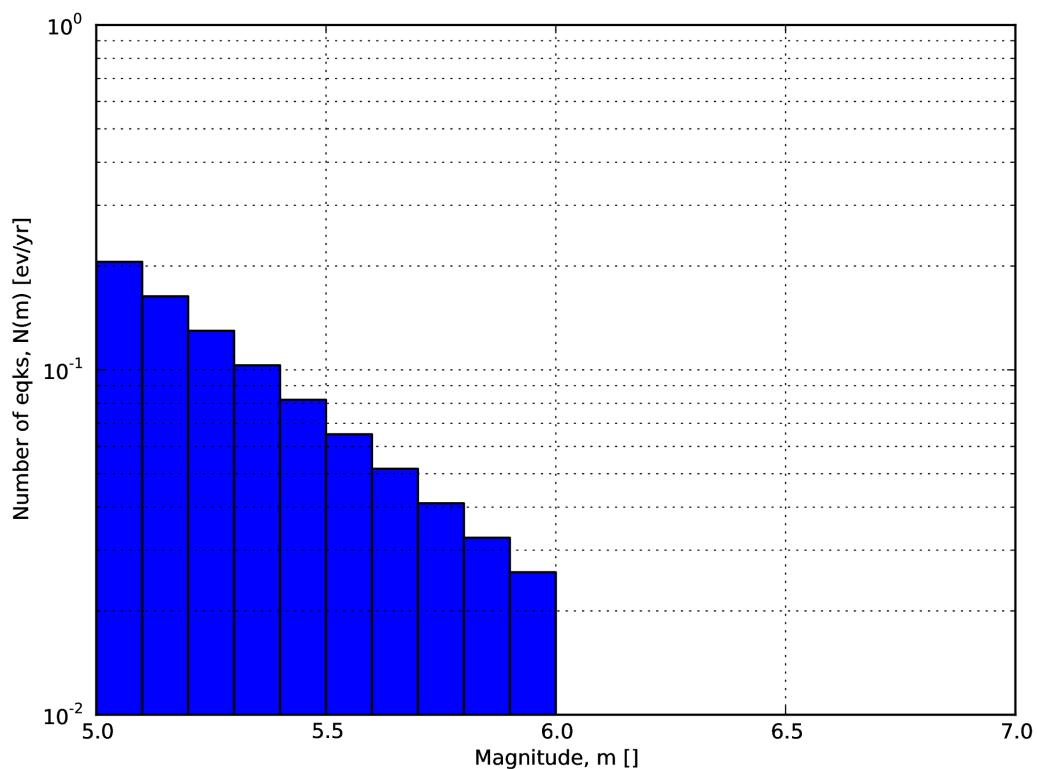


Fig. 2.6: Example of a double truncated Gutenberg-Richter magnitude-frequency distribution.

```

1 <YoungsCoppersmithMFD minmag="5.0" bValue="1.0" binWidth="0.1"
2   characteristicMag="7.0" totalMomentRate="1.
3   ↵05E19"/>

```

whereas the option to define the distribution from the rate of the characteristic events is given as:

```

1 <YoungsCoppersmithMFD minmag="5.0" bValue="1.0" binWidth="0.1"
2   characteristicMag="7.0" characteristicRate="0.
3   ↵005"/>

```

Note that in this distribution the width of the magnitude bin must be defined explicitly in the model.

“Arbitrary” Magnitude Frequency Distribution

The arbitrary magnitude frequency distribution is another non-parametric form of MFD, in which the rates are defined explicitly. Here, the magnitude frequency distribution is defined by a list of magnitudes and their corresponding rates of occurrence. There is no bin-width as the rates correspond exactly to the specific magnitude. Unlike the evenly discretised MFD, there is no requirement that the magnitudes be equally spaced. This distribution (illustrated in Fig. 2.8) can be input as:

```

1 <arbitraryMFD>
2   <occurRates>0.12 0.036 0.067 0.2</occurRates>
3   <magnitudes>8.1 8.47 8.68 9.02</magnitude>
4 </arbitraryMFD>

```

2.1.3 Magnitude-scaling relationships

We provide below a list of the magnitude-area scaling relationships implemented in the OpenQuake hazard library (oq-hazardlib):

2.1.3.1 Relationships for shallow earthquakes in active tectonic regions

- (Wells and Coppersmith 1994) - One of the most well known magnitude scaling relationships, based on a global database of historical earthquake ruptures. The implemented relationship is the one linking magnitude to rupture area, and is called with the keyword WC1994

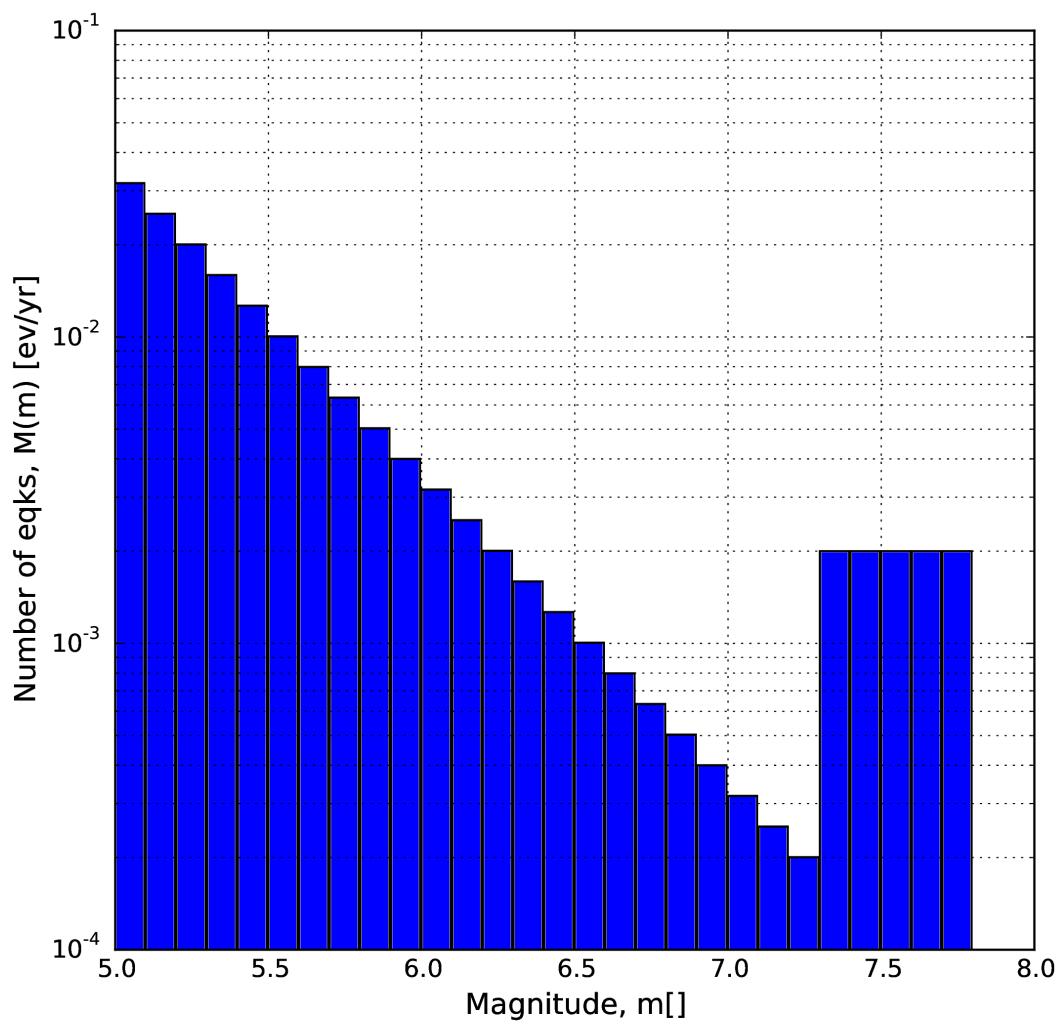


Fig. 2.7: (Youngs and Coppersmith 1985) magnitude-frequency distribution.

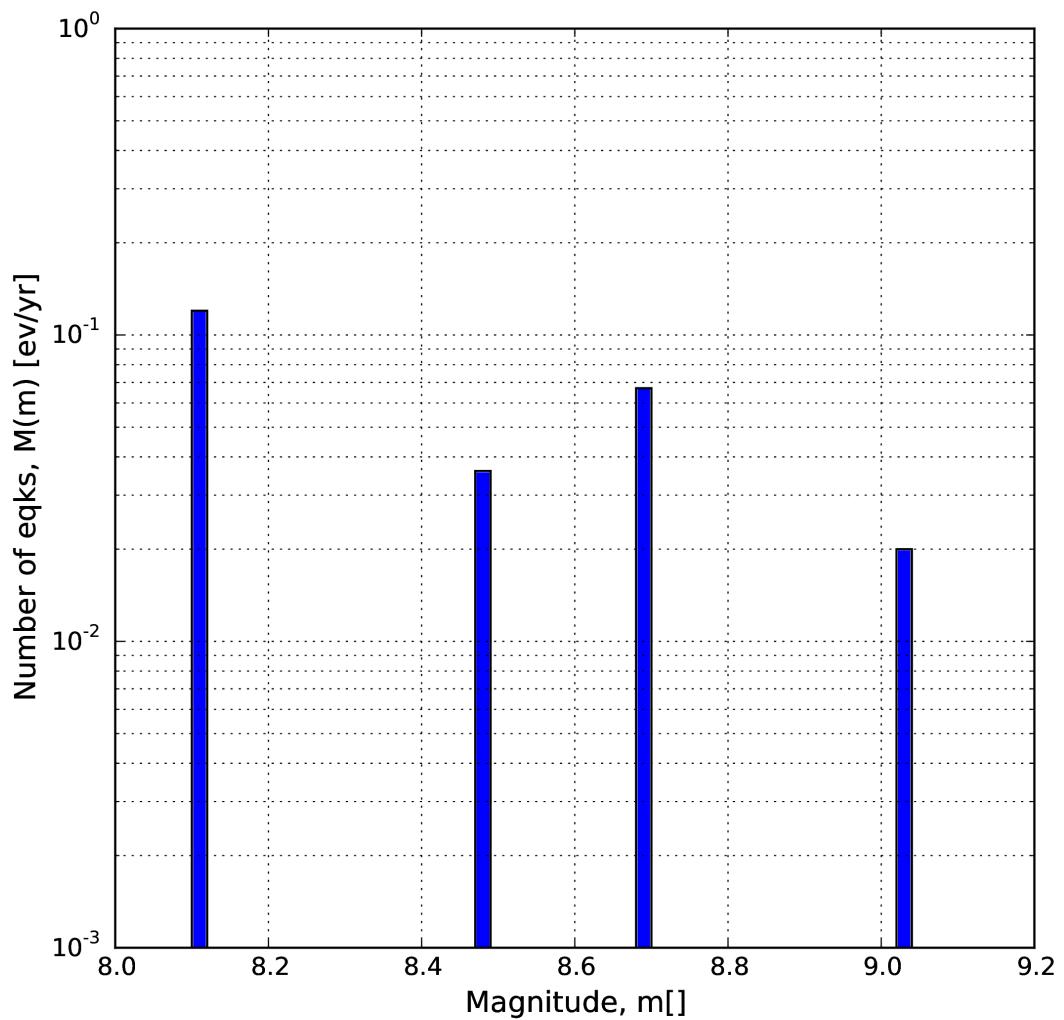


Fig. 2.8: “Arbitrary” magnitude-frequency distribution.

2.1.3.2 Magnitude-scaling relationships for subduction earthquakes

- (Strasser, Arango, and Bommer 2010) - Defines several magnitude scaling relationships for interface and in-slab earthquakes. Only the magnitude to rupture-area scaling relationships are implemented here, and are called with the keywords `StrasserInterface` and `StrasserIntraslab` respectively.
- (Thingbaijam, Mai, and Goda 2017) - Define magnitude scaling relationships for interface. Only the magnitude to rupture-area scaling relationships are implemented here, and are called with the keywords `ThingbaijamInterface`.

2.1.3.3 Magnitude-scaling relationships stable continental regions

- (EPRI 2011) - Defines a single magnitude to rupture-area scaling relationship for use in the central and eastern United States: $Area = 10.0^{M_W - 4.336}$. It is called with the keyword `CEUS2011`

2.1.3.4 Miscellaneous Magnitude-Scaling Relationships

- PeerMSR defines a simple magnitude scaling relation used as part of the Pacific Earthquake Engineering Research Center verification of probabilistic seismic hazard analysis programs: $Area = 10.0^{M_W - 4.0}$.
- PointMSR approximates a ‘point’ source by returning an infinitesimally small area for all magnitudes. Should only be used for distributed seismicity sources and not for fault sources.

2.1.4 Calculation workflows

The hazard component of the OpenQuake engine can compute seismic hazard using various approaches. Three types of analysis are currently supported:

- *Classical Probabilistic Seismic Hazard Analysis (PSHA)*, allowing calculation of hazard curves and hazard maps following the classical integration procedure ((Cornell 1968), McGuire (1976)) as formulated by (Field, Jordan, and Cornell 2003).
- *Event-Based Probabilistic Seismic Hazard Analysis*, allowing calculation of ground-motion fields from stochastic event sets. Traditional results - such as hazard curves - can be obtained by post- processing the set of computed ground-motion fields.
- *Scenario Based Seismic Hazard Analysis*, allowing the calculation of ground motion fields from a single earthquake rupture scenario taking into account ground motion aleatory variability. The ground motion fields can be conditioned to observed data, when available.

Each workflow has a modular structure, so that intermediate results can be exported and analyzed. Each calculator can be extended independently of the others so that additional calculation options and methodologies can be easily introduced, without affecting the overall calculation workflow.

2.1.4.1 Classical Probabilistic Seismic Hazard

Analysis Input data for the classical *Probabilistic Seismic Hazard Analysis* consist of a PSHA input model provided together with calculation settings.

The main calculators used to perform this analysis are the following:

- 1. Logic Tree Processor**

The Logic Tree Processor (LTP) takes as an input the *Probabilistic Seismic Hazard Analysis* Input Model and creates a Seismic Source Model. The LTP uses the information in the Initial Seismic Source Models and the Seismic Source Logic Tree to create a Seismic Source Input Model (i.e. a model describing geometry and activity rates of each source without any epistemic uncertainty).

Following a procedure similar to the one just described the Logic Tree Processor creates a Ground Motion model (i.e. a data structure that associates to each tectonic region considered in the calculation a Ground Motion Prediction Equation).

- 2. Earthquake Rupture Forecast Calculator**

The produced Seismic Source Input Model becomes an input information for the Earthquake Rupture Forecast (ERF) calculator which creates a list earthquake ruptures admitted by the source model, each one characterized by a probability of occurrence over a specified time span.

- 3. Classical PSHA Calculator**

The classical PSHA calculator uses the ERF and the Ground Motion model to compute hazard curves on each site specified in the calculation settings.

2.1.4.2 Event-Based Probabilistic Seismic Hazard

Analysis Input data for the Event-Based PSHA - as in the case of the Classical *Probabilistic Seismic Hazard Analysis* calculator - consists of a PSHA Input Model and a set of calculation settings.

The main calculators used to perform this analysis are:

- 1. Logic Tree Processor**

The Logic Tree Processor works in the same way described in the description of the Classical *Probabilistic Seismic Hazard Analysis* workflow (see Section [Classical PSHA](#)).

- 2. Earthquake Rupture Forecast Calculator**

The Earthquake Rupture Forecast Calculator was already introduced in the description of the PSHA workflow (see Section [Classical PSHA](#)).

3. Stochastic Event Set Calculator

The Stochastic Event Set Calculator generates a collection of stochastic event sets by sampling the ruptures contained in the ERF according to their probability of occurrence.

A Stochastic Event Set (SES) thus represents a potential realisation of the seismicity (i.e. a list of ruptures) produced by the set of seismic sources considered in the analysis over the time span fixed for the calculation of hazard.

4. Ground Motion Field Calculator

The Ground Motion Field Calculator computes for each event contained in a Stochastic Event Set a realization of the geographic distribution of the shaking by taking into account the aleatory uncertainties in the ground- motion model. Eventually, the Ground Motion Field calculator can consider the spatial correlation of the ground-motion during the generation of the Ground Motion Field.

5. Event-based PSHA Calculator

The event-based PSHA calculator takes a (large) set of ground-motion fields representative of the possible shaking scenarios that the investigated area can experience over a (long) time span and for each site computes the corresponding hazard curve.

This procedure is computationally intensive and is not recommended for investigating the hazard over large areas.

2.1.4.3 Scenario based Seismic Hazard Analysis

In case of Scenario Based Seismic Hazard Analysis, the engine simulates a set of ground motion fields (GMFs) at the target sites for the requested set of intensity measure types. This set of GMFs can then be used in [Scenario Damage Assessment](#) and [Scenario Risk Assessment](#) to estimate the distribution of potential damage, economic losses, fatalities, and other consequences. The scenario calculator is useful for simulating both historical and hypothetical earthquakes.

In case of Scenario Based Seismic Hazard Analysis, The input data consist of a single earthquake rupture model and one or more ground-motion models (GSIMs). Using the Ground Motion Field Calculator, multiple realizations of ground shaking can be computed, each realization sampling the aleatory uncertainties in the ground-motion model. The main calculator used to perform this analysis is the *Ground Motion Field Calculator*, which was already introduced during the description of the event based PSHA workflow (see Section [Event based PSHA](#)).

Starting from OpenQuake engine v3.16, it is possible to condition the ground shaking to observations, such as ground motion recordings and macroseismic intensity observations. The simulated ground motion fields are cross-spatially correlated, and can reduce considerably the uncertainty and bias in the resulting loss and damage estimates. The implementation of the conditioning of ground

motion fields in the engine was performed following closely the procedure proposed by Engler et al. (2022).

As the scenario calculator does not need to determine the probability of occurrence of the specific rupture, but only sufficient information to parameterise the location (as a three-dimensional surface), the magnitude and the style-of-faulting of the rupture, a more simplified NRML structure is sufficient compared to the source model structures described previously in *Source typologies*. A *rupture model* XML can be defined in the following formats:

1. *Simple Fault Rupture* - in which the geometry is defined by the trace of the fault rupture, the dip and the upper and lower seismogenic depths. An example is shown in *the listing* below:

```

1  <?xml version='1.0' encoding='utf-8'?>
2  <nrmr xmlns:gml="http://www.opengis.net/gml"
3      xmlns="http://openquake.org/xmlns/nrml/0.5">
4
5      <simpleFaultRupture>
6          <magnitude>6.7</magnitude>
7          <rake>180.0</rake>
8          <hypocenter lon="-122.02750" lat="37.61744" depth="6.7"/>
9          <simpleFaultGeometry>
10             <gml:LineString>
11                 <gml:posList>
12                     -121.80236 37.39713
13                     -121.91453 37.48312
14                     -122.00413 37.59493
15                     -122.05088 37.63995
16                     -122.09226 37.68095
17                     -122.17796 37.78233
18             </gml:posList>
19             </gml:LineString>
20             <dip>76.0</dip>
21             <upperSeismoDepth>0.0</upperSeismoDepth>
22             <lowerSeismoDepth>13.4</lowerSeismoDepth>
23         </simpleFaultGeometry>
24     </simpleFaultRupture>
25
26 </nrmr>
```

2. *Planar & Multi-Planar Rupture* - in which the geometry is defined as a collection of one or more rectangular planes, each defined by four corners. An example of a multi-planar rupture is shown below in *the listing* below:

```

1  <?xml version='1.0' encoding='utf-8'?>
2  <nrmr xmlns:gml="http://www.opengis.net/gml"
```

(continues on next page)

(continued from previous page)

```

3      xmlns="http://openquake.org/xmlns/nrml/0.5">
4
5  <multiPlanesRupture>
6      <magnitude>8.0</magnitude>
7      <rake>90.0</rake>
8      <hypocenter lat="-1.4" lon="1.1" depth="10.0"/>
9      <planarSurface strike="90.0" dip="45.0">
10         <topLeft lon="-0.8" lat="-2.3" depth="0.0" />
11         <topRight lon="-0.4" lat="-2.3" depth="0.0" />
12         <bottomLeft lon="-0.8" lat="-2.3890" depth="10.0" />
13         <bottomRight lon="-0.4" lat="-2.3890" depth="10.0" />
14     </planarSurface>
15     <planarSurface strike="30.94744" dip="30.0">
16         <topLeft lon="-0.42" lat="-2.3" depth="0.0" />
17         <topRight lon="-0.29967" lat="-2.09945" depth="0.0" /
18     <br/>
19     <bottomLeft lon="-0.28629" lat="-2.38009" depth="10.0
20     <br/>
21     <bottomRight lon="-0.16598" lat="-2.17955" depth="10.
22     <br/>
23 </multiPlanesRupture>
</nrml>
```

3. *Complex Fault Rupture* - in which the geometry is defined by the upper, lower and (if applicable) intermediate edges of the fault rupture. An example of a complex fault rupture is shown below in *the listing* below:

```

1  <?xml version='1.0' encoding='utf-8'?>
2  <nrml xmlns:gml="http://www.opengis.net/gml"
3      xmlns="http://openquake.org/xmlns/nrml/0.5">
4
5  <complexFaultRupture>
6      <magnitude>8.0</magnitude>
7      <rake>90.0</rake>
8      <hypocenter lat="-1.4" lon="1.1" depth="10.0"/>
9      <complexFaultGeometry>
10         <faultTopEdge>
11             <gml:LineString>
12                 <gml:posList>
13                     0.6 -1.5 2.0
14                     1.0 -1.3 5.0
```

(continues on next page)

(continued from previous page)

```

15          1.5 -1.0 8.0
16      </gml:posList>
17  </gml:LineString>
18 </faultTopEdge>
19 <intermediateEdge>
20   <gml:LineString>
21     <gml:posList>
22       0.65 -1.55 4.0
23       1.1  -1.4  10.0
24       1.5  -1.2  20.0
25     </gml:posList>
26   </gml:LineString>
27 </intermediateEdge>
28 <faultBottomEdge>
29   <gml:LineString>
30     <gml:posList>
31       0.65 -1.7 8.0
32       1.1  -1.6 15.0
33       1.5  -1.7 35.0
34     </gml:posList>
35   </gml:LineString>
36 </faultBottomEdge>
37 </complexFaultGeometry>
38 </complexFaultRupture>
39
40 </nrmrl>

```

2.2 Using the Hazard Module

This Chapter summarises the structure of the information necessary to define a PSHA input model to be used with the OpenQuake engine.

Input data for probabilistic based seismic hazard analysis (Classical, Event based, Disaggregation, and Uniform Hazard Spectra) are organised into:

- A general configuration file.
- A file describing the Seismic Source System, that is the set of initial source models and associated epistemic uncertainties needed to model the seismic activity in the region of interest.
- A file describing the Ground Motion System, that is the set of ground motion prediction equations, per tectonic region type, needed to model the ground motion shaking in the region of interest.

Fig. 2.9 summarises the structure of a PSHA input model for the OpenQuake engine and the relationships between the different files.

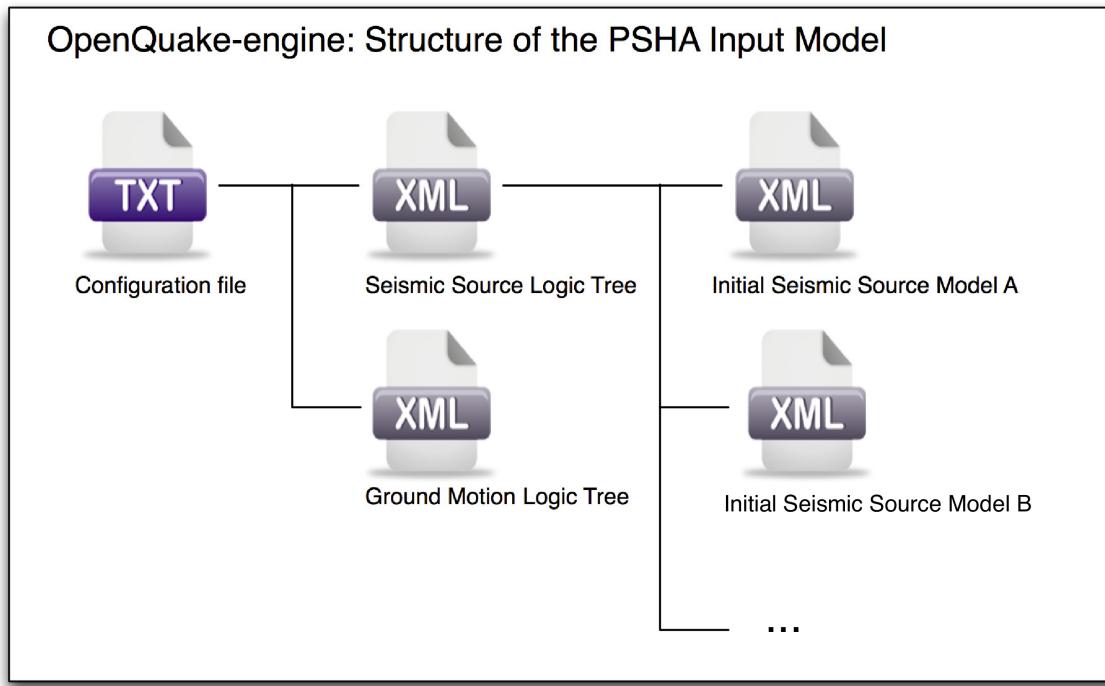


Fig. 2.9: PSHA Input Model structure

2.2.1 Defining Logic Trees

The main components of a logic tree structure in the OpenQuake engine are the following:

Branch

: the simplest component of a logic tree structure. A *Branch* represent a possible interpretation of a value assignment for a specific type of uncertainty. It is fully described by the tuple (parameter or model, weight).

Branching set

: it is a key component in the logic tree structure used by the OpenQuake engine. It groups a set of branches i.e. alternative interpretations of a parameter or a model. Each branching set is defined by:

- An ID
- An uncertainty type (for a comprehensive list of the types of uncertainty currently supported see section *Logic trees as described in the nrml schema*)
- One or more branches

This set of uncertainties can be applied to the whole initial seismic source input model or just to a subset of seismic sources. The sum of the weights/probabilities assigned to the set of branches always correspond to one.

Below we provide a simple schema illustrating the skeleton of xml file containing the description of a logic tree:

```

1 <logicTreeBranchSet branchSetID=ID
2   uncertaintyType=TYPE>
3     <logicTreeBranch>
4       <uncertaintyModel>VALUE</uncertaintyModel>
5       <uncertaintyWeight>WEIGHT</uncertaintyWeight>
6     </logicTreeBranch>
7   </logicTreeBranchSet>
```

As it appears from this example, the structure of a logic tree is a set of nested elements.

A schematic representation of the elemental components of a logic tree structure is provided in Fig. 2.10. A *Branch* set identifies a collection of branches (i.e. individual branches) whose weights sum to 1.

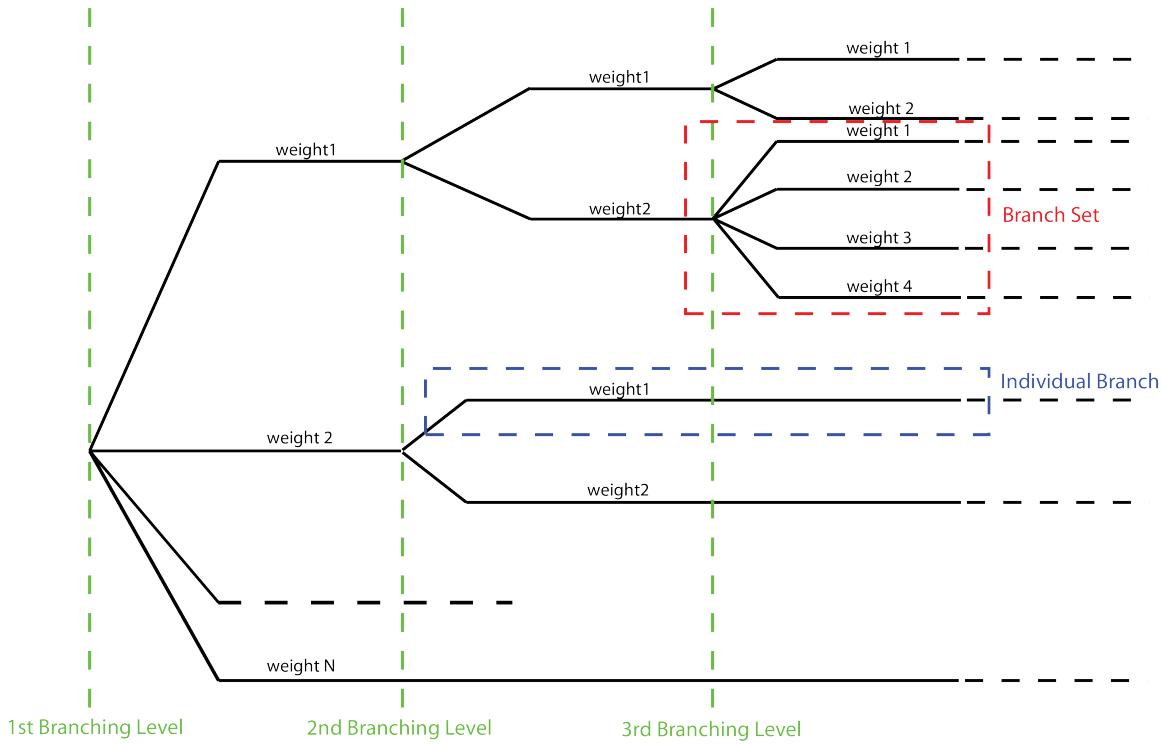


Fig. 2.10: Generic Logic Tree structure as described in terms of *Branch* sets, and individual branches.

2.2.1.1 Logic trees as described in the nrml schema

In the NRML schema, a logic tree structure is defined through the `logicTree` element:

```

1 <logicTree logicTreeID="ID">
2 ...
3 </logicTree>
```

A `logicTree` contains as a sequence of `logicTreeBranchSet` elements.

There are no restrictions on the number of *Branch* set that can be defined.

Each `logicTreeBranchSet` has two required attributes: `branchSetID` and `uncertaintyType`. The latter defines the type of epistemic uncertainty this *Branch* set is describing.

```

1 <logicTree logicTreeID="ID">
2   <logicTreeBranchSet branchSetID="ID_1"
3     uncertaintyType="UNCERTAINTY_TYPE">
4     ...
5   </logicTreeBranchSet>
6   <logicTreeBranchSet branchSetID="ID_2"
7     uncertaintyType="UNCERTAINTY_TYPE">
8     ...
9   </logicTreeBranchSet>
10  ...
11  <logicTreeBranchSet branchSetID="ID_N"
12    uncertaintyType="UNCERTAINTY_TYPE">
13    ...
14  </logicTreeBranchSet>
15  ...
16 </logicTree>
```

Possible values for the `uncertaintyType` attribute are:

- `gmpeModel`: indicates epistemic uncertainties on ground motion prediction equations
- `sourceModel`: indicates epistemic uncertainties on source models
- `maxMagGRRelative`: indicates relative (i.e. increments) epistemic uncertainties to be added (or subtracted, depending on the sign of the increment) to the Gutenberg-Richter maximum magnitude value.
- `bGRRelative`: indicates relative epistemic uncertainties to be applied to the Gutenberg-Richter b value.
- `abGRAbsolute`: indicates absolute (i.e. values used to replace original values) epistemic uncertainties on the Gutenberg-Richter a and b values.

- `maxMagGRAbsolute`: indicates (absolute) epistemic uncertainties on the Gutenberg-Richter maximum magnitude.
- `incrementalMFDAbsolute`: indicates (absolute) epistemic uncertainties on the incremental magnitude frequency distribution (i.e. alternative rates and/or minimum magnitude) of a specific source (can only be applied to individual sources)
- `simpleFaultGeometryAbsolute`: indicates alternative representations of the simple fault geometry for an individual simple fault source
- `simpleFaultDipRelative`: indicates a relative increase or decrease in fault dip for one or more simple fault sources
- `simpleFaultDipAbsolute`: indicates alternative values of fault dip for one or more simple fault sources
- `complexFaultGeometryAbsolute`: indicates alternative representations of complex fault geometry for an individual complex fault source
- `characteristicFaultGeometryAbsolute`: indicates alternative representations of the characteristic fault geometry for an individual characteristic fault source

A `branchSet` is defined as a sequence of `logicTreeBranch` elements, each specified by an `uncertaintyModel` element (a string identifying an uncertainty model; the content of the string varies with the `uncertaintyType` attribute value of the `branchSet` element) and the `uncertaintyWeight` element (specifying the probability/weight associated to the uncertainty-Model):

```

1 < logicTree logicTreeID="ID">
2 ...
3
4     < logicTreeBranchSet branchSetID="ID_#"
5         uncertaintyType="UNCERTAINTY_TYPE">
6         < logicTreeBranch branchID="ID_1">
7             <uncertaintyModel>
8                 UNCERTAINTY_MODEL
9             </uncertaintyModel>
10            <uncertaintyWeight>
11                UNCERTAINTY_WEIGHT
12            </uncertaintyWeight>
13        </ logicTreeBranch >
14 ...
15        < logicTreeBranch branchID="ID_N">
16            <uncertaintyModel>
17                UNCERTAINTY_MODEL
18            </uncertaintyModel>
19            <uncertaintyWeight>
20                UNCERTAINTY_WEIGHT

```

(continues on next page)

(continued from previous page)

```

21           </uncertaintyWeight>
22       </logicTreeBranch>
23   </logicTreeBranchSet>
24 ...
25 </logicTree >
```

Depending on the `uncertaintyType` the content of the `<uncertaintyModel>` element changes:

- if `uncertaintyType="gmpeModel"`, the uncertainty model contains the name of a ground motion prediction equation (a list of available GMPEs can be obtained using `oq info gsims` and these are also documented at: <http://docs.openquake.org/oq-engine/stable/openquake.hazardlib.gsim.html>):

```
<uncertaintyModel>GMPE_NAME</uncertaintyModel>
```

- if `uncertaintyType="sourceModel"`, the uncertainty model contains the paths to a source model file, e.g.:

```
1 <uncertaintyModel>SOURCE_MODEL_FILE_PATH</uncertaintyModel>
```

- if `uncertaintyType="maxMagGRRelative"`, the uncertainty model contains the increment to be added (or subtracted, depending on the sign) to the Gutenberg-Richter maximum magnitude:

```
<uncertaintyModel>MAX_MAGNITUDE_INCREMENT</uncertaintyModel>
```

- if `uncertaintyType="bGRRelative"`, the uncertainty model contains the increment to be added (or subtracted, depending on the sign) to the Gutenberg-Richter b value:

```
<uncertaintyModel>B_VALUE_INCREMENT</uncertaintyModel>
```

- if `uncertaintyType="abGRAbsolute"`, the uncertainty model must contain one a and b pair:

```
<uncertaintyModel>A_VALUE B_VALUE</uncertaintyModel>
```

- if `uncertaintyType="maxMagGAAbsolute"`, the uncertainty model must contain one Gutenberg-Richter maximum magnitude value:

```
<uncertaintyModel>MAX_MAGNITUDE</uncertaintyModel>
```

- if `uncertaintyType="incrementalMFDAbsolute"`, the uncertainty model must contain an instance of the incremental MFD node:

```

1 <uncertaintyModel>
2   <incrementalMFD>
3     minMag="MIN MAGNITUDE"
4     binWidth="BIN WIDTH">
5     <occurRates>RATE_1 RATE_2 ... RATE_N</occurRates>
6   </incrementalMFD>
7 </uncertaintyModel>

```

- if `uncertaintyType="simpleFaultGeometryAbsolute"` then the uncertainty model must contain a *valid* instance of the `simpleFaultGeometry` node as described in section [Simple Faults](#)
- if `uncertaintyType="simpleFaultDipRelative"` then the uncertainty model must specify the number of degrees to increase (positive) or decrease (negative) the fault dip. Note that if this increase results in an adjusted fault dip greater than 90° or less than 0° an error will occur.

```
<uncertaintyModel>DIP_INCREMENT</uncertaintyModel>
```

- if `uncertaintyType="simpleFaultDipAbsolute"` then the uncertainty model must specify the dip angle (in degrees)

```
<uncertaintyModel>DIP</uncertaintyModel>
```

- if `uncertaintyType="complexFaultGeometryAbsolute"` then the uncertainty model must contain a *valid* instance of the `complexFaultGeometry` source node as described in section [Complex Faults](#)
- if `uncertaintyType="characteristicFaultGeometryAbsolute"` then the uncertainty model must contain a *valid* instance of the `characteristicFaultGeometry` source node, as described in section [Characteristic faults](#)

There are no restrictions on the number of `logicTreeBranch` elements that can be defined in a `logicTreeBranchSet`, as long as the uncertainty weights sum to 1.0.

The `logicTreeBranchSet` element offers also a number of optional attributes allowing for complex tree definitions:

- `applyToBranches`: specifies to which `logicTreeBranch` elements (one or more), in the previous *Branch* sets, the *Branch* set is linked to. The linking is established by defining the IDs of the branches to link to:

```
applyToBranches="branchID1 branchID2 .... branchIDN"
```

The default is the keyword ALL, which means that a *Branch* set is by default linked to all branches in the previous *Branch* set. By specifying one or more branches to which the *Branch* set links to, non- symmetric logic trees can be defined.

- `applyToSources`: specifies to which source in a source model the uncertainty applies to. Sources are specified in terms of their IDs:

```
applyToSources="srcID1 srcID2 .... srcIDN"
```

- `applyToTectonicRegionType`: specifies to which tectonic region type the uncertainty applies to. Only one tectonic region type can be defined (Active Shallow Crust, Stable Shallow Crust, Subduction Interface, Subduction IntraSlab, Volcanic), e.g.:

```
applyToTectonicRegionType="Active Shallow Crust"
```

2.2.2 The Seismic Source System

The Seismic Source System contains the model (or the models) describing position, geometry and activity of seismic sources of engineering importance for a set of sites as well as the possible epistemic uncertainties to be incorporated into the calculation of seismic hazard.

2.2.2.1 The Seismic Source Logic Tree

The structure of the Seismic Source Logic Tree consists of at least one *Branch Set*. The example provided below shows the simplest Seismic Source Logic Tree structure that can be defined in a *Psha Input Model* for OpenQuake engine. It's a logic tree with just onebranchset with one *Branch* used to define the initial seismic source model (its weight will be equal to one).

```

1 <?xml version="1.0" encoding="UTF-8"?>
2 <nrm1 xmlns:gml="http://www.opengis.net/gml"
3   xmlns="http://openquake.org/xmlns/nrml/0.5">
4   <logicTree logicTreeID="lt1">
5     <logicTreeBranchSet uncertaintyType="sourceModel"
6       branchSetID="bs1">
7       <logicTreeBranch branchID="b1">
8         <uncertaintyModel>seismic_source_model.xml
9         </uncertaintyModel>
10        <uncertaintyWeight>1.0</uncertaintyWeight>
11      </logicTreeBranch>
12    </logicTreeBranchSet>
13  </logicTree>
14 </nrm1>
```

The optional branching levels will contain rules that modify parameters of the sources in the initial seismic source model.

For example, if the epistemic uncertainties to be considered are source geometry and maximum magnitude, the modeller can create a logic tree structure with three initial seismic source mod-

els (each one exploring a different definition of the geometry of sources) and one branching level accounting for the epistemic uncertainty on the maximum magnitude.

Below we provide an example of such logic tree structure. Note that the uncertainty on the maximum magnitude is specified in terms of relative increments with respect to the initial maximum magnitude defined for each source in the initial seismic source models.

```

1  <?xml version="1.0" encoding="UTF-8"?>
2  <nrmл xmlns:gml="http://www.opengis.net/gml"
3      xmlns="http://openquake.org/xmlns/nrml/0.5">
4      <logicTree logicTreeID="lt1">
5
6          <logicTreeBranchSet uncertaintyType="sourceModel"
7              branchSetID="bs1">
8              <logicTreeBranch branchID="b1">
9                  <uncertaintyModel>seismic_source_model_A.xml
10                 </uncertaintyModel>
11                 <uncertaintyWeight>0.2</uncertaintyWeight>
12             </logicTreeBranch>
13             <logicTreeBranch branchID="b2">
14                 <uncertaintyModel>seismic_source_model_B.xml
15                 </uncertaintyModel>
16                 <uncertaintyWeight>0.3</uncertaintyWeight>
17             </logicTreeBranch>
18             <logicTreeBranch branchID="b3">
19                 <uncertaintyModel>seismic_source_model_C.xml
20                 </uncertaintyModel>
21                 <uncertaintyWeight>0.5</uncertaintyWeight>
22             </logicTreeBranch>
23         </logicTreeBranchSet>
24
25         <logicTreeBranchSet branchSetID="bs21"
26             uncertaintyType="maxMagGRRelative">
27             <logicTreeBranch branchID="b211">
28                 <uncertaintyModel>+0.0</uncertaintyModel>
29                 <uncertaintyWeight>0.6</uncertaintyWeight>
30             </logicTreeBranch>
31             <logicTreeBranch branchID="b212">
32                 <uncertaintyModel>+0.5</uncertaintyModel>
33                 <uncertaintyWeight>0.4</uncertaintyWeight>
34             </logicTreeBranch>
35         </logicTreeBranchSet>
36
37     </logicTree>
38 </nrmл>
```

Starting from OpenQuake engine v2.4, it is also possible to split a source model into several files and read them as if they were a single file. The file names for the different files comprising a source model should be provided in the source model logic tree file. For instance, a source model could be split by tectonic region using the following syntax in the source model logic tree:

```

1 <?xml version="1.0" encoding="UTF-8"?>
2 <nrm1 xmlns:gml="http://www.opengis.net/gml"
3   xmlns="http://openquake.org/xmlns/nrml/0.5">
4   <logicTree logicTreeID="lt1">
5     <logicTreeBranchSet uncertaintyType="sourceModel"
6       branchSetID="bs1">
7       <logicTreeBranch branchID="b1">
8         <uncertaintyModel>
9           active_shallow_sources.xml
10          stable_shallow_sources.xml
11        </uncertaintyModel>
12        <uncertaintyWeight>1.0</uncertaintyWeight>
13      </logicTreeBranch>
14    </logicTreeBranchSet>
15  </logicTree>
16 </nrm1>
```

2.2.2.2 The Seismic Source Model

The structure of the xml file representing the seismic source model corresponds to a list of sources, each one modelled using one out of the five typologies currently supported. Below we provide a schematic example of a seismic source model:

```

1 <?xml version="1.0" encoding="UTF-8"?>
2 <nrm1 xmlns:gml="http://www.opengis.net/gml"
3   xmlns="http://openquake.org/xmlns/nrml/0.5">
4   <logicTree logicTreeID="lt1">
5     <logicTreeBranchSet uncertaintyType="sourceModel"
6       branchSetID="bs1">
7       <logicTreeBranch branchID="b1">
8         <uncertaintyModel>seismic_source_model.xml
9         </uncertaintyModel>
10        <uncertaintyWeight>1.0</uncertaintyWeight>
11      </logicTreeBranch>
12    </logicTreeBranchSet>
13  </logicTree>
14 </nrm1>
```

2.2.3 The Ground Motion System

The Ground Motion System defines the models and the possible epistemic uncertainties related to ground motion modelling to be incorporated into the calculation.

2.2.3.1 The Ground Motion Logic Tree

The structure of the *Ground Motion Logic Tree* consists of a list of ground motion prediction equations for each tectonic region used to characterise the sources in the PSHA input model.

The example below shows a simple *Ground Motion Logic Tree*. This logic tree assumes that all the sources in the PSHA input model belong to “Active Shallow Crust” and uses for calculation the B. S.-J. Chiou and Youngs (2008) Ground Motion Prediction Equation.

```
1  <?xml version="1.0" encoding="UTF-8"?>
2  <nrm1 xmlns:gml="http://www.opengis.net/gml"
3      xmlns="http://openquake.org/xmlns/nrml/0.5">
4      <logicTree logicTreeID="lt1">
5          <logicTreeBranchSet uncertaintyType="gmpeModel"
6              branchSetID="bs1"
7              applyToTectonicRegionType="Active Shallow Crust">
8
9          <logicTreeBranch branchID="b1">
10             <uncertaintyModel>
11                 ChiouYoungs2008
12             </uncertaintyModel>
13             <uncertaintyWeight>1.0</uncertaintyWeight>
14         </logicTreeBranch>
15
16     </logicTreeBranchSet>
17 </logicTree>
18 </nrm1>
```

2.2.4 Configuration file

The configuration file is the primary file controlling both the definition of the input model as well as parameters governing the calculation. We illustrate in the following different examples of the configuration file addressing different types of seismic hazard calculations.

2.2.4.1 Classical PSHA

In the following we describe the overall structure and the most typical parameters of a configuration file to be used for the computation of a seismic hazard map using a classical PSHA methodology.

Calculation type and model info

```

1 [general]
2 description = A demo OpenQuake-engine .ini file for classical PSHA
3 calculation_mode = classical
4 random_seed = 1024

```

In this section the user specifies the following parameters:

- **description**: a parameter that can be used to designate the model
- **calculation_mode**: it is used to set the kind of calculation. In this case it corresponds to **classical**. Alternative options for the **calculation_mode** are described later in this manual.
- **random_seed**: is used to control the random generator so that when Monte Carlo procedures are used calculations are replicable (if the same **random_seed** is used you get exactly the same results).

Geometry of the area (or the sites) where hazard is computed

This section is used to specify where the hazard will be computed. Two options are available:

The first option is to define a polygon (usually a rectangle) and a distance (in km) to be used to discretize the polygon area. The polygon is defined by a list of longitude-latitude tuples.

An example is provided below:

```

5 [geometry]
6 region = 10.0 43.0, 12.0 43.0, 12.0 46.0, 10.0 46.0
7 region_grid_spacing = 10.0

```

The second option allows the definition of a number of sites where the hazard will be computed. Each site is specified in terms of a longitude, latitude tuple. Optionally, if the user wants to consider the elevation of the sites, a value of depth [km] can also be specified, where positive values indicate below sea level, and negative values indicate above sea level (i.e. the topographic surface). If no value of depth is given for a site, it is assumed to be zero. An example is provided below:

```

8 [geometry]
9 sites = 10.0 43.0, 12.0 43.0, 12.0 46.0, 10.0 46.0

```

If the list of sites is too long the user can specify the name of a csv file as shown below:

```

10 [geometry]
11 sites_csv = <name_of_the_csv_file>

```

The format of the csv file containing the list of sites is a sequence of points (one per row) specified in terms of the longitude, latitude tuple. Depth values are again optional. An example is provided below:

```
179.0,90.0  
178.0,89.0  
177.0,88.0
```

Logic tree sampling

The OpenQuake engine provides two options for processing the whole logic tree structure. The first option uses Montecarlo sampling; the user in this case specifies a number of realizations.

In the second option all the possible realizations are created. Below we provide an example for the latter option. In this case we set the `number_of_logic_tree_samples` to 0. OpenQuake engine will perform a complete enumeration of all the possible paths from the roots to the leaves of the logic tree structure.

```
12 [logic_tree]  
13   number_of_logic_tree_samples = 0
```

If the seismic source logic tree and the ground motion logic tree do not contain epistemic uncertainties the engine will create a single PSHA input.

Generation of the earthquake rupture forecast

```
14 [erf]  
15   rupture_mesh_spacing = 5  
16   width_of_mfd_bin = 0.1  
17   area_source_discretization = 10
```

This section of the configuration file is used to specify the level of discretization of the mesh representing faults, the grid used to delineate the area sources and, the magnitude-frequency distribution. Note that the smaller is the mesh spacing (or the bin width) the larger are (1) the precision in the calculation and (2) the computation demand.

In cases where the source model may contain a mixture of simple and complex ruptures it is possible to define a different rupture mesh spacing for complex faults only. This may be helpful in models that permit floating ruptures over large subduction sources, in which the nearest source to site distances may be larger than 20 - 30 km, and for which a small mesh spacing would produce a very large number of ruptures. The spacing for complex faults only can be configured by the line:

```
18   complex_fault_mesh_spacing = 10
```

Parameters describing site conditions

```

18 [site_params]
19 reference_vs30_type = measured
20 reference_vs30_value = 760.0
21 reference_depth_to_2pt5km_per_sec = 5.0
22 reference_depth_to_1pt0km_per_sec = 100.0

```

In this section the user specifies local soil conditions. The simplest solution is to define uniform site conditions (i.e. all the sites have the same characteristics).

Alternatively it is possible to define spatially variable soil properties in a separate file; the engine will then assign to each investigation location the values of the closest point used to specify site conditions.

```

23 [site_params]
24 site_model_file = site_model.csv

```

The file containing the site model has the following structure:

```

lon,lat,vs30,z1pt0,z2pt5,vs30measured,backarc
10.0,40.0,800.0,19.367196734,0.588625072259,0,0
10.1,40.0,800.0,19.367196734,0.588625072259,0,0
10.2,40.0,800.0,19.367196734,0.588625072259,0,0
10.3,40.0,800.0,19.367196734,0.588625072259,0,0
10.4,40.0,800.0,19.367196734,0.588625072259,0,0

```

Notice that the 0 for the field `vs30measured` means that the `vs30` field is inferred, not measured. Most of the GMPEs are not sensitive to it, so you can usually skip it. For the `backarc` parameter 0 means false and this is the default, so you can skip such column. All columns that have defaults or are not needed by the GMPEs you are using can be skipped, while you will get an error if a relevant column is missing.

If the closest available site with soil conditions is at a distance greater than 5 km from the investigation location, a warning is generated.

Note: For backward-compatibility reasons, the site model file can also be given in XML format. That old format is deprecated but there are no plans to remove it any soon.

Calculation configuration

```

25 [calculation]
26 source_model_logic_tree_file = source_model_logic_tree.xml
27 gsim_logic_tree_file = gmpe_logic_tree.xml
28 investigation_time = 50.0
29 intensity_measure_types_and_levels = {"PGA": [0.005, ..., 2.13]}
30 truncation_level = 3
31 maximum_distance = 200.0

```

This section of the OpenQuake engine configuration file specifies the parameters that are relevant for the calculation of hazard. These include the names of the two files containing the Seismic Source System and the Ground Motion System, the duration of the time window used to compute the hazard, the ground motion intensity measure types and levels for which the probability of exceedence will be computed, the level of truncation of the Gaussian distribution of the logarithm of ground motion used in the calculation of hazard and the maximum integration distance (i.e. the distance within which sources will contribute to the computation of the hazard).

The maximum distance refers to the largest distance between a rupture and the target calculation sites in order for the rupture to be considered in the PSHA calculation. This can be input directly in terms of kilometres (as above). There may be cases, however, in which it may be appropriate to have a different maximum source to site distance depending on the tectonic region type. This may be used, for example, to eliminate the impact of small, very far-field sources in regions of high attenuation (in which case maximum distance is reduced), or conversely it may be raised to allow certain source types to contribute to the hazard at greater distances (such as in the case when the region has lower attenuation). An example configuration for a maximum distance in Active Shallow Crust of 150 km, and in Stable Continental Crust of 200 km, is shown below:

```
31 maximum_distance = {'Active Shallow Crust': 150.0,
32                      'Stable Continental Crust': 200.0}
```

Output

```
31 [output]
32 export_dir = outputs/
33 # given the specified `intensity_measure_types_and_levels`
34 mean = true
35 quantiles = 0.1 0.5 0.9
36 uniform_hazard_spectra = false
37 poes = 0.1
```

The final section of the configuration file is the one that contains the parameters controlling the types of output to be produced. Providing an export directory will tell OpenQuake where to place the output files when the `--exports` flag is used when running the program. Setting `mean` to true will result in a specific output containing the mean curves of the logic tree, likewise `quantiles` will produce separate files containing the quantile hazard curves at the quantiles listed (0.1, 0.5 and 0.9 in the example above, leave blank or omit if no quantiles are required). Setting `uniform_hazard_spectra` to true will output the uniform hazard spectra at the same probabilities of exceedence (`poes`) as those specified by the later option `poes`. The probabilities specified here correspond to the set investigation time. Specifying `poes` will output hazard maps. For more information about the outputs of the calculation, see the section: “Description of hazard outputs”.

2.2.4.2 Seismic hazard disaggregation

In this section we describe the structure of the configuration file to be used to complete a seismic hazard disaggregation. Since only a few parts of the standard configuration file need to be changed we can use the description given in Section [Classical PSHA](#) as a reference and we emphasize herein major differences.

```

1 [general]
2 description = A demo .ini file for PSHA disaggregation
3 calculation_mode = disaggregation
4 random_seed = 1024

```

The calculation mode parameter in this case is set as `disaggregation`.

Geometry of the area (or the sites) where hazard is computed

```

5 [geometry]
6 sites = 11.0 44.5

```

In the section it is necessary to specify the geographic coordinates of the site(s) where the disaggregation will be performed. The coordinates of multiple site should be separated with a comma.

Disaggregation parameters

The disaggregation parameters need to be added to the the standard configuration file. They are shown in the following example and a description of each parameter is provided below.

```

7 [disaggregation]
8 poes_disagg = 0.02, 0.1
9 mag_bin_width = 1.0
10 distance_bin_width = 25.0
11 coordinate_bin_width = 1.5
12 num_epsilon_bins = 3
13 disagg_outputs = Mag_Dist_Eps Mag_Lon_Lat
14 num_rlzs_disagg = 3

```

- `poes_disagg`: disaggregation is performed for the intensity measure levels corresponding to the probability of exceedance value(s) provided here. The computations use the `investigation_time` and the `intensity_measure_types_and_levels` defined in the “Calculation configuration” section. For the `poes_disagg` the intensity measure level(s) for the disaggregation are inferred by performing a classical calculation and by inverting the mean hazard curve. NB: this has changed in engine 3.17. In previous versions the inversion was made on the individual curves which meant some realizations could be discarded if the PoEs could not be reached.
- `iml_disagg`: the intensity measure level(s) to be disaggregated can be directly defined by specifying `iml_disagg`. Note that a disaggregation computation requires either

`poes_disagg` or `iml_disagg` to be defined, but both cannot be defined at the same time.

- `mag_bin_width`: mandatory; specifies the width of every magnitude histogram bin of the disaggregation matrix computed
- `distance_bin_width`: specifies the width of every distance histogram bin of the disaggregation matrix computed (km)
- `coordinate_bin_width`: specifies the width of every longitude-latitude histogram bin of the disaggregation matrix computed (decimal degrees)
- `num_epsilon_bins`: mandatory; specifies the number of *Epsilon* histogram bins of the disaggregation matrix. The width of the *Epsilon* bins depends on the `truncation_level` defined in the “Calculation configuration” section (page)
- `disagg_outputs`: optional; specifies the type(s) of disaggregation to be computed. The options are: `Mag`, `Dist`, `Lon_Lat`, `Lon_Lat_TRT`, `Mag_Dist`, `Mag_Dist_Eps`, `Mag_Lon_Lat`, `TRT`. If none are specified, then all are computed. More details of the disaggregation output are given in the “Outputs from Hazard Disaggregation” section)
- `disagg_by_src`: optional; if specified and set to true, disaggregation by source is computed, if possible.
- `num_rlzs_disagg`: optional; specifies the number of realizations to be used, selecting those that yield intensity measure levels closest to the mean. Starting from engine 3.17 the default is 0, which means considering all realizations.

Alternatively to `num_rlzs_disagg`, the user can specify the index or indices of the realizations to disaggregate as a list of comma-separated integers. For example:

```
7 [disaggregation]
8   rlz_index = 22,23
```

If `num_rlzs_disagg` is specified, the user cannot specify `rlz_index`, and vice versa. If `num_rlzs_disagg` or `rlz_index` are specified, the mean disaggregation is automatically computed from the selected realizations.

As mentioned above, the user also has the option to perform disaggregation by directly specifying the intensity measure level to be disaggregated, rather than specifying the probability of exceedance. An example is shown below:

```
7 [disaggregation]
8   iml_disagg = {'PGA': 0.1}
```

If `iml_disagg` is specified, the user should not include `intensity_measure_types_and_levels` in the “Calculation configuration” section since it is explicitly given here.

The OQ Engine supports the calculation of two typologies of disaggregation result involving ϵ . The standard approach used by the OQ Engine is described in the [OQ Engine Underlying Hazard](#)

Science Book . The reader interested in learning more about the ϵ^* can refer to the PEER report Probabilistic Seismic Hazard Analysis Code Verification, PEER Report 2018-03 .

To obtain disaggregation results in terms of ϵ^* the additional line below must be added to the disaggregation section of the configuration file:

```
7 [disaggregation]
8 epsilon_star = True
```

2.2.4.3 Event based PSHA

In the following we describe the sections of the configuration file that are required to complete event based PSHA calculations

Calculation type and model info

This part is almost identical to the corresponding one described in Section *Classical PSHA*.

Note the setting of the `calculation_mode` parameter which now corresponds to `event_based`.

```
1 [general]
2 description = A demo OpenQuake-engine .ini file for event based PSHA
3 calculation_mode = event_based
4 random_seed = 1024
```

Event based parameters

This section is used to specify the number of stochastic event sets to be generated for each logic tree realisation (each stochastic event set represents a potential realisation of seismicity during the `investigation_time` specified in the `calculation_configuration` part). Additionally, in this section the user can specify the spatial correlation model to be used for the generation of ground motion fields.

```
ses_per_logic_tree_path = 5
ground_motion_correlation_model = JB2009
ground_motion_correlation_params = {"vs30_clustering": True}
```

The acceptable flags for the parameter `vs30_clustering` are `False` and `True`, with a capital F and T respectively. 0 and 1 are also acceptable flags.

Output

This part substitutes the Output part described in the configuration file example described in the Section *Classical PSHA*.

```
[output]
export_dir = /tmp/xxx
```

(continues on next page)

(continued from previous page)

```
ground_motion_fields = true
# post-process ground motion fields into hazard curves,
# given the specified `intensity_measure_types_and_levels`
hazard_curves_from_gmfs = true
mean = true
quantiles = 0.15, 0.50, 0.85
poes = 0.1, 0.2
```

Starting from OpenQuake engine22, it is now possible to export information about the ruptures directly in CSV format.

The option `hazard_curves_from_gmfs` instructs the user to use the event- based ground motion values to provide hazard curves indicating the probabilities of exceeding the intensity measure levels set previously in the `intensity_measure_types_and_levels` option.

2.2.4.4 Scenario hazard

In order to run this calculator, the parameter `calculation_mode` needs to be set to `scenario`. The user can run scenario calculations with and without conditioning the ground shaking to station and macroseismic data. The ground motion fields will be computed at each of the sites and for each of the intensity measure types specified in the job configuration file.

The basic job configuration file required for running a scenario hazard calculation is shown in [the listing](#) below.

```
[general]
description = Scenario Hazard Config File
calculation_mode = scenario

[sites]
sites_csv = sites.csv

[station_data]
station_data_file = stationlist.csv

[rupture]
rupture_model_file = rupture_model.xml
rupture_mesh_spacing = 2.0

[site_params]
site_model_file = site_model.csv site_model_stations.csv

[correlation]
```

(continues on next page)

(continued from previous page)

```

ground_motion_correlation_model = JB2009
ground_motion_correlation_params = {"vs30_clustering": True}

[hazard_calculation]
intensity_measure_types = PGA, SA(0.3), SA(1.0)
random_seed = 42
truncation_level = 3.0
maximum_distance = 200.0
gsim = BooreAtkinson2008
number_of_ground_motion_fields = 1000

```

Most of the job configuration parameters required for running a scenario hazard calculation seen in the example in [the listing](#) above are the same as those described in the previous sections for the classical PSHA calculator (Section [Classical PSHA](#)) and the event-based PSHA calculator (Section [Event based PSHA](#)). The set of sites at which the ground motion fields will be produced can be specified by using the `sites` or `sites_csv` parameters, or the `region` and `region_grid_spacing` parameters, similar to the classical PSHA and event-based PSHA calculators; other options include the definition of the sites through the `site_model_file` or the exposure model (see Section [Exposure Models](#)).

The parameters unique to the scenario calculator are described below:

- `number_of_ground_motion_fields`: this parameter is used to specify the number of Monte Carlo simulations of the ground motion values at the specified sites.
- `station_data_file`: this is an optional parameter used to specify the observed intensity values for one or more intensity measure types at a set of ground motion recording stations. See example file in [Table 2.1](#).
- `gsim`: this parameter indicates the name of a ground motion prediction equation. Note: There are other option to indicate the ground motion models, see the sections below.

Note that each of the GSIMs specified for a conditioned GMF calculation must provide the within-event and between-event standard deviations separately. If a GSIM of interest provides only the total standard deviation, a (non-ideal) workaround might be for the user to specify the ratio between the within-event and between-event standard deviations, which the engine will use to add the between and within standard deviations to the GSIM.

Station data csv file This csv file contains the observed intensity values available from ground motion recordings and macroseismic intensity data. One or multiple intensity measure types can be indicated for all observations. An example of such a file is shown below in [Table 2.1](#).

When conditioning the ground motion fields to station data, all of the site parameters required by the GMMs will also need to be provided for the set of sites in the `station_data_file`. This is specified in the configuration file by including in the `site_model_file` section a `site_model_stations.csv` file.

Table 2.1: Example of station data csv file

STA-TION_ID	STA-TION_I	LON-GI-TUDE	LATI-TUDE	STA-TION_TY	PGA_	PGA	SA(0.3)	SA(0.6)	SA(1.0)	SA(1.6)	LN_SIGMA
VIGA	LAS	-	16.7587	seismic	0.355	0 0	0.5262	0 0	0.1012	0 0	
VNTA	VI-	99.23326	16.91426	seismic	0.2061	0 :	0.3415	0 :	0.1051	0 :	
COYC	GAS	-	16.99778	seismic	0.1676	0.806	0.2643	1.016	0.0872	1.0822	
UTM_14Q_	LA	99.81885	-	macro-	:	0.806	:	1.016	:	1.0822	
UTM_14Q_	VENTA	-	16.86687	seismic	0.6512	0.806	0.9535	1.016	0.4794	1.0822	
UTM_14Q_	COYUC	100.0899	16.77656	macro-	0.5797	:	0.8766	:	0.4577	:	
:	NA	-	16.86656	seismic	0.477		0.722		0.3223		
NA	99.7982	-	-	macro-	:		:				
NA	-	-	-	seismic							
	99.79761	-	-	-							
	-	-	-	-							
	99.89182	-	-	-							
	-	-	-	-							
	-	-	-	-							

The following parameters are mandatory:

- STATION_ID: string; subject to the same validity checks as the id fields in other input files.
- LONGITUDE, LATITUDE: floats; valid longitude and latitude values.
- STATION_TYPE: string; currently the only two valid options are ‘seismic’ and ‘macroseismic’.
- <IMT>_VALUE, <IMT>_LN_SIGMA, <IMT>_STDDEV: floats; for each IMT observed at the recording stations, two values should be provided:
 - for IMTs that are assumed to be lognormally distributed (eg. PGV, PGA, SA), these would be the median and lognormal standard deviation using the column headers <IMT>_VALUE, <IMT>_LN_SIGMA respectively.
 - for other IMTs (e.g., MMI), these would simply be the mean and standard deviation using the column headers <IMT>_VALUE, <IMT>_STDDEV respectively.

The following parameters are optional:

- STATION_NAME: string; free form and not subject to the same constraints as the STATION_ID field. The optional STATION_NAME field can contain information that aids in identifying a particular station.
- Other fields: could contain notes about the station, flags indicating outlier status for the values reported by the station, site information, etc., but these optional fields will not be read by the station_data_file parser.

Ground motion models The user can choose to specify one or multiple GSIMs (or GMPEs) for

the scenario calculation using any of the options below. A list of available GSIMs can be obtained using `oq info gsims` in the terminal, and these are also documented at <http://docs.openquake.org/oq-engine/stable/openquake.hazardlib.gsim.html>.

- A single ground motion model, e.g., `gsim = BooreAtkinson2008`.
- A GSIM logic tree (see Section *The Ground Motion Logic Tree*). In this case multiple ground motion models can be specified in a GMPE logic tree file using the parameter `gsim_logic_tree_file`. In this case, the OpenQuake engine generates ground motion fields for all GMPEs specified in the logic tree file. The *Branch* weights in the logic tree file are ignored in a scenario analysis and only the individual *Branch* results are computed. Mean or quantile ground motion fields will not be generated.
- A weighted average GSIM: starting from OpenQuake engine v3.8 it is possible to indicate an AvgGMPE that computes the geometric mean of the underlying GMPEs, similarly to AvgSA. In the configuration file, a weighted average GSIM can be specified as `gsim_logic_tree_file = gsim_weighted_avg.xml`, where the file `gsim_weighted_avg.xml` can be constructed using the modifiable GMPE structure for AvgGMPE as shown in the example below:

```

1  <?xml version="1.0" encoding="UTF-8"?>
2  <nrm1 xmlns:gml="http://www.opengis.net/gml"
3   xmlns="http://openquake.org/xmlns/nrml/0.4">
4  <logicTree logicTreeID='lt1'>
5    <logicTreeBranchingLevel branchingLevelID="bl1">
6      <logicTreeBranchSet
7        branchSetID="bs1"
8        uncertaintyType="gmpeModel"
9        applyToTectonicRegionType="Active Shallow Crust">
10       <logicTreeBranch branchID="br1">
11         <uncertaintyModel>
12           [AvgGMPE]
13           b1.AbrahamsonEtAl2014.weight=0.22
14           b2.BooreEtAl2014.weight=0.22
15           b3.CampbellBozorgnia2014.weight=0.22
16           b4.ChiouYoungs2014.weight=0.22
17           b5.Idriss2014.weight=0.12
18         </uncertaintyModel>
19         <uncertaintyWeight>
20           1.0
21         </uncertaintyWeight>
22       </logicTreeBranch>
23     </logicTreeBranchSet>
24   </logicTreeBranchingLevel>
25 </logicTree>
26 </nrm1>
```

2.3 Hazard Calculations and Results

In this Chapter we provide a description of the main commands available for running hazard with the OpenQuake engine and the file formats used to represent the results of the analyses.

A general introduction on the use of the OpenQuake engine is provided in [OpenQuake-engine Background](#). The reader is invited to consult this part before diving into the following sections.

2.3.1 Running OpenQuake-engine for hazard calculations

The execution of a hazard analysis using the OpenQuake-engine is straightforward. Below we provide an example of the simplest command that can be used to launch a hazard calculation. It consists in the invocation of `oq engine` together with the `--run` option, and the name of a configuration file (in the example below it corresponds to `job.ini`):

```
user@ubuntu:$ oq engine --run job.ini
```

The amount of information prompted during the execution of the analysis can be controlled through the `--log-level` flag as shown in the example below:

```
user@ubuntu:$ oq engine --run job.ini --log-level debug
```

In this example we ask the engine to provide an extensive amount of information (usually not justified for a standard analysis). Alternative options are: `debug`, `info`, `warn`, `error`, `critical`.

2.3.2 Exporting results from a hazard calculation

There are two alternative ways to get results from the OpenQuake-engine: directly through the calculation or by exporting them from the internal OpenQuake engine database once a calculation is completed.

The first option is defined at the OpenQuake-engine invocation through the flag `-exports xml`, as shown in the example below:

```
user@ubuntu:~$ oq engine --run job.ini --exports xml
```

This will export the results to the `results` directory specified in the `job.ini` file.

The second option allows the user to export the computed results or just a subset of them whenever they want. In order to obtain the list of results of the hazard calculations stored in the OpenQuake engine database the user can utilize the `--lhc` command ('list hazard calculations') to list the hazard calculations:

```
user@ubuntu:~$ oq engine --lhc
```

The execution of this command will produce a list similar to the one provided below (the numbers in red are the calculations IDs):

```
user@ubuntu:~$ oq engine --lhc
job_id | status | start_time | description
1 | failed | 2013-03-01 09:49:34 | Classical PSHA
2 | successful | 2013-03-01 09:49:56 | Classical PSHA
3 | failed | 2013-03-01 10:24:04 | Classical PSHA
4 | failed | 2013-03-01 10:28:16 | Classical PSHA
5 | failed | 2013-03-01 10:30:04 | Classical PSHA
6 | successful | 2013-03-01 10:31:53 | Classical PSHA
7 | failed | 2013-03-09 08:15:14 | Classical PSHA
8 | successful | 2013-03-09 08:18:04 | Classical PSHA
```

Subsequently the user can get the list of result stored for a specific hazard analysis by using the --list-outputs, or --lo, command, as in the example below (note that the number in blue emphasizes the result ID):

```
user@ubuntu:~$ oq engine --lo <calc_id>
id | name
3 | hcurves
```

and finally extract an xml file for a specific hazard result:

```
user@ubuntu:~$ oq engine --export-outputs <result_id> <output_folder>
```

2.3.3 Description of hazard outputs

The results generated by the OpenQuake-engine are fundamentally of two distinct typologies differentiated by the presence (or absence) of epistemic uncertainty in the PSHA input model.

When epistemic uncertainty is incorporated into the calculation, the OpenQuake-engine calculators (e.g. Classical PSHA, Event Based PSHA, Disaggregation, UHS) produce a set of results (i.e. hazard curves, ground motion fields, disaggregation outputs, UHS, for each logic-tree realisation) which reflects epistemic uncertainties introduced in the PSHA input model. For each logic tree sample, results are computed and stored. Calculation of results statistics (mean, standard deviation, quantiles) are supported by all the calculators.

By default, OpenQuake will export only the statistical results, i.e. mean curves and quantiles. If the user requires the complete results for all realizations, there is a flag to specify, please see the FAQ <https://github.com/gem/oq-engine/blob/engine-3.18/doc/faq-hazard.md>. Beware that if the logic tree contains a large number of end branches the process of exporting the results from each

end *Branch* can add a significant amount of time - possibly longer than the computation time - and result in a large volume of disk spaced being used. In this case it is best to postprocess the data programmatically. Please contact us and we will be happy to give directions on how to do that in Python.

NB: in the literature there are different algorithms for the computation of the quantiles. The OpenQuake engine uses an algorithm based on interpolation which is implemented here:

<https://github.com/gem/oq-engine/tree/master/openquake/hazardlib/stats.py>

In particular, the median is computed as the q=0.5 quantile.

2.3.3.1 Outputs from Classical PSHA

By default, the classical PSHA calculator computes and stores hazard curves for each logic tree sample considered.

When the PSHA input model doesn't contain epistemic uncertainties the results is a set of hazard curves (one for each investigated site). The command below illustrates how is possible to retrieve the group of hazard curves obtained for a calculation with a given identifier <calc_id> (see Section [Exporting results from a hazard calculation](#) for an explanation about how to obtain the list of calculations performed with their corresponding ID):

```
user@ubuntu:~$ oq engine --lo <calc_id>
id | name
*3 | Hazard Curves
4 | Realizations
```

To export from the database the outputs (in this case hazard curves) contained in one of the output identifies, one can do so with the following command:

```
user@ubuntu:~$ oq engine --export-output <output_id> <output_directory>
```

Alternatively, if the user wishes to export all of the outputs associated with a particular calculation then they can use the --export-outputs with the corresponding calculation key:

```
user@ubuntu:~$ oq engine --export-outputs <calc_id> <output_directory>
```

The exports will produce one or more CSV files containing the seismic hazard curves as represented in the listing <lst:output_hazard_curves_csv>` below.

```
1 # ,,,,"generated_by='OpenQuake engine 3.18.0-gitabf2de85b8', start_date=
  ↵ '2023-10-03T06:09:08', checksum=2107362341, kind='mean', investigation_
  ↵ time=1.0, imt='PGA'"
2 lon,lat,depth,poe-0.1000000,poe-0.4000000,poe-0.6000000
3 0.00000,0.00000,-0.10000,4.553860E-01,5.754042E-02,6.354511E-03
```

(continues on next page)

(continued from previous page)

```

4 0.10000,0.00000,-0.10000,1.522632E-01,0.000000E+00,0.000000E+00
5 0.20000,0.00000,-0.10000,3.037810E-03,0.000000E+00,0.000000E+00
6 0.30000,0.00000,-0.10000,0.000000E+00,0.000000E+00,0.000000E+00

```

Notwithstanding the intuitiveness of this file, let's have a brief overview of the information included. The overall content of this file is a list of hazard curves, one for each investigated site, computed using a PSHA input model representing one possible realisation obtained using the complete logic tree structure.

The first commented line contains some metadata like the version of the engine used to generate the file, the start date of the calculation, a checksum, the kind of hazard curves generated (in the example they are mean curves), the investigation time and the IMT used (in the example PGA).

If the hazard calculation is configured to produce results including seismic hazard maps and uniform hazard spectra, then the list of outputs would display the following:

```

user@ubuntu:~$ oq engine --lo <calc_id>
id | name
2 | Full Report
3 | Hazard Curves
4 | Hazard Maps
5 | Realizations
6 | Uniform Hazard Spectra

```

The first listing below shows a sample of the CSV file used to describe a hazard map, and *the second listing* below shows a sample of the CSC used to describe a uniform hazard spectrum.

```

1 #,"generated_by='OpenQuake engine 3.18.0-gitabf2de85b8', start_date=
  ↵'2023-10-03T06:09:09', checksum=969346546, kind='mean', investigation_
  ↵time=1.0"
2 lon,lat,PGA-0.002105,SA(0.2)-0.002105,SA(1.0)-0.002105
3 -123.23738,49.27479,3.023730E-03,1.227876E-02,1.304533E-02
4 -123.23282,49.26162,2.969411E-03,1.210481E-02,1.294509E-02
5 -123.20480,49.26786,2.971350E-03,1.211078E-02,1.294870E-02

```

```

1 #,"generated_by='OpenQuake engine 3.15.0-git7c5b3f1678', start_date=
  ↵'2022-05-14T10:44:47', checksum=2967670219, kind='rlz-001',_
  ↵investigation_time=1.0"
2 lon,lat,0.002105~PGA,0.002105~SA(0.2),0.002105~SA(1.0)
3 -123.23738,49.27479,2.651139E-03,1.120929E-02,1.218275E-02
4 -123.23282,49.26162,2.603451E-03,1.105909E-02,1.208975E-02
5 -123.20480,49.26786,2.605109E-03,1.106432E-02,1.209299E-02

```

2.3.3.2 Outputs from Hazard Disaggregation

The OpenQuake engine output of a disaggregation analysis corresponds to the combination of a hazard curve and a multidimensional matrix containing the results of the disaggregation. For a typical disaggregation calculation the list of outputs are the following:

```
user@ubuntu:~$ oq engine --lo <calc_id>
id | name
**3** | Disaggregation Outputs
5 | Full Report
6 | Realizations
```

Running `--export-output` to export the disaggregation results will produce individual files for each site. In presence of a nontrivial logic tree the user can specify the realization on which to perform the disaggregation by setting the `rlz_index` parameter in the `job.ini` file. If not specified, the engine will compute the mean disaggregation across all realizations. NB: before version 3.17 the default algorithm used was different: only the realization closest to the mean hazard curve was selected and used perform the disaggregation. This was a choice forced by performance limitations that do not apply to recent versions of the disaggregation calculator.

2.3.3.3 Outputs from Event Based PSHA

The Event Based PSHA calculator computes and stores stochastic event sets and the corresponding ground motion fields. This calculator can also produce hazard curves and hazard maps, similar to the Classical PSHA calculator. The inset below shows an example of the list of results provided by the OpenQuake engine at the end of an event-based PSHA calculation:

```
user@ubuntu:~$ oq engine --lo <calc_id>
id | name
10 | Ground Motion Fields
11 | Hazard Curves
12 | Hazard Maps
13 | Realizations
14 | Earthquake Ruptures
15 | Events
16 | Uniform Hazard Spectra
```

Exporting the outputs from the ruptures will produce a CSV file with the following columns:

1. `rup_id`: incremental number identifying the rupture
2. `multiplicity`: how many times the rupture occurs in the effective investigation time
3. `mag`: float specifying the magnitude of the rupture
4. `centroid_lon`: longitude of the centroid of the rupture

5. `centroid_lat`: latitude of the centroid of the rupture
6. `centroid_depth`: depth (in km) of the centroid of the rupture
7. `trt`: string specifying the tectonic region type
8. `strike`: strike angle of the rupture surface
9. `dip`: dip angle of the rupture surface
10. `rake`: rake angle of the rupture surface

The outputs from the Ground Motion Fields can be exported in the csv format. Exporting the outputs from the Ground Motion Fields in the csv format results in two csv files illustrated in the example files in [Table 2.2](#) and [Table 2.5](#). The sites csv file provides the association between the site ids in the Ground Motion Fields csv file with their latitude and longitude coordinates.

[Table 2.2](#): Example of a ground motion fields csv output file
for an event based hazard calculation

<code>rlz_id</code>	<code>site_id</code>	<code>event_id</code>	<code>gmv_PGA</code>	<code>gmv_SA(0.3)</code>	<code>gmv_SA(1.0)</code>
0	0	48	0.0089	0.0686	0.0065
0	0	54	0.0219	0.0325	0.0164
...
0	6	75	0.0246	0.0244	0.0036
1	0	76	0.0189	0.0327	0.0094
1	0	77	0.0286	0.0683	0.0471
...
...
7	6	1754	0.3182	1.2973	0.6127
7	6	1755	0.2219	0.6200	0.5069

The `Events` output produces a csv file with fields `event_id`, `rup_id` and `rlz_id`. The `event_id` is a 32 bit integer that identifies uniquely the event; the `rup_id` is a 64 bit integer that identifies uniquely the rupture; the `rlz_id` is a 16 bit integer that identifies uniquely the realization. The association between the `event_id` and the `rup_id` is stored inside the `Events` output.

The `Realizations` output produces a csv file listing the source model and the combination of ground shaking intensity models for each path sampled from the logic tree. An example of such a file is shown below in [Table 2.3](#).

Table 2.3: Example of a realizations file

ordinal	branch_path	weight
0	b1~b11_b21	0.1125
1	b1~b11_b22	0.075
2	b1~b12_b21	0.0375
3	b1~b12_b22	0.025
4	b2~b11_b21	0.3375
5	b2~b11_b22	0.225
6	b2~b12_b21	0.1125
7	b2~b12_b22	0.075

2.3.3.4 Outputs from Scenario Hazard Analysis

By default, the scenario hazard calculator computes and stores Ground Motion Fields for each GMPE specified in the job configuration file. The Ground Motion Fields will be computed at each of the sites and for each of the intensity measure types specified in the job configuration file.

Exporting the outputs from the Ground Motion Fields in the csv format results in two csv files illustrated in the example files in [Table 2.4](#) and [Table 2.5](#). The sites csv file provides the association between the site ids in the Ground Motion Fields csv file with their latitude and longitude coordinates.

Table 2.4: Example of a ground motion fields csv output file
for a scenario (Download example)

rlzi	sid	eid	gmv_PGA	gmv_SA(0.3)	gmv_SA(1.0)
0	0	0	0.062	0.119	0.157
0	1	0	0.086	1.533	0.260
0	2	0	0.223	1.647	0.232
...
1	4	99	2.467	0.750	1.918
1	5	99	0.601	0.828	2.272
1	6	99	0.514	0.340	1.202

In this example, the gmfs have been computed using two different GMPEs (and without conditioning the ground shaking to observations), so the realization indices ('rlzi') in the first column of the example gmfs file are either 0 or 1. The gmfs file lists the ground motion values for 100 simulations of the scenario, so the event indices ('eid') in the third column go from 0–99. There are seven sites with indices 0–6 ('sid') which are repeated in the second column for each of the 100 simulations of the event and for each of the two GMPEs. Finally, the subsequent columns list the ground motion values for each of the intensity measure types specified in the job configuration file.

Table 2.5: Example of a sites csv output file for a scenario
(Download example)

site_id	lon	lat
0	-122.57000	38.11300
1	-122.11400	38.11300
2	-122.00000	37.91000
3	-122.00000	38.00000
4	-122.00000	38.11300
5	-122.00000	38.22500
6	-121.88600	38.11300

For scenario hazard calculations that consider the conditioning of the ground shaking to seismic station or macroseismic observations, the nominal event bias, one bias value for each IMT, and for every GSIM used in the calculation is displayed and stored in the calculation log. The calculation log can be obtained using `oq engine --show-log CALC_ID` in the terminal.

2.4 Demonstrative Examples

A number of hazard calculation demos are provided with the OpenQuake engine installation, showing different examples of input and configuration files, for different use cases.

This is the list of demos which illustrate how to use the OpenQuake engine for various seismic hazard analysis:

- AreaSourceClassicalPSHA
- CharacteristicFaultSourceCase1ClassicalPSHA
- CharacteristicFaultSourceCase2ClassicalPSHA
- CharacteristicFaultSourceCase3ClassicalPSHA
- ComplexFaultSourceClassicalPSHA
- Disaggregation
- EventBasedPSHA
- LogicTreeCase1ClassicalPSHA
- LogicTreeCase2ClassicalPSHA
- LogicTreeCase3ClassicalPSHA
- PointSourceClassicalPSHA
- SimpleFaultSourceClassicalPSHA

2.4.1 Classical PSHA Demos

A number of demos have been designed to show how to perform a classical PSHA calculation using the different available source typologies and how to define non-trivial logic trees. It should be noted that the input files that will be illustrated are valid not only for a classical PSHA calculation but also for event based and disaggregation analysis.

All the classical PSHA demos illustrating the different source typologies (all demos but the ones about Logic Tree definition) share the same GSIM logic tree file, which for clarity is provided in *the listing* below.

Since this logic tree consideres only one tectonic region (i.e. Active Shallow Crust) all the seismic sources will belong be considered active shallow crust sources.

```

1  <?xml version="1.0" encoding="UTF-8"?>
2  <nrm1 xmlns:gml="http://www.opengis.net/gml"
3      xmlns="http://openquake.org/xmlns/nrml/0.5">
4      <logicTree logicTreeID="lt1">
5          <logicTreeBranchSet uncertaintyType="gmpeModel"
6              branchSetID="bs1"
7              applyToTectonicRegionType="Active Shallow Crust">
8
9          <logicTreeBranch branchID="b1">
10             <uncertaintyModel>
11                 ChiouYoungs2008
12             </uncertaintyModel>
13             <uncertaintyWeight>1.0</uncertaintyWeight>
14         </logicTreeBranch>
15
16     </logicTreeBranchSet>
17   </logicTree>
18 </nrm1>
```

2.4.1.1 Classical PSHA with different source typologies

This section discusses the following examples:

- AreaSourceClassicalPSHA
- CharacteristicFaultSourceCase1ClassicalPSHA
- CharacteristicFaultSourceCase2ClassicalPSHA
- CharacteristicFaultSourceCase3ClassicalPSHA
- ComplexFaultSourceClassicalPSHA
- PointSourceClassicalPSHA

- SimpleFaultSourceClassicalPSHA

The configuration file in *the listing* is defined to compute hazard curves for several intensity measure types (PGV, PGA and Spectral acceleration at different periods), hazard maps and uniform hazard spectra for different probabilities of exceedance:

```
[general]
description = ...
calculation_mode = classical
random_seed = 23

[geometry]
region = ...
region_grid_spacing = 5.0

[logic_tree]
number_of_logic_tree_samples = 0

[erf]
rupture_mesh_spacing = 2
width_of_mfd_bin = 0.1
area_source_discretization = 5.0

[site_params]
reference_vs30_type = measured
reference_vs30_value = 600.0
reference_depth_to_2pt5km_per_sec = 5.0
reference_depth_to_1pt0km_per_sec = 100.0

[calculation]
source_model_logic_tree_file = source_model_logic_tree.xml
gsim_logic_tree_file = gmpe_logic_tree.xml
investigation_time = 50.0
intensity_measure_types_and_levels = {"PGV": [2, 4, 6, 8, 10, ...],
                                         "PGA": [0.005, 0.007, ...],
                                         "SA(0.025)": [...],
                                         "SA(0.05)": [...],
                                         "SA(0.1)": [...],
                                         "SA(0.2)": [...],
                                         "SA(0.5)": [...],
                                         "SA(1.0)": [...],
                                         "SA(2.0)": [...]}

truncation_level = 3
maximum_distance = 200.0
```

(continues on next page)

(continued from previous page)

[output]

```
mean = false
quantiles = 0.15, 0.50, 0.85
hazard_maps = true
uniform_hazard_spectra = true
poes = 0.10, 0.02
```

Hazard maps (for PGA, 10% in 50 years) for the different demos using various oq-engine source typologies are shown in the figures below:

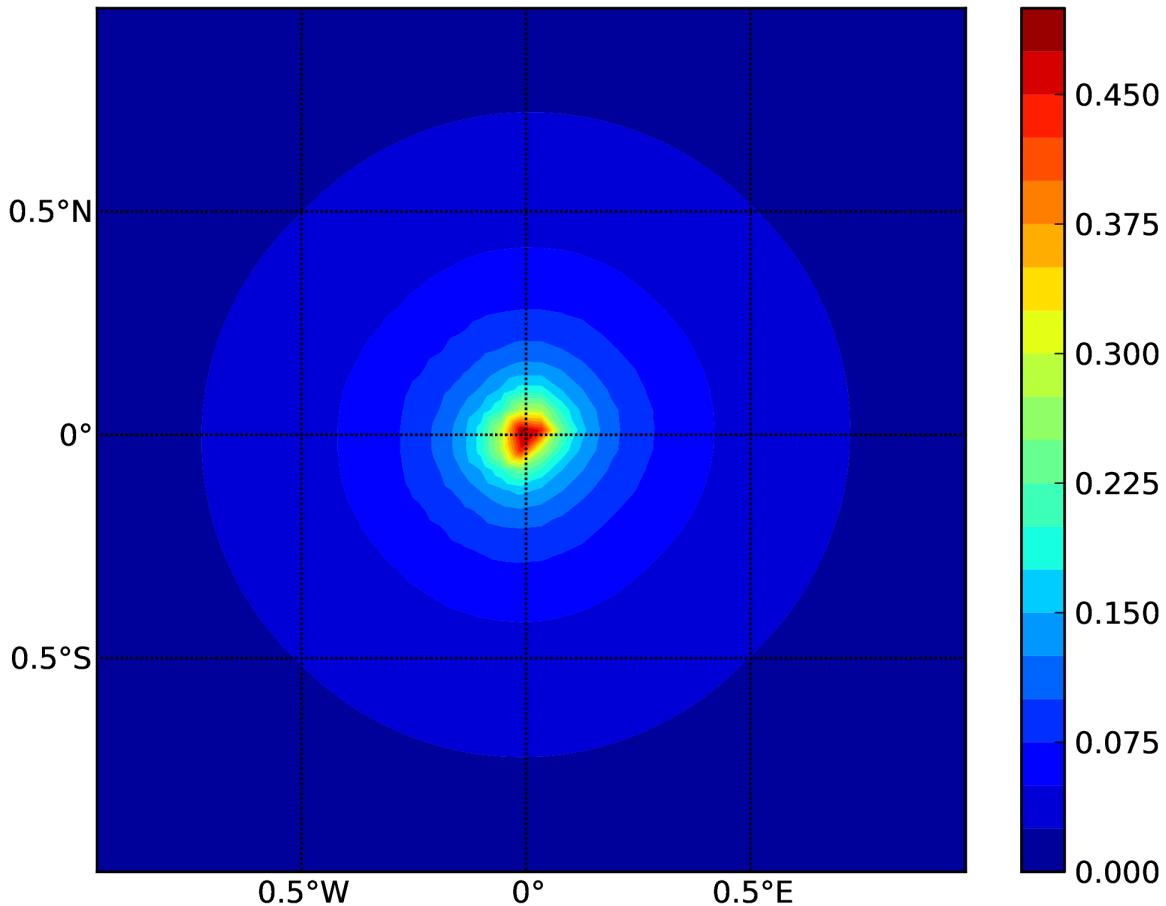


Fig. 2.11: Point Source (a).

Hazard maps (for PGA, 10% in 50 years) as obtained from characteristic fault sources with simple fault geometry (a), complex fault geometry (b), and collection of planar surfaces (c)

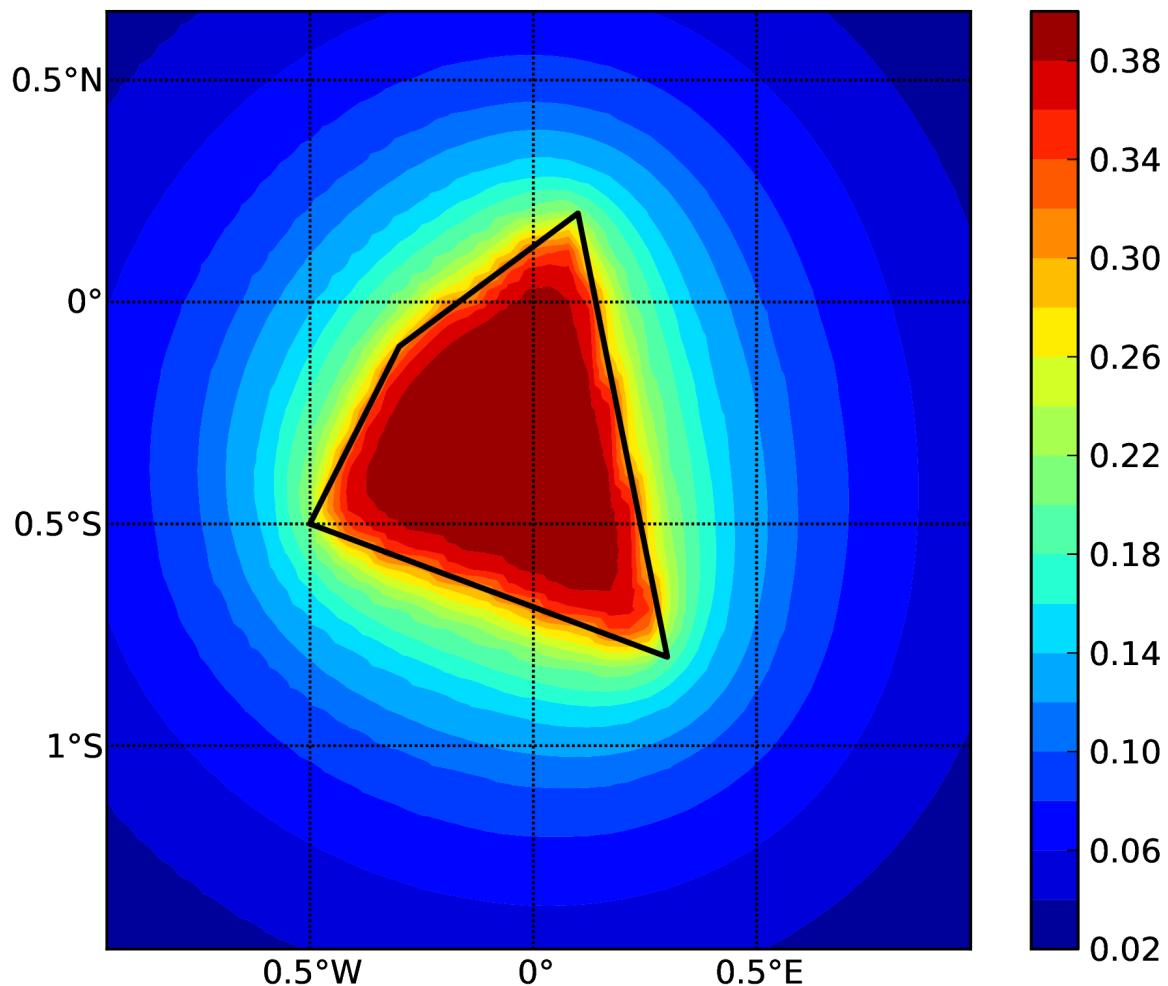


Fig. 2.12: Area source (b). The solid black line represents the area boundary.

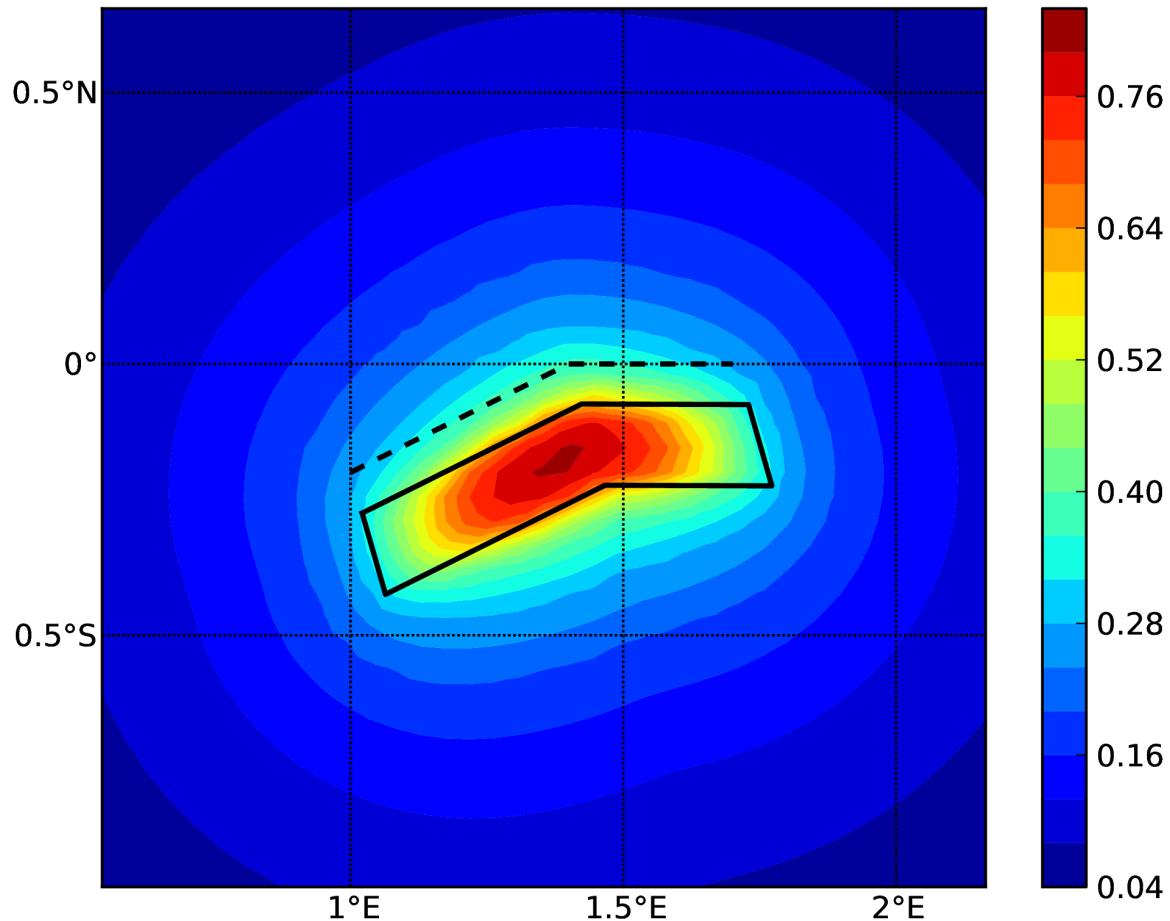


Fig. 2.13: Simple Fault Source (c). The dashed line represents the fault trace, while the solid line the fault surface projection.

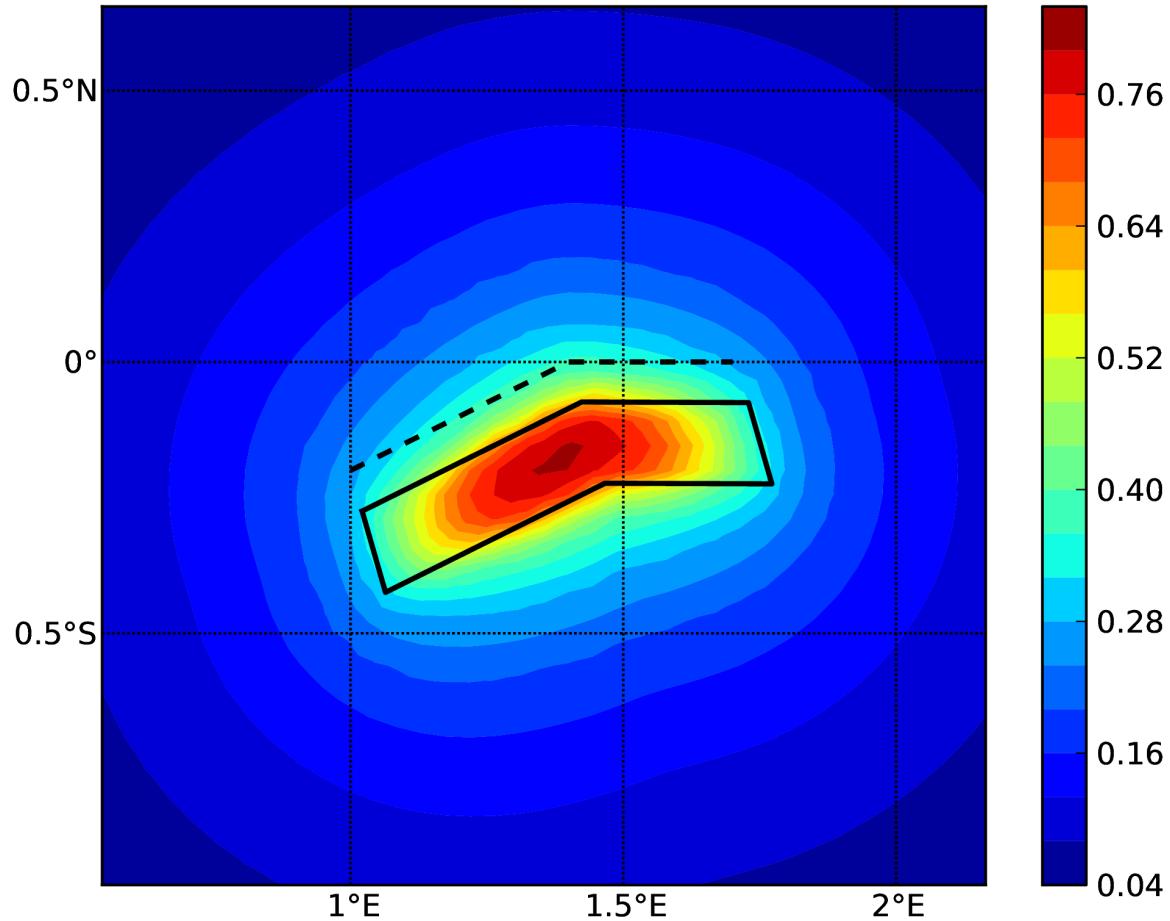


Fig. 2.14: (d) Complex Fault Source. The solid line represent the fault surface projection

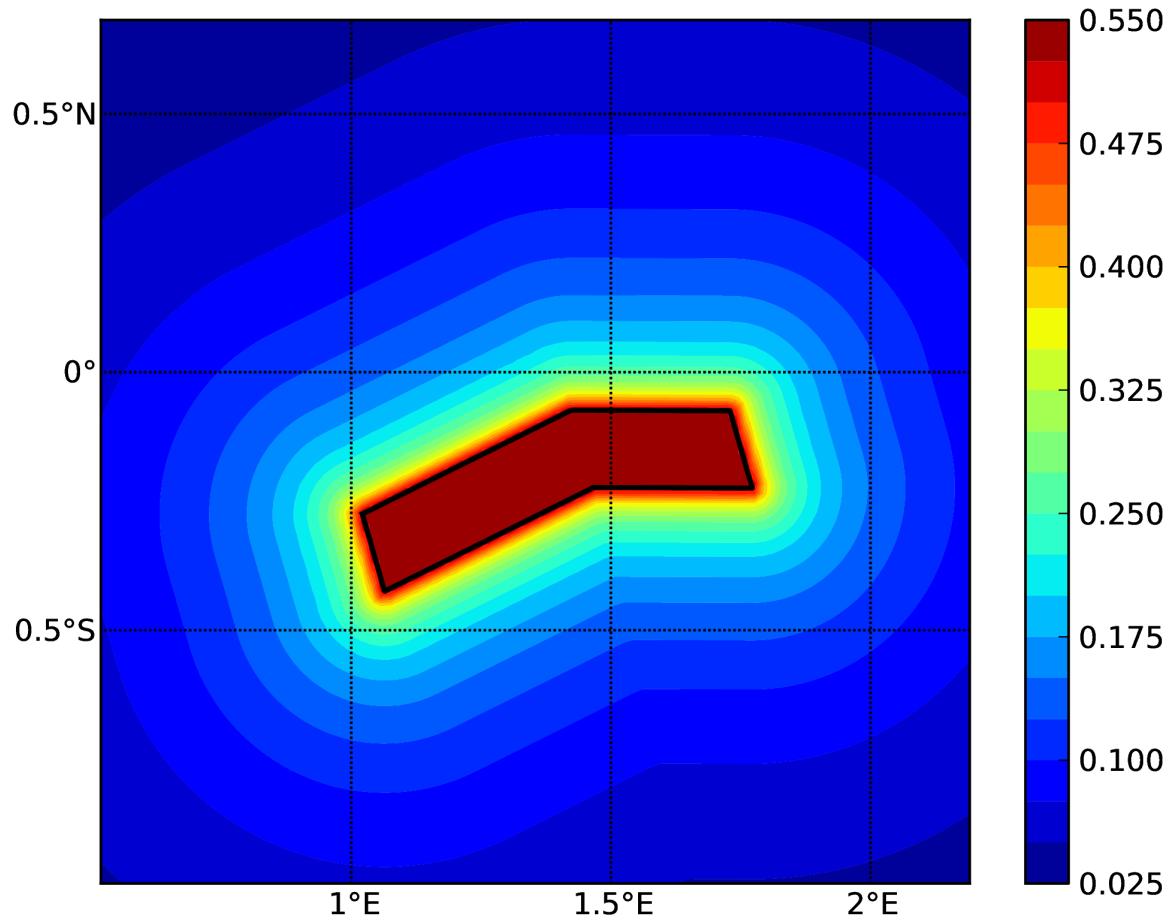


Fig. 2.15: characteristic fault source with simple fault geometry

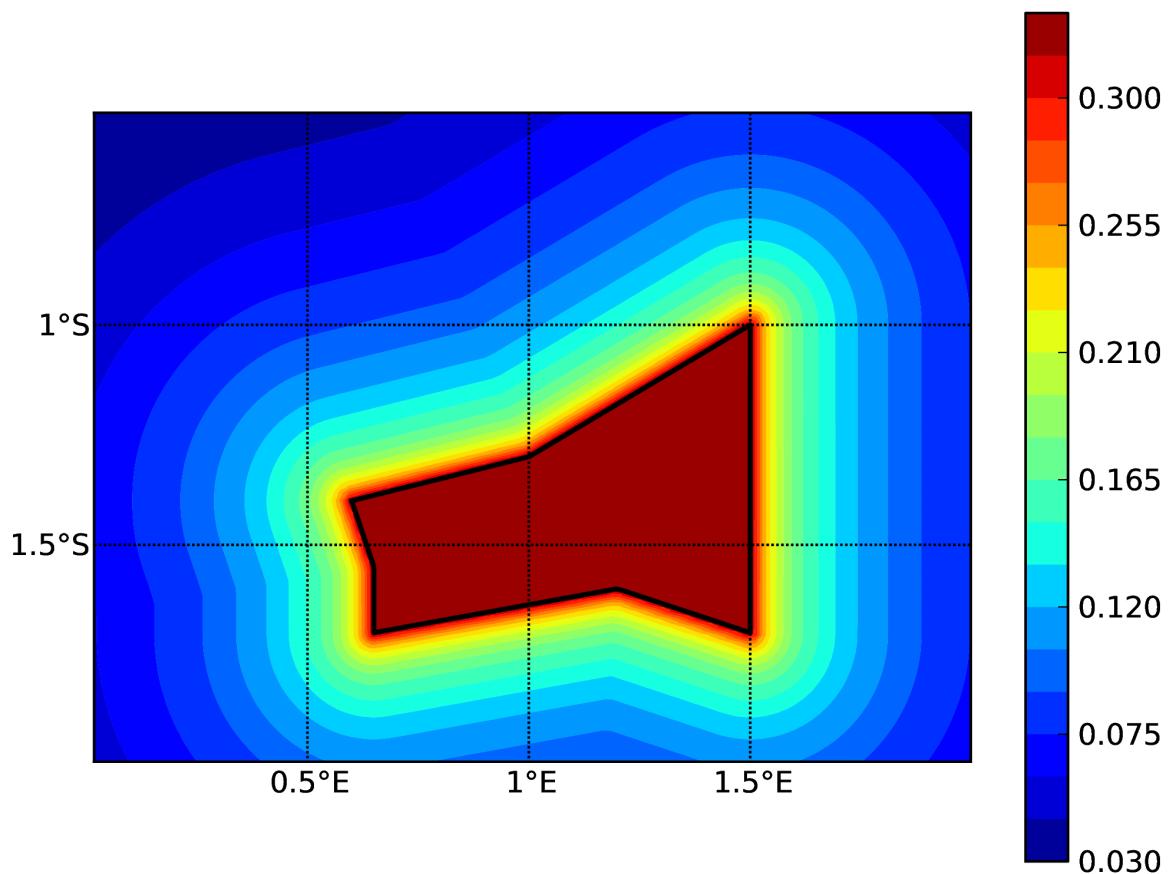


Fig. 2.16: characteristic fault source with complex fault geometry

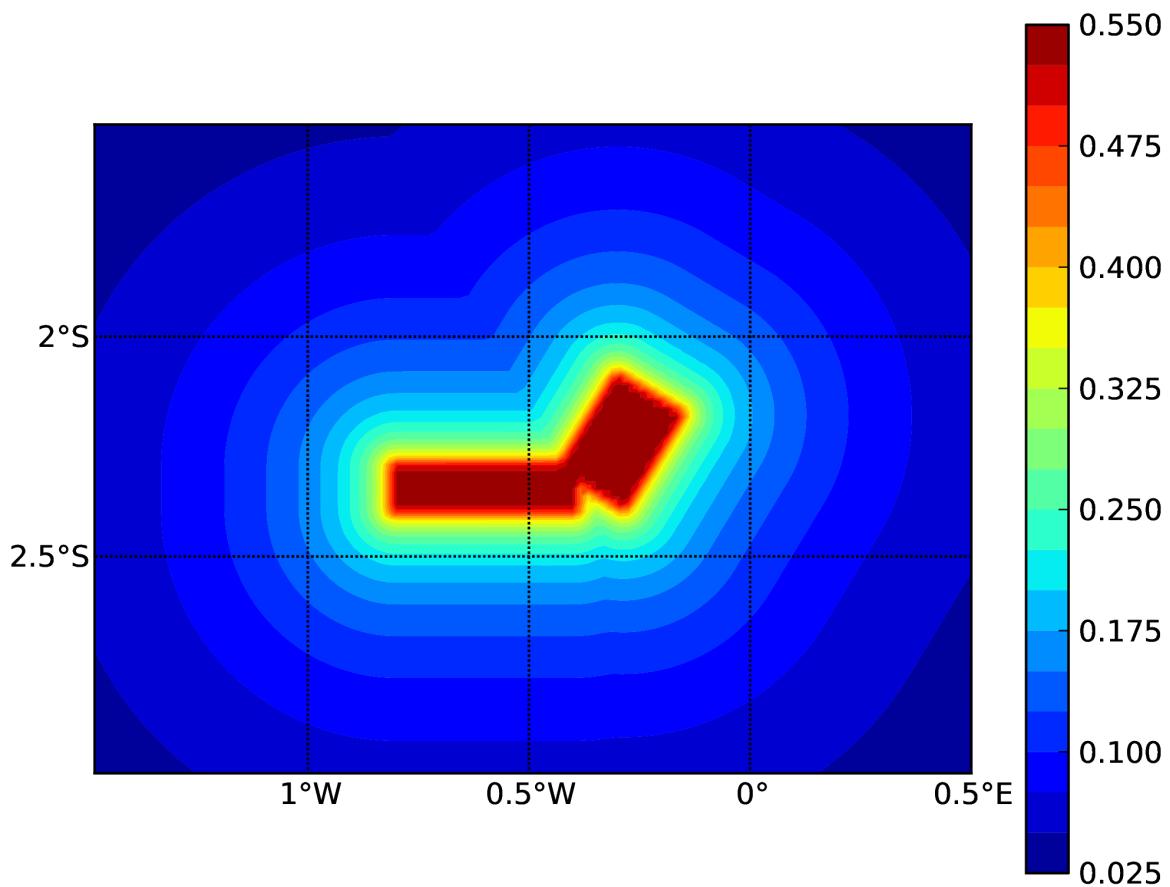


Fig. 2.17: characteristic fault source with collection of planar surfaces

2.4.1.2 Classical PSHA with non trivial logic trees

Three demos are provided to illustrate how the logic tree formalism can be used to express epistemic uncertainties in seismic hazard analysis.

LogicTreeCase1ClassicalPSHA shows an example of logic tree defining two alternative source models, with sources belonging to two different tectonic region types, and with two alternative GMPEs for each tectonic region type. The source model logic tree is therefore defined as shown in *the listing* below.

```

1  <?xml version="1.0" encoding="UTF-8"?>
2  <nrm1 xmlns:gml="http://www.opengis.net/gml"
3      xmlns="http://openquake.org/xmlns/nrml/0.5">
4      <logicTree logicTreeID="lt1">
5
6          <logicTreeBranchSet uncertaintyType="sourceModel"
7              branchSetID="bs1">
8              <logicTreeBranch branchID="b1">
9                  <uncertaintyModel>
10                     source_model_1.xml
11                 </uncertaintyModel>
12                 <uncertaintyWeight>0.5</uncertaintyWeight>
13             </logicTreeBranch>
14             <logicTreeBranch branchID="b2">
15                 <uncertaintyModel>
16                     source_model_2.xml
17                 </uncertaintyModel>
18                 <uncertaintyWeight>0.5</uncertaintyWeight>
19             </logicTreeBranch>
20         </logicTreeBranchSet>
21
22     </logicTree>
23 </nrm1>
```

The two source models are defined in two separate files: `source_model_1.xml` and `source_model_2.xml` each one associated to a corresponding weight (0.5 for both).

The GSIM logic tree file contains the structure as shown in *the listing* below.

```

1  <?xml version="1.0" encoding="UTF-8"?>
2
3  <nrm1 xmlns:gml="http://www.opengis.net/gml"
4      xmlns="http://openquake.org/xmlns/nrml/0.5">
5      <logicTree logicTreeID="lt1">
6
```

(continues on next page)

(continued from previous page)

```

7   <logicTreeBranchSet uncertaintyType="gmpeModel"
8     applyToTectonicRegionType="Active Shallow Crust"
9     branchSetID="bs1">
10    <logicTreeBranch branchID="b11">
11      <uncertaintyModel>
12        BooreAtkinson2008
13      </uncertaintyModel>
14      <uncertaintyWeight>0.5</uncertaintyWeight>
15    </logicTreeBranch>
16    <logicTreeBranch branchID="b12">
17      <uncertaintyModel>
18        ChiouYoungs2008
19      </uncertaintyModel>
20      <uncertaintyWeight>0.5</uncertaintyWeight>
21    </logicTreeBranch>
22  </logicTreeBranchSet>

23
24  <logicTreeBranchSet uncertaintyType="gmpeModel"
25    applyToTectonicRegionType="Stable Continental Crust"
26    branchSetID="bs2">
27    <logicTreeBranch branchID="b21">
28      <uncertaintyModel>
29        ToroEtAl2002</uncertaintyModel>
30      <uncertaintyWeight>0.5</uncertaintyWeight>
31    </logicTreeBranch>
32    <logicTreeBranch branchID="b22">
33      <uncertaintyModel>
34        Campbell2003</uncertaintyModel>
35      <uncertaintyWeight>0.5</uncertaintyWeight>
36    </logicTreeBranch>
37  </logicTreeBranchSet>

38
39  </logicTree>
40 </nrml>
```

The source model contains sources belonging to Active Shallow Crust and Stable Continental Crust, therefore the GSIM logic tree defines two branching levels, one for each considered tectonic region type. Moreover for each tectonic region a *Branch* set with two GMPEs is defined: Boore and Atkinson 2008 and Chiou and Youngs 2008 for Active Shallow Crust and Toro et al. 2003 and Campbell 2003 for Stable Continental Crust. By processing the above logic tree files using the logic tree path enumeration mode (enabled by setting in the configuration file `number_of_logic_tree_samples = 0`) hazard results are computed for 8 logic tree paths (2 source models x 2 GMPEs for Active x 2 GMPEs for Stable).

LogicTreeCase2ClassicalPSHA defines a single source model consisting of only two sources (area and simple fault) belonging to different tectonic region types (Active Shallow Crust and Stable Continental Region) and both characterized by a truncated Gutenberg-Richter distribution. The logic tree defines uncertainties for G-R a and b values (three possible pairs for each source), maximum magnitude (three values for each source) and uncertainties on the GMPEs for each tectonic region type (two GMPE per region type).

To accommodate such a structure the GSIM logic tree is defined as shown in *the listing* below.

```

1  <?xml version="1.0" encoding="UTF-8"?>
2  <nrm1 xmlns:gml="http://www.opengis.net/gml"
3      xmlns="http://openquake.org/xmlns/nrml/0.5">
4      <logicTree logicTreeID="lt1">
5
6          <logicTreeBranchSet uncertaintyType="sourceModel"
7              branchSetID="bs1">
8              <logicTreeBranch branchID="b11">
9                  <uncertaintyModel>
10                 source_model.xml
11             </uncertaintyModel>
12             <uncertaintyWeight>1.0</uncertaintyWeight>
13         </logicTreeBranch>
14     </logicTreeBranchSet>
15
16     <logicTreeBranchSet uncertaintyType="abGRAbsolute"
17         applyToSources="1"
18         branchSetID="bs21">
19         <logicTreeBranch branchID="b21">
20             <uncertaintyModel>4.6 1.1</uncertaintyModel>
21             <uncertaintyWeight>0.333</uncertaintyWeight>
22         </logicTreeBranch>
23         <logicTreeBranch branchID="b22">
24             <uncertaintyModel>4.5 1.0</uncertaintyModel>
25             <uncertaintyWeight>0.333</uncertaintyWeight>
26         </logicTreeBranch>
27         <logicTreeBranch branchID="b23">
28             <uncertaintyModel>4.4 0.9</uncertaintyModel>
29             <uncertaintyWeight>0.334</uncertaintyWeight>
30         </logicTreeBranch>
31     </logicTreeBranchSet>
32
33     <logicTreeBranchSet uncertaintyType="abGRAbsolute"
34         applyToSources="2"
35         branchSetID="bs31">
36         <logicTreeBranch branchID="b31">
```

(continues on next page)

(continued from previous page)

```
37      <uncertaintyModel>3.3 1.0</uncertaintyModel>
38      <uncertaintyWeight>0.333</uncertaintyWeight>
39  </logicTreeBranch>
40  <logicTreeBranch branchID="b32">
41      <uncertaintyModel>3.2 0.9</uncertaintyModel>
42      <uncertaintyWeight>0.333</uncertaintyWeight>
43  </logicTreeBranch>
44  <logicTreeBranch branchID="b33">
45      <uncertaintyModel>3.1 0.8</uncertaintyModel>
46      <uncertaintyWeight>0.334</uncertaintyWeight>
47  </logicTreeBranch>
48 </logicTreeBranchSet>

49
50 <logicTreeBranchSet uncertaintyType="maxMagGRAbsolute"
51     applyToSources="1"
52     branchSetID="bs41">
53  <logicTreeBranch branchID="b41">
54      <uncertaintyModel>7.0</uncertaintyModel>
55      <uncertaintyWeight>0.333</uncertaintyWeight>
56  </logicTreeBranch>
57  <logicTreeBranch branchID="b42">
58      <uncertaintyModel>7.3</uncertaintyModel>
59      <uncertaintyWeight>0.333</uncertaintyWeight>
60  </logicTreeBranch>
61  <logicTreeBranch branchID="b43">
62      <uncertaintyModel>7.6</uncertaintyModel>
63      <uncertaintyWeight>0.334</uncertaintyWeight>
64  </logicTreeBranch>
65 </logicTreeBranchSet>

66
67 <logicTreeBranchSet uncertaintyType="maxMagGRAbsolute"
68     applyToSources="2"
69     branchSetID="bs51">
70  <logicTreeBranch branchID="b51">
71      <uncertaintyModel>7.5</uncertaintyModel>
72      <uncertaintyWeight>0.333</uncertaintyWeight>
73  </logicTreeBranch>
74  <logicTreeBranch branchID="b52">
75      <uncertaintyModel>7.8</uncertaintyModel>
76      <uncertaintyWeight>0.333</uncertaintyWeight>
77  </logicTreeBranch>
78  <logicTreeBranch branchID="b53">
79      <uncertaintyModel>8.0</uncertaintyModel>
```

(continues on next page)

(continued from previous page)

```

80         <uncertaintyWeight>0.334</uncertaintyWeight>
81     </logicTreeBranch>
82   </logicTreeBranchSet>
83
84 </logicTree>
85 </nrml>
```

The first branching level defines the source model. For each source, two branching levels are created, one defining uncertainties on G-R a and b values (defined by setting `uncertaintyType="abGRAbsolute"`) and G-R maximum magnitude (`uncertaintyType="maxMagGRAbsolute"`).

It is important to notice that each *Branch* set is applied to a specific source by defining the attribute `applyToSources`, followed by the source ID. The GSIM logic tree file is the same as used for LogicTreeCase1ClassicalPSHA. By setting in the configuration file `number_of_logic_tree_samples = 0`, hazard results are obtained for 324 paths (1 source model x 3 (a, b) pairs for source 1 x 3 (a, b) pairs for source 2 x 3 max magnitude values for source 1 x 3 max magnitude values for source 2 x 2 GMPEs for Active Shallow Crust X 2 GMPEs for Stable Continental Crust), see Fig. 2.18.

LogicTreeCase3ClassicalPSHA illustrates an example of logic tree defining relative uncertainties on G-R maximum magnitude and b value. A single source model is considered containing two sources belonging to different tectonic region types and both characterized by a G-R magnitude frequency distribution. The source model logic tree for this demo is as shown in *the listing* below.

```

1 <?xml version="1.0" encoding="UTF-8"?>
2 <nrml xmlns:gml="http://www.opengis.net/gml"
3   xmlns="http://openquake.org/xmlns/nrml/0.5">
4   <logicTree logicTreeID="lt1">
5
6     <logicTreeBranchSet uncertaintyType="sourceModel"
7       branchSetID="bs1">
8       <logicTreeBranch branchID="b11">
9         <uncertaintyModel>
10        source_model.xml
11        </uncertaintyModel>
12        <uncertaintyWeight>1.0</uncertaintyWeight>
13      </logicTreeBranch>
14    </logicTreeBranchSet>
15
16    <logicTreeBranchSet uncertaintyType="bGRRelative"
17      branchSetID="bs21">
18      <logicTreeBranch branchID="b21">
19        <uncertaintyModel>+0.1</uncertaintyModel>
```

(continues on next page)

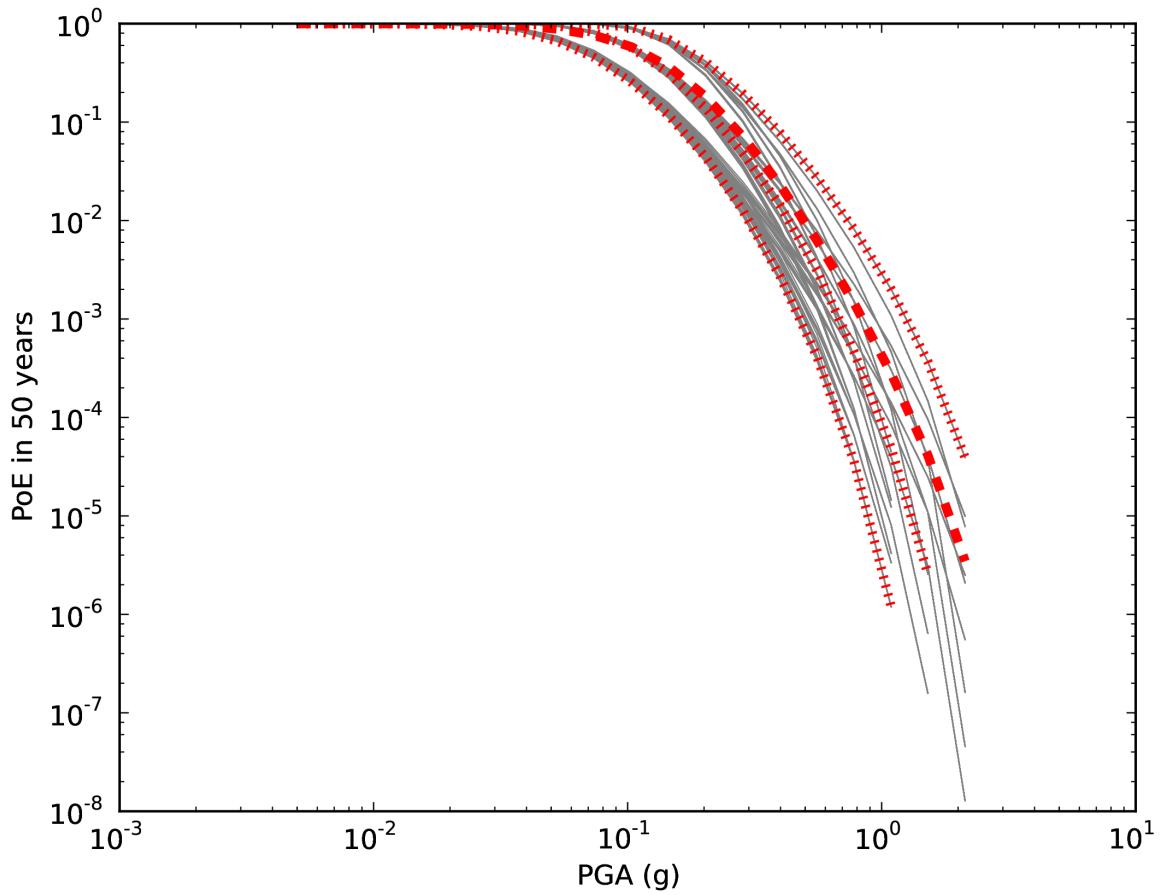


Fig. 2.18: Hazard curves as obtained from the LogicTreeCase2 demo. Solid gray lines represent individual hazard curves from the different logic tree path (a total of 324 curves). The red dashed line represents the mean hazard curve, while the red dotted lines depict the quantile levels (0.15, 0.5, 0.95).

(continued from previous page)

```

20      <uncertaintyWeight>0.333</uncertaintyWeight>
21    </logicTreeBranch>
22    <logicTreeBranch branchID="b22">
23      <uncertaintyModel>0.0</uncertaintyModel>
24      <uncertaintyWeight>0.333</uncertaintyWeight>
25    </logicTreeBranch>
26    <logicTreeBranch branchID="b23">
27      <uncertaintyModel>-0.1</uncertaintyModel>
28      <uncertaintyWeight>0.334</uncertaintyWeight>
29    </logicTreeBranch>
30  </logicTreeBranchSet>

31
32  <logicTreeBranchSet uncertaintyType="maxMagGRRelative"
33    branchSetID="bs31">
34    <logicTreeBranch branchID="b31">
35      <uncertaintyModel>0.0</uncertaintyModel>
36      <uncertaintyWeight>0.333</uncertaintyWeight>
37    </logicTreeBranch>
38    <logicTreeBranch branchID="b32">
39      <uncertaintyModel>+0.5</uncertaintyModel>
40      <uncertaintyWeight>0.333</uncertaintyWeight>
41    </logicTreeBranch>
42    <logicTreeBranch branchID="b33">
43      <uncertaintyModel>+1.0</uncertaintyModel>
44      <uncertaintyWeight>0.334</uncertaintyWeight>
45    </logicTreeBranch>
46  </logicTreeBranchSet>

47
48  </logicTree>
49 </nrml>
```

After the first branching level defining the source model, two additional branching levels are defined, one defining relative uncertainties on b value (`bGRRelative` applied consistently to all sources in the source model) and the second uncertainties on maximum magnitude (`maxMagGRRelative`). Similar to the other cases, two GMPEs are considered for each tectonic region type and therefore the total number of logic tree path is 36 (1 source model x 3 b value increments x 3 maximum magnitude increments x 2 GMPE for Active x 2 GMPEs for Stable).

2.4.2 Hazard Disaggregation Demos

An example of disaggregation calculation is given considering a source model consisting of two sources (area and simple fault) belonging to two different tectonic region types.

The calculation is defined with the following configuration file:

```
[general]
description = ...
calculation_mode = disaggregation
random_seed = 23

[geometry]
sites = 0.5 -0.5

[logic_tree]
number_of_logic_tree_samples = 0

[erf]
rupture_mesh_spacing = 2
width_of_mfd_bin = 0.1
area_source_discretization = 5.0

[site_params]
reference_vs30_type = measured
reference_vs30_value = 600.0
reference_depth_to_2pt5km_per_sec = 5.0
reference_depth_to_1pt0km_per_sec = 100.0

[calculation]
source_model_logic_tree_file = source_model_logic_tree.xml
gsim_logic_tree_file = gmpe_logic_tree.xml
investigation_time = 50.0
intensity_measure_types_and_levels = {"PGA": [...]}
truncation_level = 3
maximum_distance = 200.0

[disaggregation]
poes_disagg = 0.1
mag_bin_width = 1.0
distance_bin_width = 10.0
coordinate_bin_width = 0.2
num_epsilon_bins = 3
```

(continues on next page)

(continued from previous page)

```
[output]
export_dir = ...
```

Disaggregation matrices are computed for a single site (located between the two sources) for a ground motion value corresponding to a probability value equal to 0.1 (poes_disagg = 0.1). Magnitude values are classified in one magnitude unit bins (mag_bin_width = 1.0), distances in bins of 10 km (distance_bin_width = 10.0), coordinates in bins of 0.2 degrees (coordinate_bin_width = 0.2). 3 epsilon bins are considered (num_epsilon_bins = 3).

2.4.3 Event Based PSHA Demos

A demo showing an example of Event Based PSHA calculation is provided with the following configuration file:

```
[general]
description = Event Based PSHA using Area Source
calculation_mode = event_based
random_seed = 23

[geometry]
sites = 0.5 -0.5

[logic_tree]
number_of_logic_tree_samples = 0

[erf]
rupture_mesh_spacing = 2
width_of_mfd_bin = 0.1
area_source_discretization = 5.0

[site_params]
reference_vs30_type = measured
reference_vs30_value = 600.0
reference_depth_to_2pt5km_per_sec = 5.0
reference_depth_to_1pt0km_per_sec = 100.0

[calculation]
source_model_logic_tree_file = source_model_logic_tree.xml
gsim_logic_tree_file = gmpe_logic_tree.xml
investigation_time = 50.0
intensity_measure_types_and_levels = {"PGA": [...]}
truncation_level = 3
```

(continues on next page)

(continued from previous page)

```
maximum_distance = 200.0

[event_based_params]
ses_per_logic_tree_path = 100
ground_motion_correlation_model =
ground_motion_correlation_params =

[output]
export_dir = ...
ground_motion_fields = true
hazard_curves_from_gmfs = true
mean = false
quantiles =
hazard_maps = true
poes = 0.1
```

The source model consist of one source (area). 100 stochastic event sets are generated (`ses_per_logic_tree_path = 100`) (an example can be seen in [Fig. 2.19](#)). Ground motion fields are computed (`ground_motion_fields = true`, [Fig. 2.20](#) and [Fig. 2.21](#)) and also hazard curves from ground motion fields are extracted (`hazard_curves_from_gmfs = true`). The corresponding hazard maps for 0.1 probability are also calculated (`hazard_maps = true`)

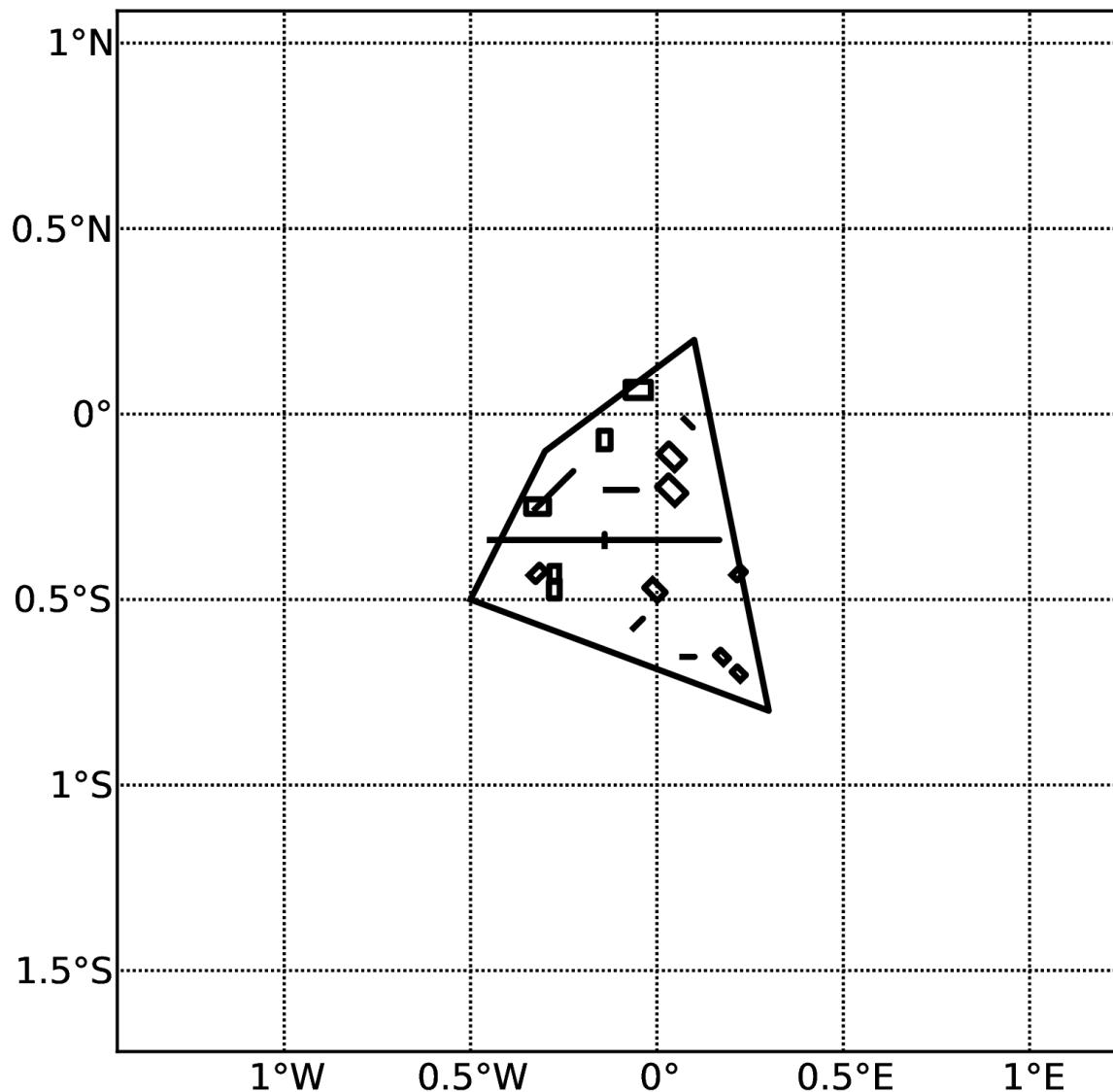


Fig. 2.19: A stochastic event set generated with the event based PSHA demo. The area source defines a nodal plane distribution which distributes events among vertical and dipping (50 degrees) faults with equal weights. Vertical ruptures are then distributed equally in the range 0-180 degrees while the dipping ones in the range 0-360, both with a step of 45 degrees.

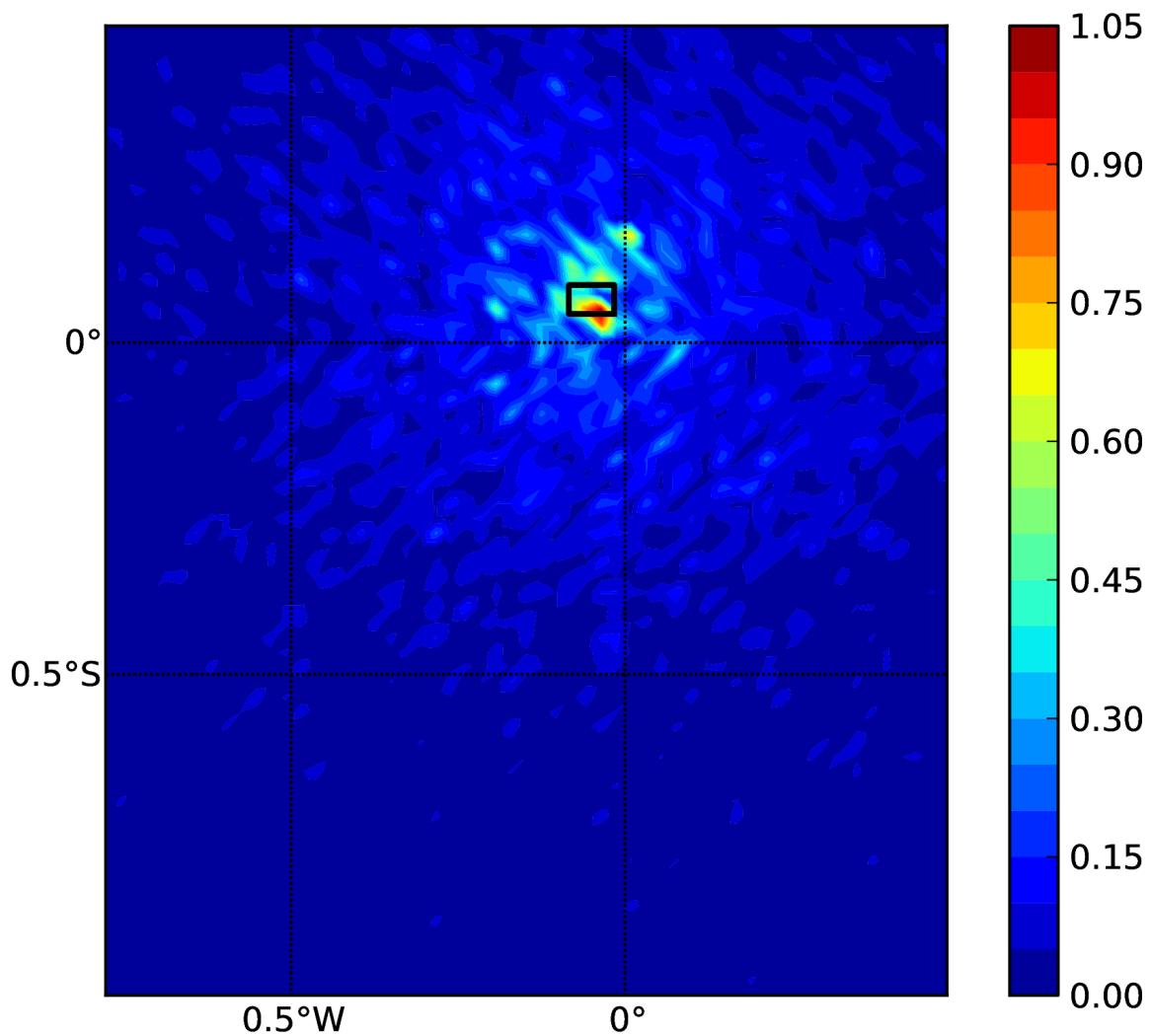


Fig. 2.20: Ground motion fields (PGA) with no spatial correlation

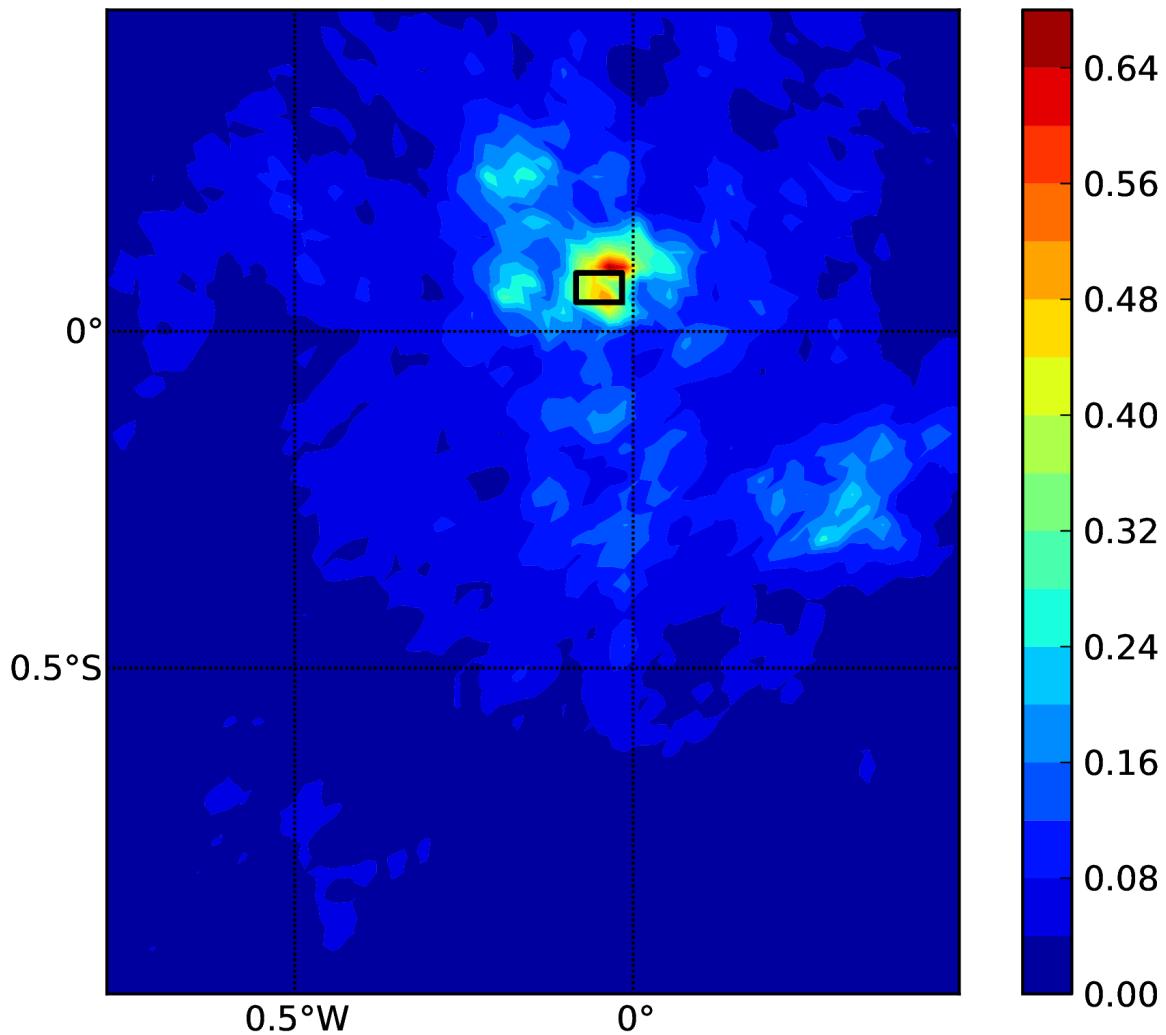


Fig. 2.21: Ground motion fields (PGA) with spatial correlation

**CHAPTER
THREE**

RISK

3.1 Introduction to the Risk Module

The seismic risk results are calculated using the OpenQuake risk library, an open-source suite of tools for seismic risk assessment and loss estimation. This library is written in the Python programming language and available in the form of a “developers” release at the following location: <https://github.com/gem/oq-engine/tree/master/openquake/risklib>.

The risk component of the OpenQuake engine can compute both scenario-based and probabilistic seismic damage and risk using various approaches. The following types of analysis are currently supported:

- **Scenario Damage Assessment**, for the calculation of damage distribution statistics for a portfolio of buildings from a single earthquake rupture scenario taking into account aleatory and epistemic ground-motion variability.
- **Scenario Risk Assessment**, for the calculation of individual asset and portfolio loss statistics due to a single earthquake rupture scenario taking into account aleatory and epistemic ground-motion variability. Correlation in the vulnerability of different assets of the same typology can also be taken into consideration.
- **Classical Probabilistic Seismic Damage Analysis**, for the calculation of damage state probabilities over a specified time period, and probabilistic collapse maps, starting from the hazard curves computed following the classical integration procedure ((Cornell 1968), McGuire (1976)) as formulated by (Field, Jordan, and Cornell 2003).
- **Classical Probabilistic Seismic Risk Analysis**, for the calculation of loss curves and loss maps, starting from the hazard curves computed following the classical integration procedure ((Cornell 1968), McGuire (1976)) as formulated by (Field, Jordan, and Cornell 2003).
- **Stochastic Event Based Probabilistic Seismic Damage Analysis**, for the calculation of event damage tables starting from stochastic event sets. Other results such as damage-state-exceedance curves, probabilistic damage maps, and average annual damages or collapses can be obtained by post-processing the event damage tables.

- **Stochastic Event Based Probabilistic Seismic Risk Analysis**, for the calculation of event loss tables starting from stochastic event sets. Other results such as loss-exceedance curves, probabilistic loss maps, and average annual losses can be obtained by post-processing the event loss tables.
- **Retrofit Benefit-Cost Ratio Analysis**, which is useful in estimating the net-present value of the potential benefits of performing retrofitting for a portfolio of assets (in terms of decreased losses in seismic events), measured relative to the upfront cost of retrofitting.

Each calculation workflow has a modular structure, so that intermediate results can be saved and analyzed. Moreover, each calculator can be extended independently of the others so that additional calculation options and methodologies can be easily introduced, without affecting the overall calculation workflow. Each workflow is described in more detail in the following sections.

3.1.1 Scenario Damage Assessment

The scenario damage calculator computes damage distribution statistics for all assets in a given *Exposure Model* for a single specified rupture. Damage distribution statistics include the mean and standard deviation of damage fractions for different damage states. This calculator requires the definition of a finite *Rupture Model*, an *Exposure Model* and a *Fragility Model*; the main results are the damage distribution statistics per asset, aggregated damage distribution statistics per taxonomy, aggregated damage distribution statistics for the region, and collapse maps, which contain the spatial distribution of the number or area of collapsed buildings throughout the region of interest.

The rupture characteristics—i.e. the magnitude, hypocenter and fault geometry—are modelled as deterministic in the scenario calculators. Multiple simulations of different possible Ground Motion Fields due to the single rupture are generated, taking into consideration both the inter-event variability of ground motions, and the intra-event residuals obtained from a spatial correlation model for ground motion residuals. The use of logic trees allows for the consideration of uncertainty in the choice of a ground motion model for the given tectonic region.

As an alternative to computing the Ground Motion Fields with OpenQuake engine, users can also provide their own sets of Ground Motion Fields as input to the scenario damage calculator.

Note: The damage simulation algorithm for the scenario damage calculator has changed starting from OpenQuake engine39 to use a full Monte Carlo simulation of damage states.

For each Ground Motion Field, a damage state is simulated for each building for every asset in the *Exposure Model* using the provided *Fragility Model*, and finally the mean damage distribution across all realizations is calculated. The calculator also provides aggregated damage distribution statistics for the portfolio, such as mean damage fractions for each taxonomy in the *Exposure Model*, and the mean damage for the entire region of study.

The required input files required for running a scenario damage calculation and the resulting output files are depicted in Fig. 3.1.

Consequence Model files can also be provided as inputs for a scenario damage calculation in addition to fragilitymodels files, in order to estimate consequences based on the calculated damage

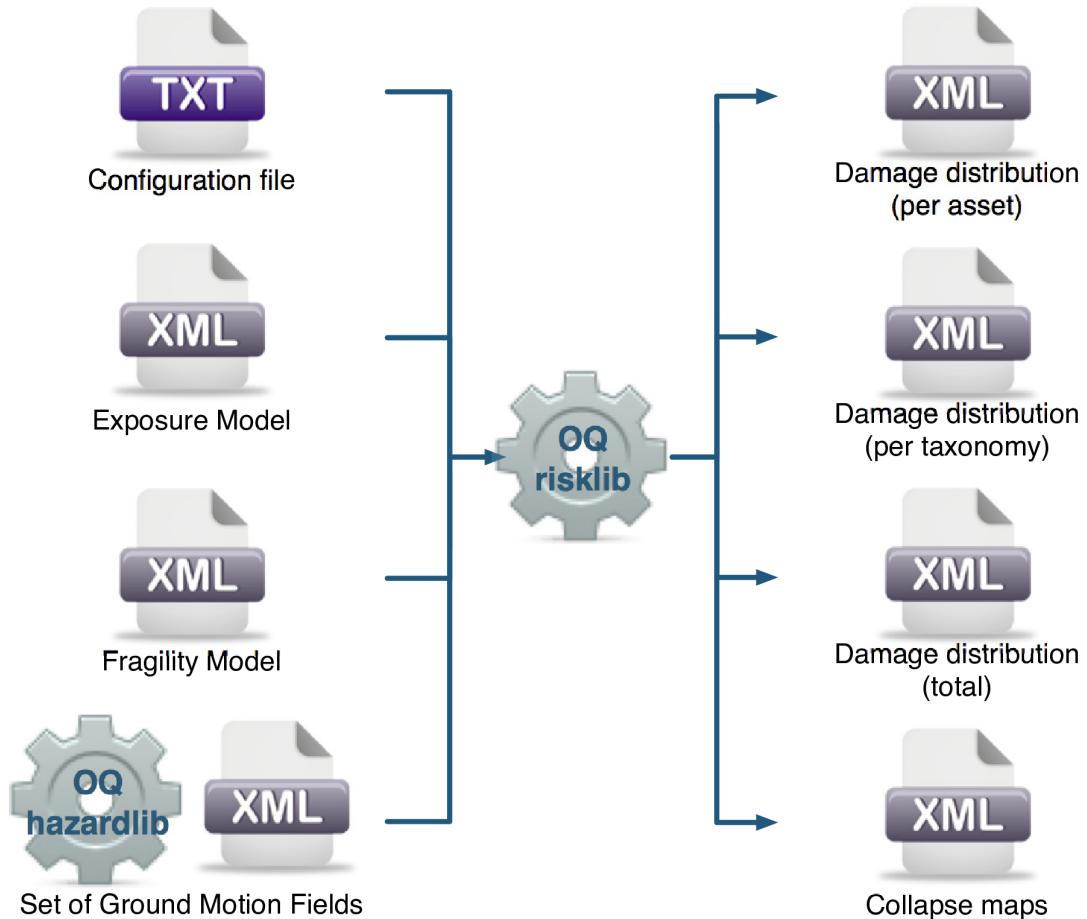


Fig. 3.1: Scenario Damage Calculator input/output structure.

distribution. The user may provide one *Consequence Model* file corresponding to each loss type (amongst structural, nonstructural, contents, and business interruption) for which a *Fragility Model* file is provided. Whereas providing a *Fragility Model* file for at least one loss type is mandatory for running a Scenario Damage calculation, providing corresponding *Consequence Model* files is optional.

3.1.2 Scenario Risk Assessment

The scenario risk calculator computes loss statistics for all assets in a given *Exposure Model* for a single specified rupture. Loss statistics include the mean and standard deviation of ground-up losses for each loss type considered in the analysis. Loss statistics can currently be computed for five different loss types using this calculator: structural losses, nonstructural losses, contents losses, downtime losses, and occupant fatalities. This calculator requires the definition of a finite *Rupture Model*, an *Exposure Model* and a *Vulnerability Model* for each loss type considered; the main results are the loss statistics per asset and mean loss maps.

The rupture characteristics—i.e. the magnitude, hypocenter and fault geometry—are modelled as deterministic in the scenario calculators. Multiple simulations of different possible Ground Motion Fields due to the single rupture are generated, taking into consideration both the inter-event variability of ground motions, and the intra-event residuals obtained from a spatial correlation model for ground motion residuals. The use of logic trees allows for the consideration of uncertainty in the choice of a ground motion model for the given tectonic region.

As an alternative to computing the Ground Motion Fields with OpenQuake, users can also provide their own sets of Ground Motion Fields as input to the scenario risk calculator.

For each Ground Motion Field simulation, a loss ratio is sampled for every asset in the *Exposure Model* using the provided probabilistic *Vulnerability Model* taking into consideration the correlation model for vulnerability of different assets of a given taxonomy. Finally loss statistics, i.e., the mean loss and standard deviation of loss for ground-up losses across all simulations, are calculated for each asset. Mean loss maps are also generated by this calculator, describing the mean ground-up losses caused by the scenario event for the different assets in the *Exposure Model*.

The required input files required for running a scenario risk calculation and the resulting output files are depicted in Fig. 3.2.

3.1.3 Classical Probabilistic Seismic Damage Analysis

The classical PSHA-based damage calculator integrates the fragility functions for an asset with the seismic hazard curve at the location of the asset, to give the expected damage distribution for the asset within a specified time period. The calculator requires the definition of an *Exposure Model*, a *Fragility Model* with fragility functions for each taxonomy represented in the *Exposure Model*, and hazard curves calculated in the region of interest. The main results of this calculator are the expected damage distribution for each asset, which describe the probability of the asset being in different damage states, and collapse maps for the region, which describe the probability of collapse

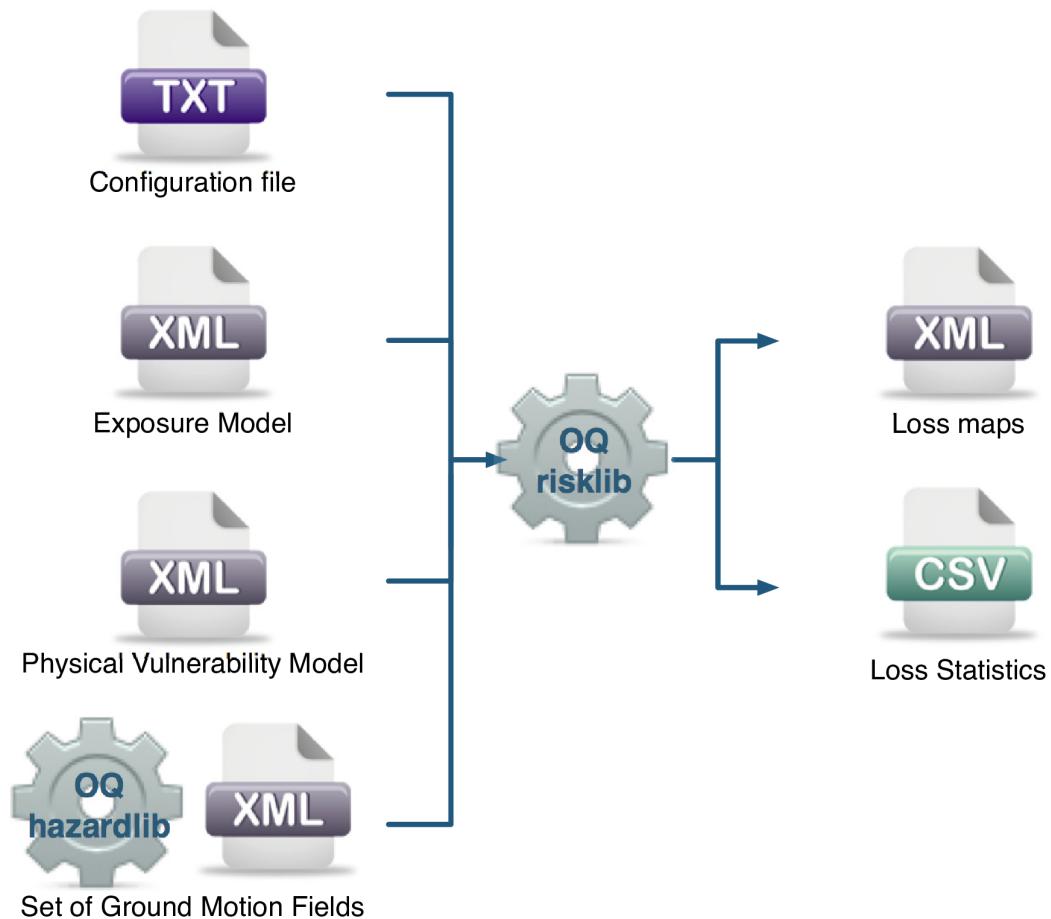


Fig. 3.2: Scenario Risk Calculator input/output structure.

for different assets in the portfolio over the specified time period. Damage distribution aggregated by taxonomy or of the total portfolio (considering all assets in the *Exposure Model*) can not be extracted using this calculator, as the spatial correlation of the ground motion residuals is not taken into consideration.

The hazard curves required for this calculator can be calculated by the OpenQuake engine for all asset locations in the *Exposure Model* using the classical PSHA approach (Cornell 1968; McGuire 1976).

The required input files required for running a classical probabilistic damage calculation and the resulting output files are depicted in Fig. 3.3.

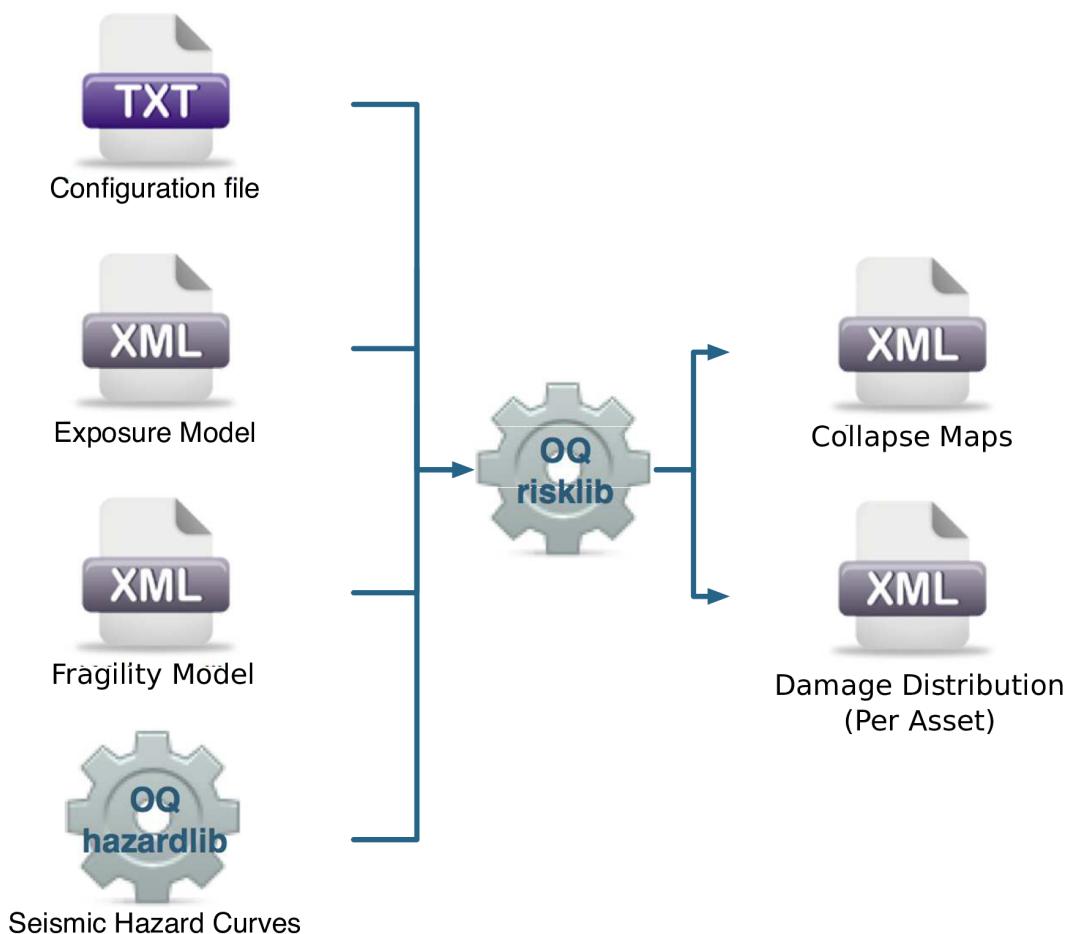


Fig. 3.3: Classical PSHA-based Damage Calculator input/output structure.

3.1.4 Classical Probabilistic Seismic Risk Analysis

The classical PSHA-based risk calculator convolves through numerical integration, the probabilistic vulnerability functions for an asset with the seismic hazard curve at the location of the asset, to give the loss distribution for the asset within a specified time period. The calculator requires the definition of an *Exposure Model*, a *Vulnerability Model* for each loss type of interest with vulnerability functions for each taxonomy represented in the *Exposure Model*, and hazard curves calculated in the region of interest. Loss curves and loss maps can currently be calculated for five different loss types using this calculator: structural losses, nonstructural losses, contents losses, downtime losses, and occupant fatalities. The main results of this calculator are loss exceedance curves for each asset, which describe the probability of exceedance of different loss levels over the specified time period, and loss maps for the region, which describe the loss values that have a given probability of exceedance over the specified time.

Unlike the probabilistic event-based risk calculator, an aggregate loss curve (considering all assets in the *Exposure Model*) can not be extracted using this calculator, as the correlation of the ground motion residuals and vulnerability uncertainty is not taken into consideration in this calculator.

The hazard curves required for this calculator can be calculated by the OpenQuake engine for all asset locations in the *Exposure Model* using the classical PSHA approach (Cornell 1968; McGuire 1976). The use of logic-trees allows for the consideration of model uncertainty in the choice of a ground motion prediction equation for the different tectonic region types in the region. Unlike what was described in the previous calculator, a total loss curve (considering all assets in the *Exposure Model*) can not be extracted using this calculator, as the correlation of the ground motion residuals and vulnerability uncertainty is not taken into consideration.

The required input files required for running a classical probabilistic risk calculation and the resulting output files are depicted in Fig. 3.4.

3.1.5 Stochastic Event Based Probabilistic Seismic Damage Analysis

This calculator employs an event-based Monte Carlo simulation approach to probabilistic damage assessment in order to estimate the damage distribution for individual assets and aggregated damage distribution for a spatially distributed portfolio of assets within a specified time period. The calculator requires the definition of an *Exposure Model*, a *Fragility Model* for each loss type of interest with fragility functions for each damage state for every typology represented in the *Exposure Model*, and a Stochastic Event Set representative of the seismicity of the region over the specified time period. Damage state curves and damage maps corresponding to specified return periods can also be obtained using this calculator.

As an alternative to computing the Ground Motion Fields with OpenQuake engine, users can also provide their own sets of Ground Motion Fields as input to the event-based damage calculator.

The main results of this calculator are the event damage tables; these tables describe the total number of buildings in each damage state for the portfolio of assets for each seismic event in the Stochastic Event Set.

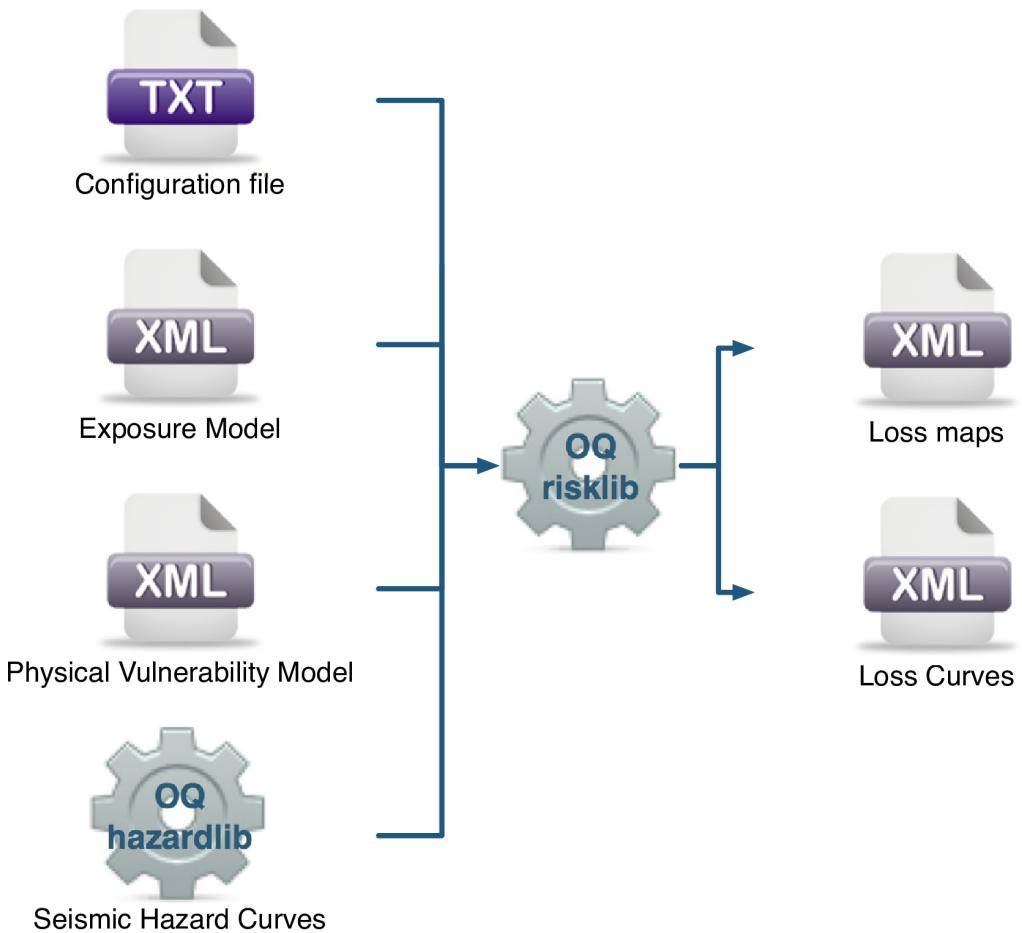


Fig. 3.4: Classical PSHA-based Risk Calculator input/output structure.

Asset-level event damage tables are generated by the calculator, but are not exportable in csv format due to the large file sizes that may be involved. Interested users can access the asset-level event damage tables within the datastore for the completed calculation.

This calculator relies on the probabilistic event-based hazard calculator, which simulates the seismicity of the chosen time period T by producing a Stochastic Event Set. For each rupture generated by a *Seismic Source*, the number of occurrences in the given time span T is simulated by sampling the corresponding probability distribution as given by $P_{rup}(k|T)$. A Stochastic Event Set is therefore a *sample* of the full population of ruptures as defined by a Seismic Source Model. Each rupture is present zero, one or more times, depending on its probability. Symbolically, we can define a Stochastic Event Set as:

$$SES(T) = \{k \times rup, k \sim P_{rup}(k|T) \quad \forall rup \text{ in } Src \quad \forall Src \text{ in } SSM\}$$

where k , the number of occurrences, is a random sample of $P_{rup}(k|T)$, and $k \times rup$ means that rupture rup is repeated k times in the Stochastic Event Set.

For each rupture or event in the Stochastic Event Sets, a spatially correlated Ground Motion Field realisation is generated, taking into consideration both the inter-event variability of ground motions, and the intra-event residuals obtained from a spatial correlation model for ground motion residuals (if one is specified in the job file). The use of logic trees allows for the consideration of uncertainty in the choice of a Seismic Source Model, and in the choice of groundmotionmodels for the different tectonic regions.

For each Ground Motion Field realization, a damage state is simulated for each building of every asset in the *Exposure Model* using the provided *Fragility Model*. The asset-level event damage table is saved to the datastore. Time-averaged damage distributions at the asset-level can be obtained from the event damage table. Finally damage state exceedance curves can be computed.

The required input files required for running a probabilistic stochastic event-based damage calculation and the resulting output files are depicted in Fig. 3.5.

Similar to the scenario damage calculator, *Consequence Model* files can also be provided as inputs for an event-based damage calculation in addition to fragilitymodels files, in order to estimate consequences based on the calculated damage distribution. The user may provide one *Consequence Model* file corresponding to each loss type (amongst structural, nonstructural, contents, and business interruption) for which a *Fragility Model* file is provided. Whereas providing a *Fragility Model* file for at least one loss type is mandatory for running an Event-Based Damage calculation, providing corresponding *Consequence Model* files is optional.

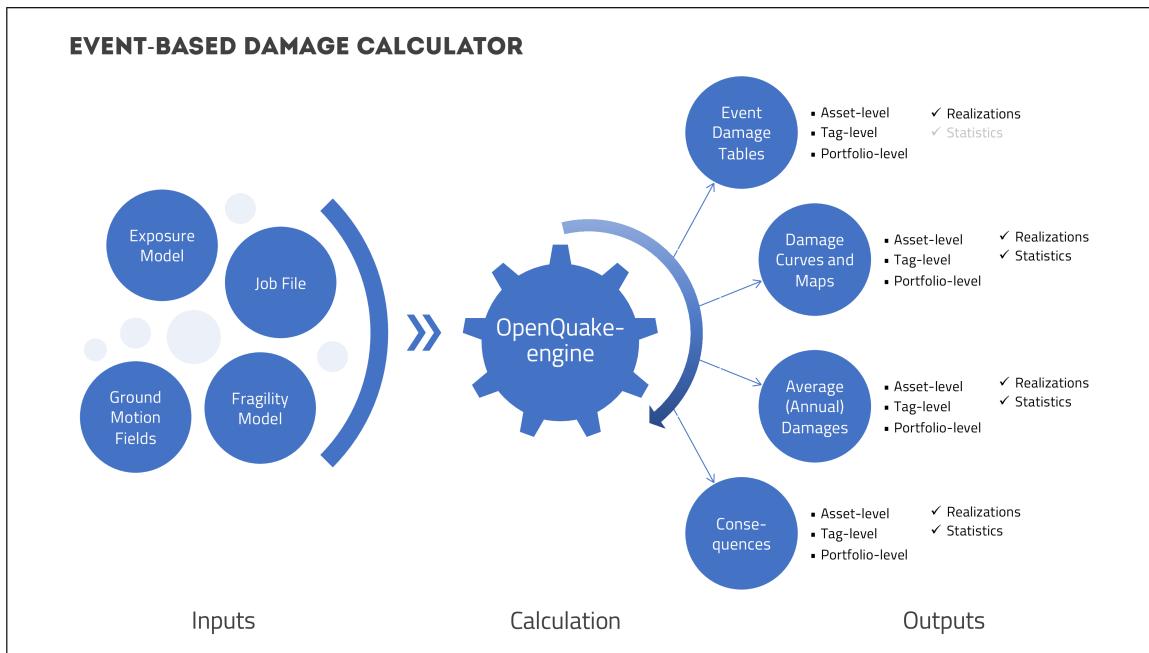


Fig. 3.5: Probabilistic Event-based Damage Calculator input/output structure.

3.1.6 Stochastic Event Based Probabilistic Seismic Risk Analysis

This calculator employs an event-based Monte Carlo simulation approach to probabilistic risk assessment in order to estimate the loss distribution for individual assets and aggregated loss distribution for a spatially distributed portfolio of assets within a specified time period. The calculator requires the definition of an *Exposure Model*, a *Vulnerability Model* for each loss type of interest with vulnerability functions for each taxonomy represented in the *Exposure Model*, and a Stochastic Event Set (also known as a *synthetic catalog*) representative of the seismicity of the region over the specified time period. Loss curves and loss maps can currently be calculated for five different loss types using this calculator: structural losses, nonstructural losses, contents losses, downtime losses, and occupant fatalities.

As an alternative to computing the Ground Motion Fields with OpenQuake engine, users can also provide their own sets of Ground Motion Fields as input to the event-based risk calculator, starting from OpenQuake engine28.

The main results of this calculator are loss exceedance curves for each asset, which describe the probability of exceedance of different loss levels over the specified time period, and loss maps for the region, which describe the loss values that have a given probability of exceedance over the specified time period. Aggregate loss exceedance curves can also be produced using this calculator; these describe the probability of exceedance of different loss levels for all assets in the portfolio. Finally, event loss tables can be produced using this calculator; these tables describe the total loss across the portfolio for each seismic event in the Stochastic Event Set.

This calculator relies on the probabilistic event-based hazard calculator, which simulates the seismicity of the chosen time period T by producing a Stochastic Event Set. For each rupture generated by a *Seismic Source*, the number of occurrences in the given time span T is simulated by sampling the corresponding probability distribution as given by $P_{rup}(k|T)$. A Stochastic Event Set is therefore a *sample* of the full population of ruptures as defined by a Seismic Source Model. Each rupture is present zero, one or more times, depending on its probability. Symbolically, we can define a Stochastic Event Set as:

$$SES(T) = \{k \times rup, k \sim P_{rup}(k|T) \quad \forall rup \text{ in } Src \quad \forall Src \text{ in } SSM\}$$

where k , the number of occurrences, is a random sample of $P_{rup}(k|T)$, and $k \times rup$ means that rupture rup is repeated k times in the Stochastic Event Set.

For each rupture or event in the Stochastic Event Sets, a spatially correlated Ground Motion Field realisation is generated, taking into consideration both the inter-event variability of ground motions, and the intra-event residuals obtained from a spatial correlation model for ground motion residuals (if one is specified in the job file). The use of logic trees allows for the consideration of uncertainty in the choice of a Seismic Source Model, and in the choice of groundmotionmodels for the different tectonic regions.

For each Ground Motion Field realization, a loss ratio is sampled for every asset in the *Exposure Model* using the provided probabilistic *Vulnerability Model*, taking into consideration the correlation model for vulnerability of different assets of a given taxonomy. Finally loss exceedance curves are computed for ground-up losses.

The required input files required for running a probabilistic stochastic event-based risk calculation and the resulting output files are depicted in Fig. 3.6.

3.1.7 Retrofit Benefit-Cost Ratio Analysis

This calculator represents a decision-support tool for deciding whether the employment of retrofitting measures to a collection of existing buildings is advantageous from an economical point of view. For this assessment, the expected losses considering the original and retrofitted configuration of the buildings are estimated, and the economic benefit due to the better seismic design is divided by the retrofitting cost, leading to the benefit/cost ratio. These loss curves are computed using the previously described Classical PSHA- based Risk calculator. The output of this calculator is a benefit/cost ratio for each asset, in which a ratio above one indicates that employing a retrofitting intervention is economically viable.

In Fig. 3.7, the input/output structure for this calculator is depicted.

For further information regarding the theoretical background of the methodologies used for each calculator, users are referred to the OpenQuake- engine Book (Risk).

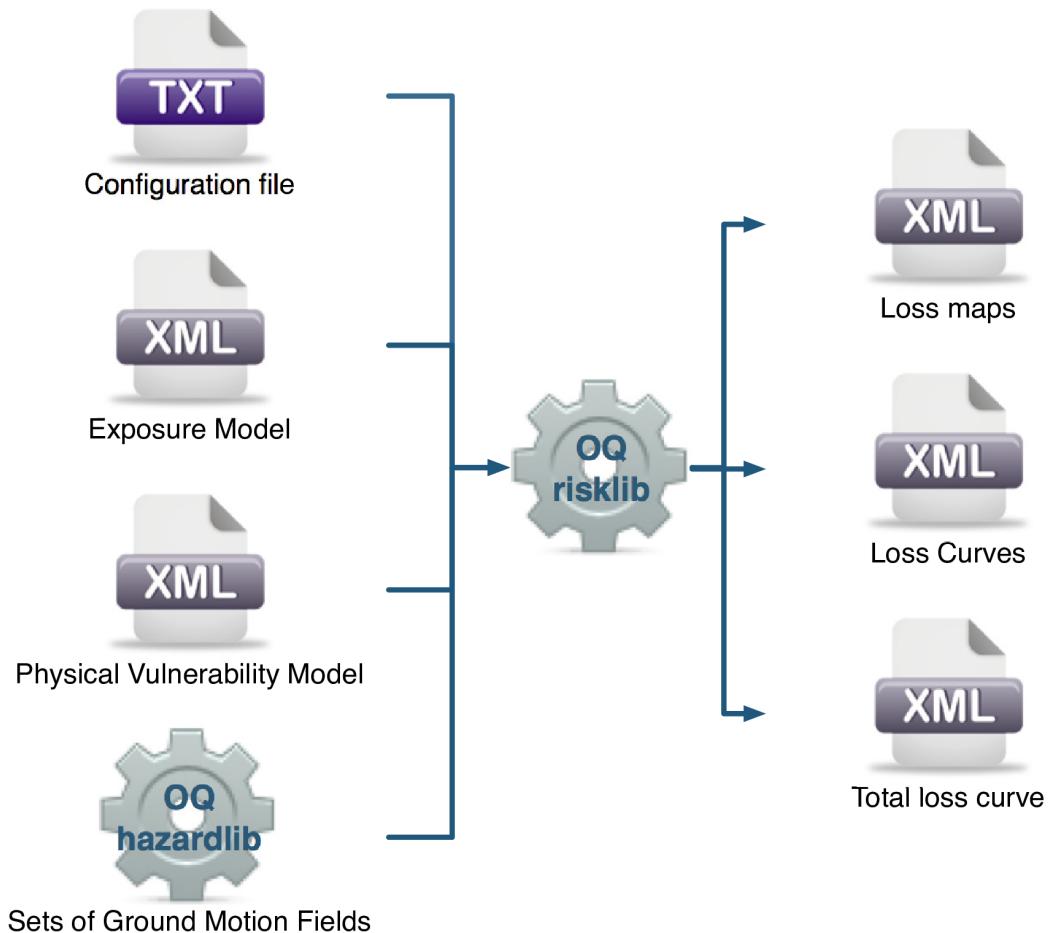


Fig. 3.6: Probabilistic Event-based Risk Calculator input/output structure.

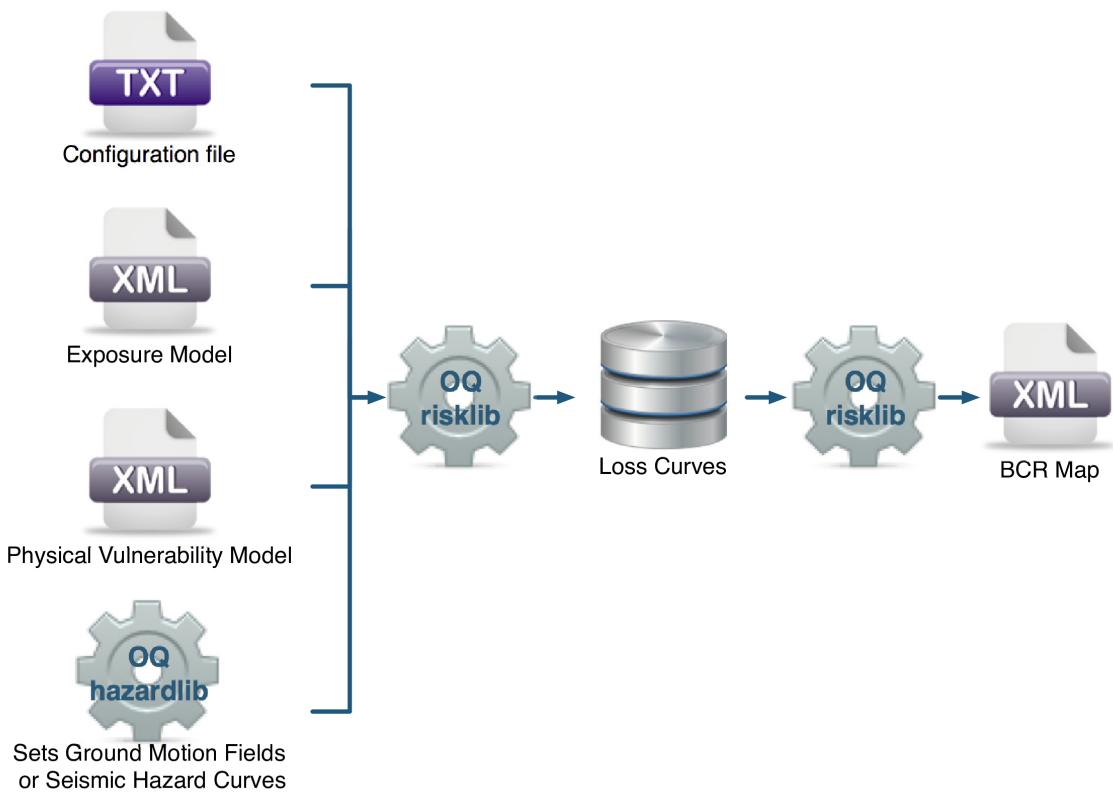


Fig. 3.7: Retrofitting Benefit/Cost Ratio Calculator input/output structure.

3.1.8 Infrastructure Risk Analysis

3.1.8.1 Rationale

Critical infrastructures, whose components are interconnected and behave as a system, are vital for the functioning of the society. Unlike the portfolio of the buildings whose total loss can be calculated by simply aggregating the losses from the individual component unit, it is not straightforward for critical infrastructures as they possess the complex network property to behave synergistically.

Risk assessment of critical infrastructures is limited due to the underlying complexities and lack of integrated tools that can compute from hazard characterization to risk assessment at system level. Therefore, in order to aid the assessment of infrastructures extensively and globally, this implementation has been carried out.

As of now, risk assessment at connectivity level using topology based network analysis has been carried out. This can be uniformly used for different types of critical infrastructures including water supply systems, electric power networks, transportation systems, natural gas, etc.

3.1.8.2 Specification of the Input Model

Critical infrastructures are represented as graph-like components consisting of nodes/vertices connected by edges/links. The graph can be simple undirected, directed, multi or multidirected type. To each of these types, the graph can be weighted or unweighted. If not specified, the default is simple unweighted undirected graph. In order to generate the graphs, the adjustment should be made in the **exposure.csv** file. Additional to the usual information, it should also include the columns **type**, **start_node**, **end_node**, **demand_or_supply**.

A snippet of exposure model for nodes and edges for a simple unweighted graph is shown in Fig. 3.8 and Fig. 3.9.

id	lon	lat	taxonomy	number	type	start_node	end_node	supply_or_demand
A	22.933	40.635	demand	1	node	NA	NA	demand
D	22.955	40.650	tank	1	node	NA	NA	source
C	22.941	40.649	tank	1	node	NA	NA	source
E	22.955	40.637	demand	1	node	NA	NA	demand
B	22.945	40.637	connection	1	node	NA	NA	connection
F	22.970	40.643	tank	1	node	NA	NA	source
G	22.982	40.636	demand	1	node	NA	NA	demand

Fig. 3.8: Example of the exposure model of nodes of the infrastructure

If the weights are to be added, there should be a column name **weights**, and weights can be travel time, distance, importance factor, etc., according to the user requirement.

Note: If weight is not present, it assigns 1 as weight to every edge while calculating Weighted Connectivity Loss(WCL) and Efficiency Loss(EL)

id	lon	lat	taxonomy	number	type	start_node	end_node	supply_or_demand
L1	22.955	40.644	CI_pipe	1	edge	D	E	NA
L2	22.976	40.640	CI_pipe	1	edge	F	G	NA
L3	22.939	40.636	CI_pipe	1	edge	A	B	NA
L4	22.943	40.643	PVC_pipe	1	edge	B	C	NA
L5	22.962	40.640	PVC_pipe	1	edge	E	F	NA
L6	22.948	40.650	CI_pipe	1	edge	C	D	NA
L7	22.948	40.643	CI_pipe	1	edge	C	E	NA

Fig. 3.9: Example of the exposure model of edges of the infrastructure

If the user wants to specify the graph type, another column **graphtype** must be added. It can be either “directed”, “multi”, “multidirected” or “simple”.

Hazard model and fragility model are similar to other computations. In order to do the network analysis, it is important to define if each component is functional/operational or not, which is defined by the damage states. For this, an additional consequence model is necessary (see Fig. 3.10). As of now, only the binary state is considered i.e “functional/operational” or “non-functional/non-operational”.

taxonomy	consequence	loss_type	slight	moderate	extensive	complete
tank_RC	collapsed	structural	0	0	1	1
pumpingstation	collapsed	structural	0	0	1	1
pipe_CI100	collapsed	structural	0	0	1	1
pipe_CI200	collapsed	structural	0	0	1	1
demand	collapsed	structural	0	0	1	1
connection	collapsed	structural	0	0	1	1

Fig. 3.10: Example of the consequence model (*Note: 0 implies still operational and 1 implies non-operational*)

3.1.8.3 Calculation Steps

1. Preparation of input models, which includes:
 - Exposure model
 - Hazard model
 - Fragility model
 - Consequence model
2. Computation of the specific damage states and assignment of functionality/operationality to each component

3. Creation of original network from the exposure model
4. Update of the functionality of each component to the originally created infrastructure network and removal of the non-functional/non-operational components
5. Network analysis based on the original and updated infrastructure network
6. Computation of the following performance metrics, based on connectivity analysis:
 - Complete Connectivity Loss (CCL)
 - Partial Connectivity Loss (PCL)
 - Weighted Connectivity Loss (WCL)
 - Efficiency Loss (EL)

In summary, for the computation of infrastructure risk at connectivity level in OpenQuake, the input requirements and the outputs obtained are shown in Fig. 3.11.

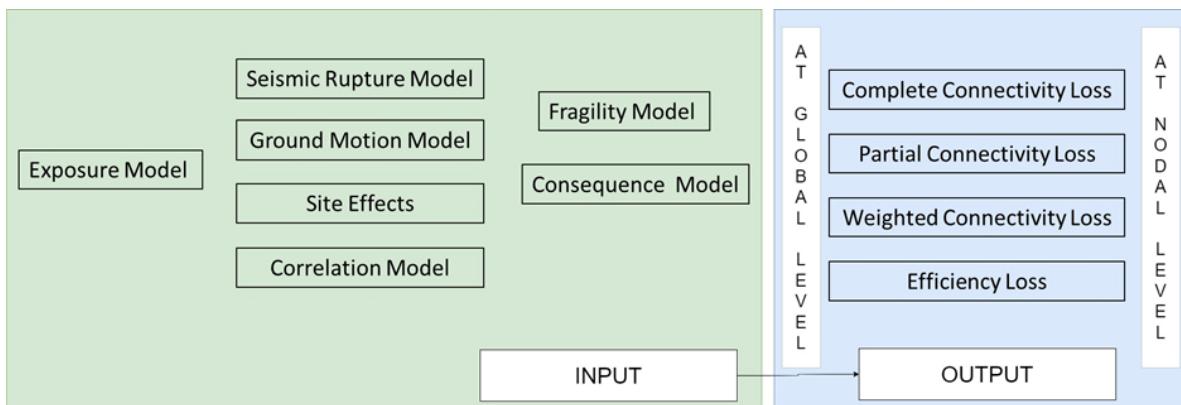


Fig. 3.11: Input models required, and output obtained in OpenQuake for infrastructure risk assessment at connectivity level

3.1.8.4 Specification of the Outputs Obtained

- For the classic generic case where “demand” and “supply” are explicitly mentioned in the column **demand_or_supply**, all four metrics are computed for overall network. Also, at nodal level, all the four metrics are calculated.
- If some nodes behave as both supply and demand, and are assigned as “both” or “TAZ” (traffic analysis zone) in the column **demand_or_supply**, PCL, WCL and EL are computed for both nodal level and overall network.
- If there is no assignment of “demand” or “supply” to the column **demand_or_supply**, only EL is computed for overall network. Also, at nodal level, for all the nodes, EL only is computed.

For the simplification, Fig. 3.12 has been added to understand what can be obtained by various specifications.

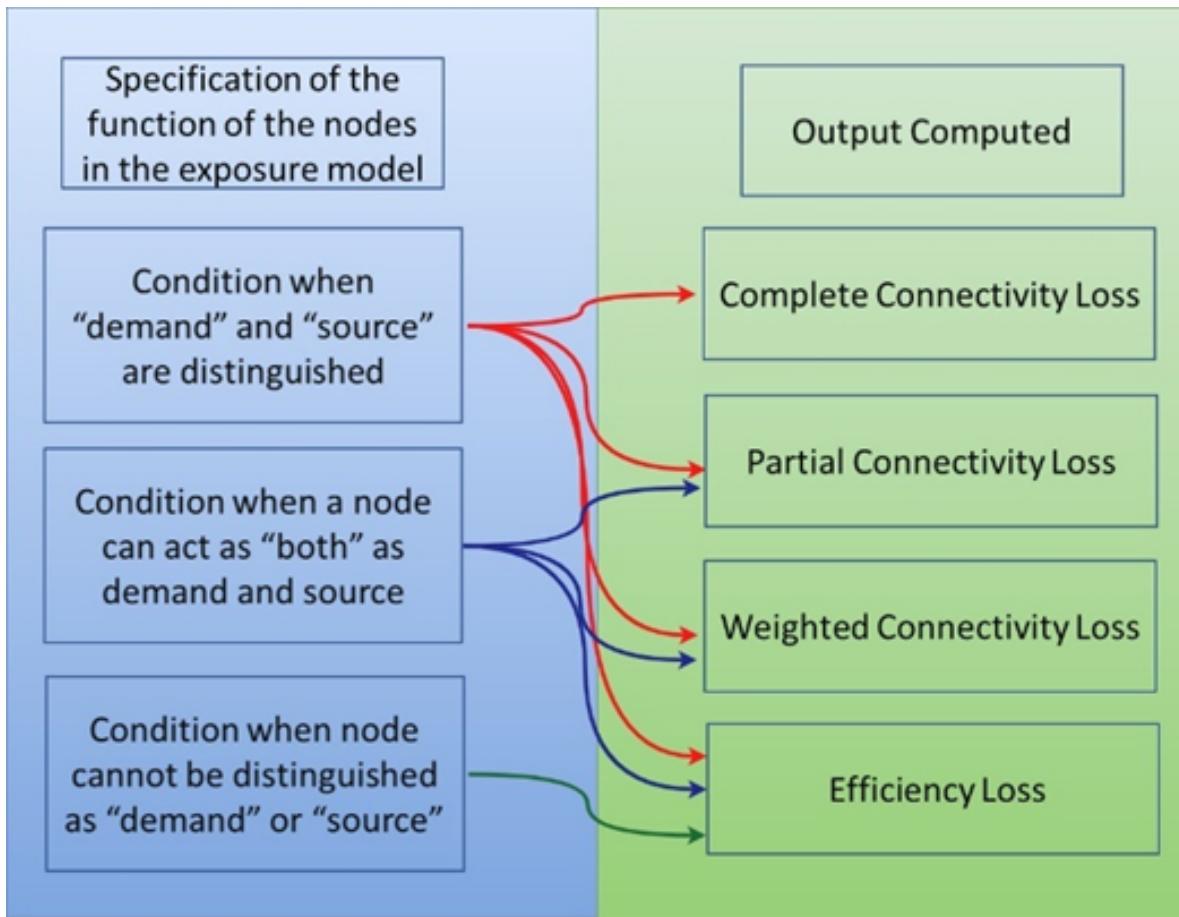


Fig. 3.12: Output computed from the implementation according to the specification of the function of the nodes

Mainly, the library, NetworkX (Aric et al. 2008) has been used during the implementation. Further details can be found in Poudel et al. 2023. Also, much concept during the implementation has been drawn from Pitilakis et al. 2014.

3.1.8.5 References

1. Aric A. Hagberg, Daniel A. Schult and Pieter J. Swart (2008) Exploring network structure, dynamics, and function using NetworkX, in Proceedings of the 7th Python in Science Conference (SciPy2008), Gaël Varoquaux, Travis Vaught, and Jarrod Millman (Eds), (Pasadena, CA USA), pp. 11–15
2. Poudel, A., Pitilakis, K., Silva, V. and Rao, A., (2023). Infrastructure seismic risk assessment: an overview and integration to contemporary open tool towards global usage. Bulletin of Earthquake Engineering. DOI: <https://doi.org/10.1007/s10518-023-01693-z>

3. Pitilakis, K, Franchin P, Khazai B, & Wenzel H, (Eds.) (2014) SYNER-G: systemic seismic vulnerability and risk assessment of complex urban, utility, lifeline systems and critical facilities: methodology and applications (Vol. 31), Springer, DOI: <https://doi.org/10.1007/978-94-017-8835-9>

3.1.8.6 Acknowledgements

The present work has been done in the framework of grant agreement No. 813137 funded by the European Commission ITN-Marie Skłodowska-Curie project “New Challenges for Urban Engineering Seismology (URBASIS-EU)” by Astha Poudel, ESR 4.5 (Aristotle University of Thessaloniki, Université Grenoble Alpes) with the support from Kyriazis Pitilakis, Vitor Silva, Anirudh Rao, and Michele Simionato. Also, we would like to acknowledge the contributors of the SYNER-G project that was funded from the European Community’s 7th Framework Program under grant No. 244061 from which many conceptual frameworks have been built upon.

3.2 Risk Input Models

The following sections describe the basic inputs required for a risk calculation, including exposuremodels, fragilitymodels, consequencemodels, and vulnerabilitymodels. In addition, each risk calculator also requires the appropriate hazard inputs computed in the region of interest. Hazard inputs include hazard curves for the classical probabilistic damage and risk calculators, Ground Motion Field for the scenario damage and risk calculators, or Stochastic Event Sets for the probabilistic event based calculators.

3.2.1 Exposure Models

All risk calculators in the OpenQuake engine require an *Exposure Model* that needs to be provided in the Natural hazards’ Risk Markup Language schema, the use of which is illustrated through several examples in this section. The information included in an *Exposure Model* comprises a metadata section listing general information about the exposure, followed by a cost conversions section that describes how the different areas, costs, and occupancies for the assets will be specified, followed by data regarding each individual asset in the portfolio.

Note: Starting from OpenQuake engine30, the *Exposure Model* may be provided using csv files listing the asset information, along with an xml file containing the metadata section for the exposure model that has been described in the examples above. See Example 8 below for an illustration of an exposure model using csv files.

A simple *Exposure Model* comprising a single asset is shown in *the listing* below.

```
1  <?xml version="1.0" encoding="UTF-8"?>
2  <nrm1 xmlns:gml="http://www.opengis.net/gml"
```

(continues on next page)

(continued from previous page)

```

3   xmlns="http://openquake.org/xmlns/nrml/0.5">
4
5 <exposureModel id="exposure_example"
6   category="buildings"
7   taxonomySource="GEM_Building_Taxonomy_2.0">
8   <description>Exposure Model Example</description>
9
10  <conversions>
11    <costTypes>
12      <costType name="structural" type="per_area" unit="USD" />
13    </costTypes>
14    <area type="per_asset" unit="SQM" />
15  </conversions>
16
17  <assets>
18    <asset id="a1" taxonomy="Adobe" number="5" area="100" >
19      <location lon="-122.000" lat="38.113" />
20      <costs>
21        <cost type="structural" value="10000" />
22      </costs>
23      <occupancies>
24        <occupancy occupants="20" period="day" />
25      </occupancies>
26    </asset>
27  </assets>
28
29 </exposureModel>
30
31 </nrml>
```

Let us take a look at each of the sections in the above example file in turn. The first part of the file contains the metadata section:

```

1  <?xml version="1.0" encoding="UTF-8"?>
2  <nrml xmlns:gml="http://www.opengis.net/gml"
3    xmlns="http://openquake.org/xmlns/nrml/0.5">
4
5  <exposureModel id="exposure_example"
6    category="buildings"
7    taxonomySource="GEM_Building_Taxonomy_2.0">
8    <description>Exposure Model Example</description>
9
10   <conversions>
```

(continues on next page)

(continued from previous page)

```

11 <costTypes>
12   <costType name="structural" type="per_area" unit="USD" />
13 </costTypes>
14   <area type="per_asset" unit="SQM" />
15 </conversions>
16
17 <assets>
18   <asset id="a1" taxonomy="Adobe" number="5" area="100" >
19     <location lon="-122.000" lat="38.113" />
20     <costs>
21       <cost type="structural" value="10000" />
22     </costs>
23     <occupancies>
24       <occupancy occupants="20" period="day" />
25     </occupancies>
26   </asset>
27 </assets>
28
29 </exposureModel>
30
31 </nrml>
```

The information in the metadata section is common to all of the assets in the portfolio and needs to be incorporated at the beginning of every *Exposure Model* file. There are a number of parameters that compose the metadata section, which is intended to provide general information regarding the assets within the *Exposure Model*. These parameters are described below:

- **id**: mandatory; a unique string used to identify the *Exposure Model*. This string can contain letters (a–z; A–Z), numbers (0–9), dashes (–), and underscores (_), with a maximum of 100 characters.
- **category**: an optional string used to define the type of assets being stored (e.g: buildings, lifelines).
- **taxonomySource**: an optional attribute used to define the taxonomy being used to classify the assets.
- **description**: mandatory; a brief string (ASCII) with further information about the *Exposure Model*.

Next, let us look at the part of the file describing the area and cost conversions:

```

1 <?xml version="1.0" encoding="UTF-8"?>
2 <nrml xmlns:gml="http://www.opengis.net/gml"
3   xmlns="http://openquake.org/xmlns/nrml/0.5">
```

(continues on next page)

(continued from previous page)

```

4
5 <exposureModel id="exposure_example"
6   category="buildings"
7   taxonomySource="GEM_Building_Taxonomy_2.0">
8   <description>Exposure Model Example</description>
9
10  <conversions>
11    <costTypes>
12      <costType name="structural" type="per_area" unit="USD" />
13    </costTypes>
14    <area type="per_asset" unit="SQM" />
15  </conversions>
16
17  <assets>
18    <asset id="a1" taxonomy="Adobe" number="5" area="100" >
19      <location lon="-122.000" lat="38.113" />
20      <costs>
21        <cost type="structural" value="10000" />
22      </costs>
23      <occupancies>
24        <occupancy occupants="20" period="day" />
25      </occupancies>
26    </asset>
27  </assets>
28
29 </exposureModel>
30
31 </nrml>
```

Notice that the `costType` element defines a `name`, a `type`, and a `unit` attribute.

The Natural hazards' Risk Markup Language schema for the *Exposure Model* allows the definition of a structural cost, a nonstructural components cost, a contents cost, and a business interruption or downtime cost for each asset in the portfolio. Thus, the valid values for the `name` attribute of the `costType` element are the following:

- `structural`: used to specify the structural replacement cost of assets
- `nonstructural`: used to specify the replacement cost for the nonstructural components of assets
- `contents`: used to specify the contents replacement cost
- `business_interruption`: used to specify the cost that will be incurred per unit time that a damaged asset remains closed following an earthquake

The *Exposure Model* shown in the example above defines only the structural values for the assets. However, multiple cost types can be defined for each asset in the same *Exposure Model*.

The `unit` attribute of the `costType` element is used for specifying the currency unit for the corresponding cost type. Note that the OpenQuake engine itself is agnostic to the currency units; the `unit` is thus a descriptive attribute which is used by the OpenQuake engine to annotate the results of a risk assessment. This attribute can be set to any valid Unicode string.

The `type` attribute of the `costType` element specifies whether the costs will be provided as an aggregated value for an asset, or per building or unit comprising an asset, or per unit area of an asset. The valid values for the `type` attribute of the `costType` element are the following:

- `aggregated`: indicates that the replacement costs will be provided as an aggregated value for each asset
- `per_asset`: indicates that the replacement costs will be provided per structural unit comprising each asset
- `per_area`: indicates that the replacement costs will be provided per unit area for each asset

If the costs are to be specified `per_area` for any of the `costTypes`, the `area` element will also need to be defined in the conversions section. The `area` element defines a `type`, and a `unit` attribute.

The `unit` attribute of the `area` element is used for specifying the units for the area of an asset. The OpenQuake engine itself is agnostic to the area units; the `unit` is thus a descriptive attribute which is used by the OpenQuake engine to annotate the results of a risk assessment. This attribute can be set to any valid ASCII string.

The `type` attribute of the `area` element specifies whether the area will be provided as an aggregated value for an asset, or per building or unit comprising an asset. The valid values for the `type` attribute of the `area` element are the following:

- `aggregated`: indicates that the area will be provided as an aggregated value for each asset
- `per_asset`: indicates that the area will be provided per building or unit comprising each asset

The way the information about the characteristics of the assets in an *Exposure Model* are stored can vary strongly depending on how and why the data was compiled. As an example, if national census information is used to estimate the distribution of assets in a given region, it is likely that the number of buildings within a given geographical area will be used to define the dataset, and will be used for estimating the number of collapsed buildings for a scenario earthquake. On the other hand, if simplified methodologies based on proxy data such as population distribution are used to develop the *Exposure Model*, then it is likely that the built up area or economic cost of each building typology will be directly derived, and will be used for the estimation of economic losses.

Finally, let us look at the part of the file describing the set of assets in the portfolio to be used in seismic damage or risk calculations:

```

1 <?xml version="1.0" encoding="UTF-8"?>
2 <nrm1 xmlns:gml="http://www.opengis.net/gml"
3   xmlns="http://openquake.org/xmlns/nrml/0.5">
4
5 <exposureModel id="exposure_example"
6   category="buildings"
7   taxonomySource="GEM_Building_Taxonomy_2.0">
8   <description>Exposure Model Example</description>
9
10  <conversions>
11    <costTypes>
12      <costType name="structural" type="per_area" unit="USD" />
13    </costTypes>
14    <area type="per_asset" unit="SQM" />
15  </conversions>
16
17  <assets>
18    <asset id="a1" taxonomy="Adobe" number="5" area="100" >
19      <location lon="-122.000" lat="38.113" />
20      <costs>
21        <cost type="structural" value="10000" />
22      </costs>
23      <occupancies>
24        <occupancy occupants="20" period="day" />
25      </occupancies>
26    </asset>
27  </assets>
28
29 </exposureModel>
30
31 </nrm1>
```

Each asset definition involves specifying a set of mandatory and optional attributes concerning the asset. The following set of attributes can be assigned to each asset based on the current schema for the *Exposure Model*:

- **id**: mandatory; a unique string used to identify the given asset, which is used by the Open-Quake engine to relate each asset with its associated results. This string can contain letters (a–z; A–Z), numbers (0–9), dashes (-), and underscores (_), with a maximum of 100 characters.
- **taxonomy**: mandatory; this string specifies the building typology of the given asset. The taxonomy strings can be user-defined, or based on an existing classification scheme such as the GEM Taxonomy, PAGER, or EMS-98.

- **number:** the number of individual structural units comprising a given asset. This attribute is mandatory for damage calculations. For risk calculations, this attribute must be defined if either the area or any of the costs are provided per structural unit comprising each asset.
- **area:** area of the asset, at a given location. As mentioned earlier, the area is a mandatory attribute only if any one of the costs for the asset is specified per unit area.
- **location:** mandatory; specifies the longitude (between -180° to 180°) and latitude (between -90° to 90 °) of the given asset, both specified in decimal degrees².
- **costs:** specifies a set of costs for the given asset. The replacement value for different cost types must be provided on separate lines within the **costs** element. As shown in the example above, each cost entry must define the type and the value. Currently supported valid options for the cost type are: **structural**, **nonstructural**, **contents**, and **business_interruption**.
- **occupancies:** mandatory only for probabilistic or scenario risk calculations that specify an **occupants_vulnerability_file**. Each entry within this element specifies the number of occupants for the asset for a particular period of the day. As shown in the example above, each occupancy entry must define the period and the occupants. Currently supported valid options for the period are: **day**, **transit**, and **night**. Currently, the number of **occupants** for an asset can only be provided as an aggregated value for the asset.

For the purposes of performing a retrofitting benefit/cost analysis, it is also necessary to define the retrofitting cost (**retrofitted**). The combination between the possible options in which these three attributes can be defined leads to four ways of storing the information about the assets. For each of these cases a brief explanation and example is provided in this section.

Example 1

This example illustrates an *Exposure Model* in which the aggregated cost (structural, nonstructural, contents and business interruption) of the assets of each taxonomy for a set of locations is directly provided. Thus, in order to indicate how the various costs will be defined, the following information needs to be stored in the *Exposure Model* file, as shown in *the listing* below.

```

1 <?xml version="1.0" encoding="UTF-8"?>
2 <nrm1 xmlns:gml="http://www.opengis.net/gml"
3   xmlns="http://openquake.org/xmlns/nrml/0.5">
4
5 <exposureModel id="exposure_example"
6   category="buildings"
7   taxonomySource="GEM_Building_Taxonomy_2.0">
8 <description>
9   Exposure model with aggregated replacement costs for each asset
10 </description>
```

(continues on next page)

² Within the OpenQuake engine, longitude and latitude coordinates are internally rounded to a precision of 5 digits after the decimal point.

(continued from previous page)

```

11 <conversions>
12   <costTypes>
13     <costType name="structural" type="aggregated" unit="USD" />
14     <costType name="nonstructural" type="aggregated" unit="USD" />
15     <costType name="contents" type="aggregated" unit="USD" />
16     <costType name="business_interruption" type="aggregated" unit="USD/
17       ↪month"/>
18   </costTypes>
19 </conversions>
20 <assets>
21   <asset id="a1" taxonomy="Adobe" >
22     <location lon="-122.000" lat="38.113" />
23     <costs>
24       <cost type="structural" value="20000" />
25       <cost type="nonstructural" value="30000" />
26       <cost type="contents" value="10000" />
27       <cost type="business_interruption" value="4000" />
28     </costs>
29   </asset>
30 </assets>
31 </exposureModel>
32
</nrml>
```

In this case, the cost type of each component has been defined as aggregated. Once the way in which each cost is going to be defined has been established, the values for each asset can be stored according to the format shown in *the listing*.

```

1  <?xml version="1.0" encoding="UTF-8"?>
2  <nrml xmlns:gml="http://www.opengis.net/gml"
3    xmlns="http://openquake.org/xmlns/nrml/0.5">
4
5  <exposureModel id="exposure_example"
6    category="buildings"
7    taxonomySource="GEM_Building_Taxonomy_2.0">
8    <description>
9      Exposure model with aggregated replacement costs for each asset
10     </description>
11     <conversions>
12       <costTypes>
13         <costType name="structural" type="aggregated" unit="USD" />
14         <costType name="nonstructural" type="aggregated" unit="USD" />
15         <costType name="contents" type="aggregated" unit="USD" />
```

(continues on next page)

(continued from previous page)

```

16   <costType name="business_interruption" type="aggregated" unit="USD/
17   ↪month"/>
18   </costTypes>
19   </conversions>
20   <assets>
21     <asset id="a1" taxonomy="Adobe" >
22       <location lon="-122.000" lat="38.113" />
23       <costs>
24         <cost type="structural" value="20000" />
25         <cost type="nonstructural" value="30000" />
26         <cost type="contents" value="10000" />
27         <cost type="business_interruption" value="4000" />
28       </costs>
29     </asset>
30   </assets>
31 </exposureModel>
32
</nrml>
```

Each asset is uniquely identified by its `id`. Then, a pair of coordinates (latitude and longitude) for a `location` where the asset is assumed to exist is defined. Each asset must be classified according to a `taxonomy`, so that the OpenQuake engine is capable of employing the appropriate *Vulnerability Function* or *Fragility Function* in the risk calculations. Finally, the cost values of each `type` are stored within the `costs` attribute. In this example, the aggregated value for all structural units (within a given asset) at each location is provided directly, so there is no need to define other attributes such as `number` or `area`. This mode of representing an *Exposure Model* is probably the simplest one.

Example 2

In the snippet shown in *the listing* below, an *Exposure Model* containing the number of structural units and the associated costs per unit of each asset is presented.

```

1  <?xml version="1.0" encoding="UTF-8"?>
2  <nrml xmlns:gml="http://www.opengis.net/gml"
3    xmlns="http://openquake.org/xmlns/nrml/0.5">
4
5  <exposureModel id="exposure_example"
6    category="buildings"
7    taxonomySource="GEM_Building_Taxonomy_2.0">
8    <description>
9      Exposure model with replacement costs per building for each asset
10     </description>
11     <conversions>
```

(continues on next page)

(continued from previous page)

```

12 <costTypes>
13   <costType name="structural" type="per_asset" unit="USD" />
14   <costType name="nonstructural" type="per_asset" unit="USD" />
15   <costType name="contents" type="per_asset" unit="USD" />
16   <costType name="business_interruption" type="per_asset" unit="USD/
17   ↪month"/>
18 </costTypes>
19 </conversions>
20 <assets>
21   <asset id="a1" number="2" taxonomy="Adobe" >
22     <location lon="-122.000" lat="38.113" />
23     <costs>
24       <cost type="structural" value="7500" />
25       <cost type="nonstructural" value="11250" />
26       <cost type="contents" value="3750" />
27       <cost type="business_interruption" value="1500" />
28     </costs>
29   </asset>
30 </assets>
31 </exposureModel>
32 </nrml>
```

For this case, the cost type has been set to per_asset. Then, the information from each asset can be stored following the format shown in *the listing* below.

```

1 <?xml version="1.0" encoding="UTF-8"?>
2 <nrml xmlns:gml="http://www.opengis.net/gml"
3   xmlns="http://openquake.org/xmlns/nrml/0.5">
4
5 <exposureModel id="exposure_example"
6   category="buildings"
7   taxonomySource="GEM_Building_Taxonomy_2.0">
8   <description>
9     Exposure model with replacement costs per building for each asset
10    </description>
11    <conversions>
12      <costTypes>
13        <costType name="structural" type="per_asset" unit="USD" />
14        <costType name="nonstructural" type="per_asset" unit="USD" />
15        <costType name="contents" type="per_asset" unit="USD" />
16        <costType name="business_interruption" type="per_asset" unit="USD/
17        ↪month"/>
```

(continues on next page)

(continued from previous page)

```

17   </costTypes>
18   </conversions>
19   <assets>
20     <asset id="a1" number="2" taxonomy="Adobe" >
21       <location lon="-122.000" lat="38.113" />
22       <costs>
23         <cost type="structural" value="7500" />
24         <cost type="nonstructural" value="11250" />
25         <cost type="contents" value="3750" />
26         <cost type="business_interruption" value="1500" />
27       </costs>
28     </asset>
29   </assets>
30 </exposureModel>
31
32 </nrml>
```

In this example, the various costs for each asset is not provided directly, as in the previous example. In order to carry out the risk calculations in which the economic cost of each asset is provided, the OpenQuake engine multiplies, for each asset, the number of units (buildings) by the “per asset” replacement cost. Note that in this case, there is no need to specify the attribute area.

Example 3

The example shown in *the listing* below comprises an *Exposure Model* containing the built up area of each asset, and the associated costs are provided per unit area.

```

1  <?xml version="1.0" encoding="UTF-8"?>
2  <nrml xmlns:gml="http://www.opengis.net/gml"
3    xmlns="http://openquake.org/xmlns/nrml/0.5">
4
5  <exposureModel id="exposure_example"
6    category="buildings"
7    taxonomySource="GEM_Building_Taxonomy_2.0">
8    <description>
9      Exposure model with replacement costs per unit area;
10     and areas provided as aggregated values for each asset
11    </description>
12    <conversions>
13      <area type="aggregated" unit="SQM" />
14      <costTypes>
15        <costType name="structural" type="per_area" unit="USD" />
16        <costType name="nonstructural" type="per_area" unit="USD" />
17        <costType name="contents" type="per_area" unit="USD" />
```

(continues on next page)

(continued from previous page)

```

18   <costType name="business_interruption" type="per_area" unit="USD/
19     ↪month"/>
20   </costTypes>
21 </conversions>
22 <assets>
23   <asset id="a1" area="1000" taxonomy="Adobe" >
24     <location lon="-122.000" lat="38.113" />
25     <costs>
26       <cost type="structural" value="5" />
27       <cost type="nonstructural" value="7.5" />
28       <cost type="contents" value="2.5" />
29       <cost type="business_interruption" value="1" />
30     </costs>
31   </asset>
32 </assets>
33 </exposureModel>
34

```

In order to compile an *Exposure Model* with this structure, the cost type should be set to `per_area`. In addition, it is also necessary to specify if the area that is being stored represents the aggregated area of number of units within an asset, or the average area of a single unit. In this particular case, the area that is being stored is the aggregated built up area per asset, and thus this attribute was set to aggregated. *The listing* below illustrates the definition of the assets for this example.

```

1  <?xml version="1.0" encoding="UTF-8"?>
2  <nrm1 xmlns:gml="http://www.opengis.net/gml"
3    xmlns="http://openquake.org/xmlns/nrml/0.5">
4
5  <exposureModel id="exposure_example"
6    category="buildings"
7    taxonomySource="GEM_Building_Taxonomy_2.0">
8    <description>
9      Exposure model with replacement costs per unit area;
10     and areas provided as aggregated values for each asset
11   </description>
12   <conversions>
13     <area type="aggregated" unit="SQM" />
14     <costTypes>
15       <costType name="structural" type="per_area" unit="USD" />
16       <costType name="nonstructural" type="per_area" unit="USD" />
17       <costType name="contents" type="per_area" unit="USD" />
18       <costType name="business_interruption" type="per_area" unit="USD/

```

(continues on next page)

(continued from previous page)

```

19   ↵month"/>
20   </costTypes>
21 </conversions>
22 <assets>
23   <asset id="a1" area="1000" taxonomy="Adobe" >
24     <location lon="-122.000" lat="38.113" />
25     <costs>
26       <cost type="structural" value="5" />
27       <cost type="nonstructural" value="7.5" />
28       <cost type="contents" value="2.5" />
29       <cost type="business_interruption" value="1" />
30     </costs>
31   </asset>
32 </assets>
33 </exposureModel>
34
</nrml>
```

Once again, the OpenQuake engine needs to carry out some calculations in order to compute the different costs per asset. In this case, this value is computed by multiplying the aggregated built up area of each asset by the associated cost per unit area. Notice that in this case, there is no need to specify the attribute `number`.

Example 4

This example demonstrates an *Exposure Model* that defines the number of structural units for each asset, the average built up area per structural unit and the associated costs per unit area. *The listing* below shows the metadata definition for an *Exposure Model* built in this manner.

```

1 <?xml version="1.0" encoding="UTF-8"?>
2 <nrml xmlns:gml="http://www.opengis.net/gml"
3   xmlns="http://openquake.org/xmlns/nrml/0.5">
4
5 <exposureModel id="exposure_example"
6   category="buildings"
7   taxonomySource="GEM_Building_Taxonomy_2.0">
8   <description>
9     Exposure model with replacement costs per unit area;
10    and areas provided per building for each asset
11  </description>
12  <conversions>
13    <area type="per_asset" unit="SQM" />
14    <costTypes>
15      <costType name="structural" type="per_area" unit="USD" />
```

(continues on next page)

(continued from previous page)

```

16   <costType name="nonstructural" type="per_area" unit="USD" />
17   <costType name="contents" type="per_area" unit="USD" />
18   <costType name="business_interruption" type="per_area" unit="USD/
19   ↵month"/>
20   </costTypes>
21 </conversions>
22 <assets>
23   <asset id="a1" number="3" area="400" taxonomy="Adobe" >
24     <location lon="-122.000" lat="38.113" />
25     <costs>
26       <cost type="structural" value="10" />
27       <cost type="nonstructural" value="15" />
28       <cost type="contents" value="5" />
29       <cost type="business_interruption" value="2" />
30     </costs>
31   </asset>
32 </assets>
33 </exposureModel>
34
</nrml>
```

Similarly to what was described in the previous example, the various costs type also need to be established as per_area, but the type of area is now defined as per_asset. *The listing* below illustrates the definition of the assets for this example.

```

1 <?xml version="1.0" encoding="UTF-8"?>
2 <nrml xmlns:gml="http://www.opengis.net/gml"
3   xmlns="http://openquake.org/xmlns/nrml/0.5">
4
5 <exposureModel id="exposure_example"
6   category="buildings"
7   taxonomySource="GEM_Building_Taxonomy_2.0">
8 <description>
9   Exposure model with replacement costs per unit area;
10  and areas provided per building for each asset
11 </description>
12 <conversions>
13   <area type="per_asset" unit="SQM" />
14   <costTypes>
15     <costType name="structural" type="per_area" unit="USD" />
16     <costType name="nonstructural" type="per_area" unit="USD" />
17     <costType name="contents" type="per_area" unit="USD" />
18     <costType name="business_interruption" type="per_area" unit="USD/
```

(continues on next page)

(continued from previous page)

```

19   ↵month"/>
20   </costTypes>
21 </conversions>
22 <assets>
23   <asset id="a1" number="3" area="400" taxonomy="Adobe" >
24     <location lon="-122.000" lat="38.113" />
25     <costs>
26       <cost type="structural" value="10" />
27       <cost type="nonstructural" value="15" />
28       <cost type="contents" value="5" />
29       <cost type="business_interruption" value="2" />
30     </costs>
31   </asset>
32 </assets>
33 </exposureModel>
34
</nrml>
```

In this example, the OpenQuake engine will make use of all the parameters to estimate the various costs of each asset, by multiplying the number of structural units by its average built up area, and then by the respective cost per unit area.

Example 5

In this example, additional information will be included, which is required for other risk analysis besides loss estimation, such as the benefit/cost analysis.

In order to perform a benefit/cost assessment, it is necessary to indicate the retrofitting cost. This parameter is handled in the same manner as the structural cost, and it should be stored according to the format shown in *the listing* below.

```

1  <?xml version="1.0" encoding="UTF-8"?>
2  <nrml xmlns:gml="http://www.opengis.net/gml"
3    xmlns="http://openquake.org/xmlns/nrml/0.5">
4
5  <exposureModel id="exposure_example"
6    category="buildings"
7    taxonomySource="GEM_Building_Taxonomy_2.0">
8    <description>Exposure model illustrating retrofit costs</description>
9    <conversions>
10   <costTypes>
11     <costType name="structural" type="aggregated" unit="USD"
12       retrofittedType="per_asset" retrofittedUnit="USD" />
13   </costTypes>
```

(continues on next page)

(continued from previous page)

```

14 </conversions>
15 <assets>
16   <asset id="a1" taxonomy="Adobe" number="1" >
17     <location lon="-122.000" lat="38.113" />
18     <costs>
19       <cost type="structural" value="10000" retrofitted="2000" />
20     </costs>
21   </asset>
22 </assets>
23 </exposureModel>
24
25 </nrml>

```

Despite the fact that for the demonstration of how the retrofitting cost can be stored the per building type of cost structure described in Example 1 was used, it is important to mention that any of the other cost storing approaches can also be employed (Examples 2–4).

Example 6

The OpenQuake engine is also capable of estimating human losses, based on the number of occupants in an asset, at a certain time of the day. The example *Exposure Model* shown in *the listing* below illustrates how this parameter is defined for each asset. In addition, this example also serves the purpose of presenting an *Exposure Model* in which three cost types have been defined using three different options.

As previously mentioned, in this example only three costs are being stored, and each one follows a different approach. The **structural** cost is being defined as the aggregate replacement cost for all of the buildings comprising the asset (Example 1), the **nonstructural** value is defined as the replacement cost per unit area where the area is defined per building comprising the asset (Example 4), and the **contents** and **business_interruption** values are provided per building comprising the asset (Example 2). The number of occupants at different times of the day are also provided as aggregated values for all of the buildings comprising the asset.

```

1 <?xml version="1.0" encoding="UTF-8"?>
2 <nrml xmlns:gml="http://www.opengis.net/gml"
3   xmlns="http://openquake.org/xmlns/nrml/0.5">
4
5   <exposureModel id="exposure_example"
6     category="buildings"
7     taxonomySource="GEM_Building_Taxonomy_2.0">
8     <description>Exposure model example with occupants</description>
9     <conversions>
10    <costTypes>
11      <costType name="structural" type="aggregated" unit="USD" />

```

(continues on next page)

(continued from previous page)

```

12   <costType name="nonstructural" type="per_area" unit="USD" />
13   <costType name="contents" type="per_asset" unit="USD" />
14   <costType name="business_interruption" type="per_asset" unit="USD/
15   ↵month" />
16   </costTypes>
17   <area type="per_asset" unit="SQM" />
18 </conversions>
19 <assets>
20   <asset id="a1" taxonomy="Adobe" number="5" area="200" >
21     <location lon="-122.000" lat="38.113" />
22     <costs>
23       <cost type="structural" value="20000" />
24       <cost type="nonstructural" value="15" />
25       <cost type="contents" value="2400" />
26       <cost type="business_interruption" value="1500" />
27     </costs>
28     <occupancies>
29       <occupancy occupants="6" period="day" />
30       <occupancy occupants="10" period="transit" />
31       <occupancy occupants="20" period="night" />
32     </occupancies>
33   </asset>
34 </assets>
35 </exposureModel>
36

```

Example 7

Starting from OpenQuake engine27, the user may also provide a set of tags for each asset in the *Exposure Model*. The primary intended use case for the tags is to enable aggregation or accumulation of risk results (casualties / damages / losses) for each tag. The tags could be used to specify location attributes, occupancy types, or insurance policy codes for the different assets in the *Exposure Model*.

The example *Exposure Model* shown in *the listing* below illustrates how one or more tags can be defined for each asset.

```

1  <?xml version="1.0" encoding="UTF-8"?>
2  <nrm1 xmlns:gml="http://www.opengis.net/gml"
3    xmlns="http://openquake.org/xmlns/nrml/0.5">
4
5  <exposureModel id="exposure_example_with_tags"
6    category="buildings"

```

(continues on next page)

(continued from previous page)

```

7      taxonomySource="GEM_Building_Taxonomy_2.0">
8 <description>Exposure Model Example with Tags</description>
9
10 <conversions>
11   <costTypes>
12     <costType name="structural" type="per_area" unit="USD" />
13   </costTypes>
14   <area type="per_asset" unit="SQM" />
15 </conversions>
16
17 <tagNames>state county tract city zip cresta</tagNames>
18
19 <assets>
20   <asset id="a1" taxonomy="Adobe" number="5" area="100" >
21     <location lon="-122.000" lat="38.113" />
22     <costs>
23       <cost type="structural" value="10000" />
24     </costs>
25     <occupancies>
26       <occupancy occupants="20" period="day" />
27     </occupancies>
28     <tags state="California" county="Solano" tract="252702"
29           city="Suisun" zip="94585" cresta="A.11"/>
30   </asset>
31 </assets>
32
33 </exposureModel>
34
35 </nrml>
```

The list of tag names that will be used in the *Exposure Model* must be provided in the metadata section of the exposure file, as shown in the following snippet from the full file:

```

1 <?xml version="1.0" encoding="UTF-8"?>
2 <nrml xmlns:gml="http://www.opengis.net/gml"
3   xmlns="http://openquake.org/xmlns/nrml/0.5">
4
5 <exposureModel id="exposure_example_with_tags"
6   category="buildings"
7   taxonomySource="GEM_Building_Taxonomy_2.0">
8 <description>Exposure Model Example with Tags</description>
9
10 <conversions>
```

(continues on next page)

(continued from previous page)

```

11 <costTypes>
12   <costType name="structural" type="per_area" unit="USD" />
13 </costTypes>
14   <area type="per_asset" unit="SQM" />
15 </conversions>

16
17 <tagNames>state county tract city zip cresta</tagNames>
18

19 <assets>
20   <asset id="a1" taxonomy="Adobe" number="5" area="100" >
21     <location lon="-122.000" lat="38.113" />
22     <costs>
23       <cost type="structural" value="10000" />
24     </costs>
25     <occupancies>
26       <occupancy occupants="20" period="day" />
27     </occupancies>
28     <tags state="California" county="Solano" tract="252702"
29       city="Suisun" zip="94585" cresta="A.11"/>
30   </asset>
31 </assets>

32
33 </exposureModel>
34
35 </nrml>
```

The tag values for the different tags can then be specified for each asset as shown in the following snippet from the same file:

```

1 <?xml version="1.0" encoding="UTF-8"?>
2 <nrml xmlns:gml="http://www.opengis.net/gml"
3   xmlns="http://openquake.org/xmlns/nrml/0.5">
4
5 <exposureModel id="exposure_example_with_tags"
6   category="buildings"
7   taxonomySource="GEM_Building_Taxonomy_2.0">
8   <description>Exposure Model Example with Tags</description>
9
10  <conversions>
11    <costTypes>
12      <costType name="structural" type="per_area" unit="USD" />
13    </costTypes>
14    <area type="per_asset" unit="SQM" />
```

(continues on next page)

(continued from previous page)

```

15 </conversions>

16
17 <tagNames>state county tract city zip cresta</tagNames>

18
19 <assets>
20   <asset id="a1" taxonomy="Adobe" number="5" area="100" >
21     <location lon="-122.000" lat="38.113" />
22     <costs>
23       <cost type="structural" value="10000" />
24     </costs>
25     <occupancies>
26       <occupancy occupants="20" period="day" />
27     </occupancies>
28     <tags state="California" county="Solano" tract="252702"
29           city="Suisun" zip="94585" cresta="A.11"/>
30   </asset>
31 </assets>

32
33 </exposureModel>

34
35 </nrml>
```

Note that it is not mandatory that every tag name specified in the metadata section must be provided with a tag value for each asset.

Example 8

This example illustrates the use of multiple csv files containing the assets information, in conjunction with the metadata section in the usual xml format.

Let us take a look at the metadata section of the *Exposure Model*, which is listed as usual in an xml file:

```

1  <?xml version="1.0" encoding="UTF-8"?>
2  <nrml xmlns:gml="http://www.opengis.net/gml"
3    xmlns="http://openquake.org/xmlns/nrml/0.5">
4
5  <exposureModel id="exposure_example_with_csv_files"
6    category="buildings"
7    taxonomySource="GEM_Building_Taxonomy_3.0">
8    <description>Exposure Model Example with CSV Files</description>
9
10   <conversions>
11     <costTypes>
```

(continues on next page)

(continued from previous page)

```
12 <costType name="structural" type="aggregated" unit="USD" />
13 <costType name="nonstructural" type="aggregated" unit="USD" />
14 <costType name="contents" type="aggregated" unit="USD" />
15 </costTypes>
16 <area type="per_asset" unit="SQFT" />
17 </conversions>
18
19 <occupancyPeriods>night</occupancyPeriods>
20
21 <tagNames>occupancy state_id state county_id county tract</tagNames>
22
23 <assets>
24   Washington.csv
25   Oregon.csv
26   California.csv
27 </assets>
28
29 </exposureModel>
30
31 </nrml>
```

As in all previous examples, the information in the metadata section is common to all of the assets in the portfolio.

The asset data can be provided in one or more csv files. The path to each of the csv files containing the asset data must be listed between the `<assets>` and `</assets>` xml tags.

In the example shown above, the exposure information is provided in three csv files, Washington.csv, Oregon.csv, and California.csv. To illustrate the format of the csv files, we have shown below the header and first few lines of the file Washington.csv in [Table 3.1](#).

Table 3.1: Example exposure csv file

id	lon	lat	taxonomy	num-ber	struc-tural	area	occu-pancy	state	county
A1	-122.7	46.5	AGR1-W1-LC	7.6	898000	18	Agr	Washington	Lewis County
A2	-122.7	46.5	AGR1-PC1-LC	0.6	67000	1	Agr	Washington	Lewis County
A3	-122.7	46.5	AGR1-C2L-PC	0.6	67000	1	Agr	Washington	Lewis County
A4	-122.7	46.5	AGR1-PC1-PC	1.5	179000	4	Agr	Washington	Lewis County
A5	-122.7	46.5	AGR1-S2L-LC	0.6	67000	1	Agr	Washington	Lewis County
A6	-122.7	46.5	AGR1-S1L-PC	1.1	133000	3	Agr	Washington	Lewis County
A7	-122.7	46.5	AGR1-S2L-PC	1.5	182000	4	Agr	Washington	Lewis County
A8	-122.7	46.5	AGR1-S3-PC	1.1	133000	3	Agr	Washington	Lewis County
A9	-122.7	46.5	AGR1-RM1L-LC	0.6	68000	1	Agr	Washington	Lewis County

Note that the xml metadata section for exposure models provided using csv files must include the xml tag `<occupancyPeriods>` listing the periods of day for which the number of occupants in each asset will be listed in the csv files. In case the number of occupants are not listed in the csv files, a self-closing tag `<occupancyPeriods />` should be included in the xml metadata section.

A web-based tool to build an *Exposure Model* in the Natural hazards' Risk Markup Language schema starting from a csv file or a spreadsheet can be found at the OpenQuake platform at the following address: <https://platform.openquake.org/ipt/>.

3.2.2 Fragility Models

This section describes the schema currently used to store fragilitymodels, which are required for the Scenario Damage Calculator and the Classical Probabilistic Seismic Damage Calculator. In order to perform probabilistic or scenario damage calculations, it is necessary to define a *Fragility Function* for each building typology present in the *Exposure Model*. A *Fragility Model* defines a set of fragilityfunctions, describing the probability of exceeding a set of limit, or damage, states. The fragilityfunctions can be defined using either a discrete or a continuous format, and the *Fragility Model* file can include a mix of both types of fragilityfunctions.

For discrete fragilityfunctions, sets of probabilities of exceedance (one set per limit state) are defined for a list of intensity measure levels, as illustrated in Fig. 3.13.

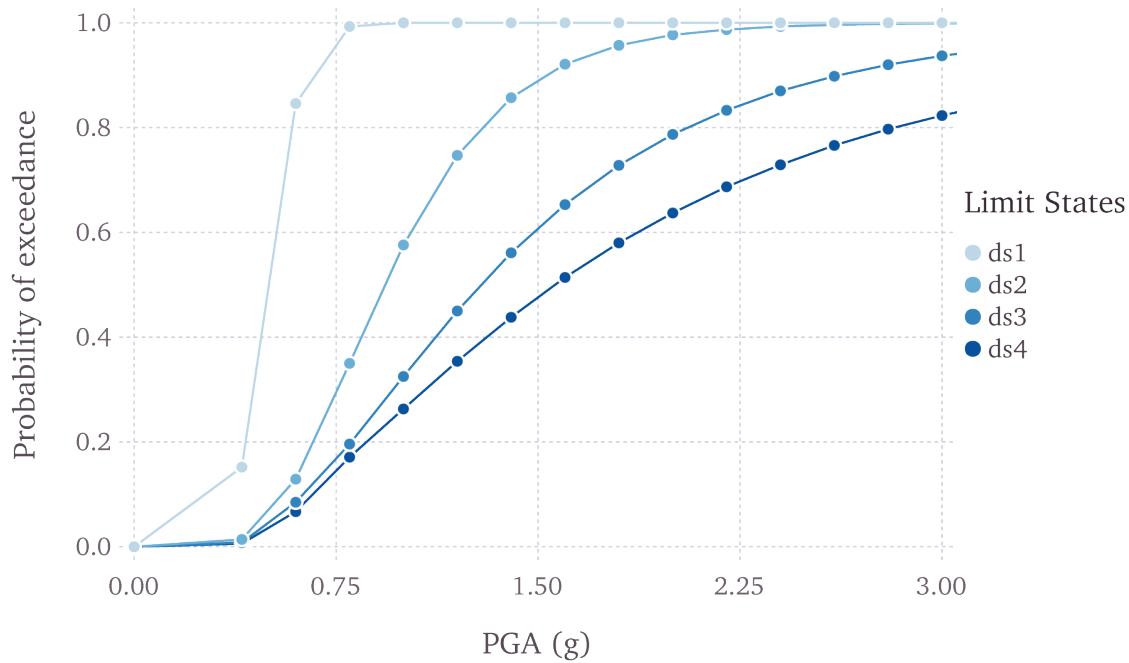


Fig. 3.13: Graphical representation of a discrete fragility model

The fragility functions can also be defined as continuous functions, through the use of cumulative lognormal distribution functions. In Fig. 3.14, a continuous *Fragility Model* is presented.

An example *Fragility Model* comprising one discrete *Fragility Function* and one continuous *Fragility Function* is shown in *the listing* below.

```

1 <?xml version="1.0" encoding="UTF-8"?>
2 <nrm1 xmlns="http://openquake.org/xmlns/nrml/0.5">
3
4 <fragilityModel id="fragility_example"
5   assetCategory="buildings"
6   lossCategory="structural">
7
8   <description>Fragility Model Example</description>
9   <limitStates>slight moderate extensive complete</limitStates>
10
11   <fragilityFunction id="Woodframe_TwoStorey" format="discrete">
12     <imls imt="PGA" noDamageLimit="0.05">0.005 0.2 0.4 0.6 0.8 1.0 1.2</
13     <imls>
14       <poes ls="slight">0.00 0.01 0.15 0.84 0.99 1.00 1.00</poes>
15       <poes ls="moderate">0.00 0.00 0.01 0.12 0.35 0.57 0.74</poes>
         <poes ls="extensive">0.00 0.00 0.00 0.08 0.19 0.32 0.45</poes>

```

(continues on next page)

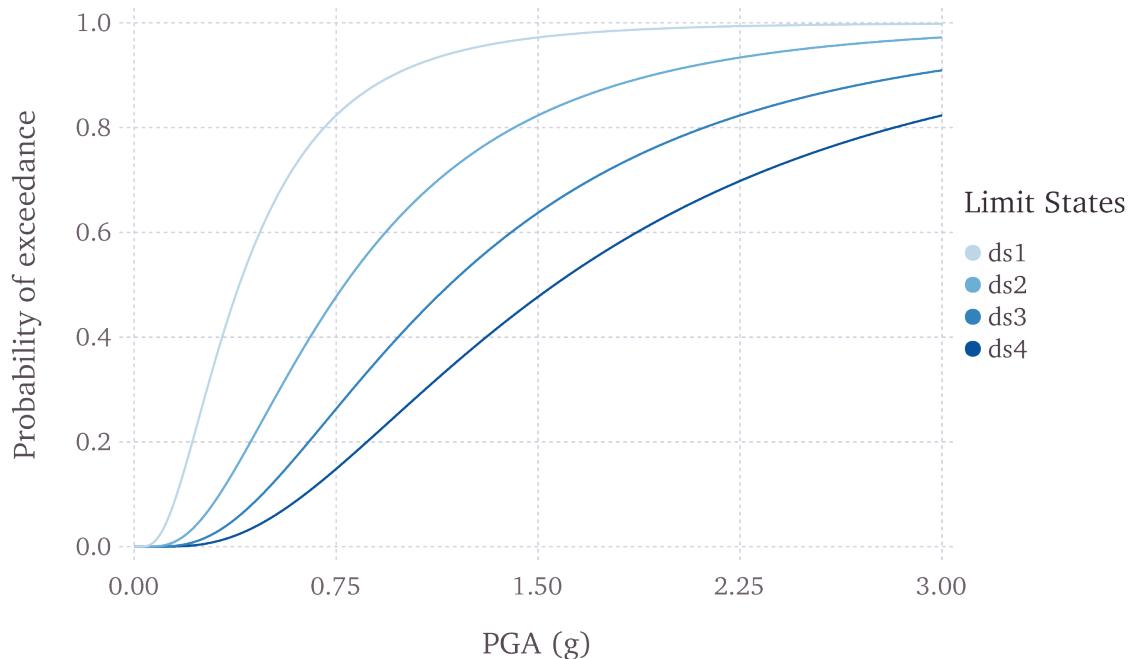


Fig. 3.14: Graphical representation of a continuous fragility model

(continued from previous page)

```

16   <poes ls="complete">0.00 0.00 0.00 0.06 0.17 0.26 0.35</poes>
17 </fragilityFunction>

18
19 <fragilityFunction id="RC_LowRise" format="continuous" shape="logncdf">
20   <imls imt="SA(0.3)" noDamageLimit="0.05" minIML="0.0" maxIML="5.0"/>
21   <params ls="slight" mean="0.50" stddev="0.10"/>
22   <params ls="moderate" mean="1.00" stddev="0.40"/>
23   <params ls="extensive" mean="1.50" stddev="0.90"/>
24   <params ls="complete" mean="2.00" stddev="1.60"/>
25 </fragilityFunction>

26
27 </fragilityModel>
28
29 </nrml>
```

The initial portion of the schema contains general information that describes some general aspects of the *Fragility Model*. The information in this metadata section is common to all of the functions in the *Fragility Model* and needs to be included at the beginning of every *Fragility Model* file. The parameters of the metadata section are shown in *the snippet* below and described after the snippet:

```

4 <fragilityModel id="fragility_example"
5   assetCategory="buildings"
6   lossCategory="structural">
7
8   <description>Fragility Model Example</description>
9   <limitStates>slight moderate extensive complete</limitStates>

```

- **id**: mandatory; a unique string used to identify the *Fragility Model*. This string can contain letters (a–z; A–Z), numbers (0–9), dashes (-), and underscores (_), with a maximum of 100 characters.
- **assetCategory**: an optional string used to specify the type of assets for which fragility-functions will be defined in this file (e.g: buildings, lifelines).
- **lossCategory**: mandatory; valid strings for this attribute are “structural”, “nonstructural”, “contents”, and “business_interruption”.
- **description**: mandatory; a brief string (ASCII) with further relevant information about the *Fragility Model*, for example, which building typologies are covered or the source of the functions in the *Fragility Model*.
- **limitStates**: mandatory; this field is used to define the number and nomenclature of each limit state. Four limit states are employed in the example above, but it is possible to use any number of discrete states, as long as a fragility curve is always defined for each limit state. The limit states must be provided as a set of strings separated by whitespaces between each limit state. Each limit state string can contain letters (a–z; A–Z), numbers (0–9), dashes (-), and underscores (_). Please ensure that there is no whitespace within the name of any individual limit state.

The following snippet from the above *Fragility Model example file* defines a discrete *Fragility Function*:

```

19 <fragilityFunction id="Woodframe_TwoStorey" format="discrete">
20   <imls imt="PGA" noDamageLimit="0.05">0.005 0.2 0.4 0.6 0.8 1.0 1.2</
21   <imls>
22     <poes ls="slight">0.00 0.01 0.15 0.84 0.99 1.00 1.00</poes>
23     <poes ls="moderate">0.00 0.00 0.01 0.12 0.35 0.57 0.74</poes>
24     <poes ls="extensive">0.00 0.00 0.00 0.08 0.19 0.32 0.45</poes>
25     <poes ls="complete">0.00 0.00 0.00 0.06 0.17 0.26 0.35</poes>
</fragilityFunction>

```

The following attributes are needed to define a discrete *Fragility Function*:

- **id**: mandatory; a unique string used to identify the taxonomy for which the function is being defined. This string is used to relate the *Fragility Function* with the relevant asset in the *Exposure Model*. This string can contain letters (a–z; A–Z), numbers (0–9), dashes (-), and underscores (_), with a maximum of 100 characters.

- **format:** mandatory; for discrete fragilityfunctions, this attribute should be set to “discrete”.
- **imls:** mandatory; this attribute specifies the list of intensity levels for which the limit state probabilities of exceedance will be defined. In addition, it is also necessary to define the intensity measure type (**imt**). Optionally, a **noDamageLimit** can be specified, which defines the intensity level below which the probability of exceedance for all limit states is taken to be zero.
- **poes:** mandatory; this field is used to define the probabilities of exceedance (**poes**) for each limit state for each discrete *Fragility Function*. It is also necessary to specify which limit state the exceedance probabilities are being defined for using the attribute **ls**. The probabilities of exceedance for each limit state must be provided on a separate line; and the number of exceedance probabilities for each limit state defined by the **poes** attribute must be equal to the number of intensity levels defined by the attribute **imls**. Finally, the number and names of the limit states in each fragility function must be equal to the number of limit states defined earlier in the metadata section of the *Fragility Model* using the attribute **limitStates**.

The following snippet from the above *Fragility Model example file* defines a continuous *Fragility Function*:

```

11 <fragilityFunction id="RC_LowRise" format="continuous" shape="logncdf">
12   <imls imt="SA(0.3)" noDamageLimit="0.05" minIML="0.0" maxIML="5.0"/>
13   <params ls="slight" mean="0.50" stddev="0.10"/>
14   <params ls="moderate" mean="1.00" stddev="0.40"/>
15   <params ls="extensive" mean="1.50" stddev="0.90"/>
16   <params ls="complete" mean="2.00" stddev="1.60"/>
17 </fragilityFunction>
```

The following attributes are needed to define a continuous *Fragility Function*:

- **id:** mandatory; a unique string used to identify the taxonomy for which the function is being defined. This string is used to relate the *Fragility Function* with the relevant asset in the *Exposure Model*. This string can contain letters (a–z; A–Z), numbers (0–9), dashes (-), and underscores (_), with a maximum of 100 characters.
- **format:** mandatory; for continuous fragilityfunctions, this attribute should be set to “continuous”.
- **shape:** mandatory; for continuous fragilityfunctions using the lognormal cumulative distribution, this attribute should be set to “logncdf”. At present, only the lognormal cumulative distribution function can be used for representing continuous fragilityfunctions.
- **imls:** mandatory; this element specifies aspects related to the intensity measure used by the the *Fragility Function*. The range of intensity levels for which the continuous fragilityfunctions are valid is specified using the attributes **minIML** and **maxIML**. In addition, it is also necessary to define the intensity measure type **imt**. Optionally, a **noDamageLimit** can be specified, which defines the intensity level below which the probability of exceedance for all

limit states is taken to be zero.

- **params**: mandatory; this field is used to define the parameters of the continuous curve for each limit state for this *Fragility Function*. For a lognormal cumulative distribution function, the two parameters required to specify the function are the mean and standard deviation of the intensity level. These parameters are defined for each limit state using the attributes `mean` and `stddev` respectively. The attribute `ls` specifies the limit state for which the parameters are being defined. The parameters for each limit state must be provided on a separate line. The number and names of the limit states in each *Fragility Function* must be equal to the number of limit states defined earlier in the metadata section of the *Fragility Model* using the attribute `limitStates`. A point worth clarifying is that the parameters to be defined in the fragility input file are the mean and standard deviation of the intensity measure level (IML) for each damage state, and not the mean and standard deviation of log(IML). Thus, if the intensity measure is PGA or SA for instance, the units for the input parameters will be 'g'.

Note that the schema for representing fragilitymodels has changed between Natural hazards' Risk Markup Language v0.4 (used prior to OpenQuake engine17) and Natural hazards' Risk Markup Language v0.5 (introduced in OpenQuake engine17).

A deprecation warning is printed every time you attempt to use a *Fragility Model* in the old Natural hazards' Risk Markup Language v0.4 format in an OpenQuake engine17 (or later) risk calculation. To get rid of the warning you must upgrade the old fragilitymodels files to Natural hazards' Risk Markup Language v0.5. You can use the command `upgrade_nrml` with oq to do this as follows:

```
user@ubuntu:~$ oq upgrade_nrml <directory-name>
```

The above command will upgrade all of your old *Fragility Model* files to Natural hazards' Risk Markup Language v0.5. The original files will be kept, but with a .bak extension appended. Notice that you will need to set the `lossCategory` attribute to its correct value manually. This is easy to do, since if you try to run a computation you will get a clear error message telling the expected value for the `lossCategory` for each file.

Several methodologies to derive fragilityfunctions are currently being evaluated by GEM Foundation and have been included as part of the Risk Modeller's Toolkit, the code for which can be found on a public repository at GitHub at the following address: <http://github.com/gemscientcetools/rmtk>.

A web-based tool to build a *Fragility Model* in the Natural hazards' Risk Markup Language schema are also under development, and can be found at the OpenQuake platform at the following address: <https://platform.openquake.org/ipt/>.

3.2.3 Consequence Models

Starting from OpenQuake engine17, the Scenario Damage calculator also accepts consequence models in addition to fragility models, in order to estimate consequences based on the calculated damage distribution. The user may provide one *Consequence Model* file corresponding to each loss type (amongst structural, nonstructural, contents, and business interruption) for which a *Fragility Model* file is provided. Whereas providing a *Fragility Model* file for at least one loss type is mandatory for running a Scenario Damage calculation, providing corresponding *Consequence Model* files is optional.

This section describes the schema currently used to store consequencemodels, which are optional inputs for the Scenario Damage Calculator. A *Consequence Model* defines a set of consequence-functions, describing the distribution of the loss (or consequence) ratio conditional on a set of discrete limit (or damage) states. These *Consequence Function* can be currently defined in OpenQuake engine by specifying the parameters of the continuous distribution of the loss ratio for each limit state specified in the fragility model for the corresponding loss type, for each taxonomy defined in the exposure model.

An example *Consequence Model* is shown in *the listing* below.

```

1  <?xml version="1.0" encoding="UTF-8"?>
2  <nrm1 xmlns="http://openquake.org/xmlns/nrml/0.5">
3
4  <consequenceModel id="consequence_example"
5      assetCategory="buildings"
6      lossCategory="structural">
7
8      <description>Consequence Model Example</description>
9      <limitStates>slight moderate extensive complete</limitStates>
10
11     <consequenceFunction id="RC_LowRise" dist="LN">
12         <params ls="slight" mean="0.04" stddev="0.00"/>
13         <params ls="moderate" mean="0.16" stddev="0.00"/>
14         <params ls="extensive" mean="0.32" stddev="0.00"/>
15         <params ls="complete" mean="0.64" stddev="0.00"/>
16     </consequenceFunction>
17
18 </consequenceModel>
19
20 </nrm1>
```

The initial portion of the schema contains general information that describes some general aspects of the *Consequence Model*. The information in this metadata section is common to all of the functions in the *Consequence Model* and needs to be included at the beginning of every *Consequence Model* file. The parameters are described below:

- **id**: a unique string used to identify the *Consequence Model*. This string can contain letters (a–z; A–Z), numbers (0–9), dashes (-), and underscores (_), with a maximum of 100 characters.
- **assetCategory**: an optional string used to specify the type of assets for which consequence-functions will be defined in this file (e.g: buildings, lifelines).
- **lossCategory**: mandatory; valid strings for this attribute are “structural”, “nonstructural”, “contents”, and “business_interruption”.
- **description**: mandatory; a brief string (ASCII) with further information about the *Consequence Model*, for example, which building typologies are covered or the source of the functions in the *Consequence Model*.
- **limitStates**: mandatory; this field is used to define the number and nomenclature of each limit state. Four limit states are employed in the example above, but it is possible to use any number of discrete states. The limit states must be provided as a set of strings separated by whitespaces between each limit state. Each limit state string can contain letters (a–z; A–Z), numbers (0–9), dashes (-), and underscores (_). Please ensure that there is no whitespace within the name of any individual limit state. The number and nomenclature of the limit states used in the *Consequence Model* should match those used in the corresponding *Fragility Model*.

```

4 <consequenceModel id="consequence_example"
5   assetCategory="buildings"
6   lossCategory="structural">
7
8 <description>Consequence Model Example</description>
9 <limitStates>slight moderate extensive complete</limitStates>
```

The following snippet from the above *Consequence Model* example file defines a *Consequence Function* using a lognormal distribution to model the uncertainty in the consequence ratio for each limit state:

```

11 <consequenceFunction id="RC_LowRise" dist="LN">
12   <params ls="slight" mean="0.04" stddev="0.00"/>
13   <params ls="moderate" mean="0.16" stddev="0.00"/>
14   <params ls="extensive" mean="0.32" stddev="0.00"/>
15   <params ls="complete" mean="0.64" stddev="0.00"/>
16 </consequenceFunction>
```

The following attributes are needed to define a *Consequence Function*:

- **id**: mandatory; a unique string used to identify the taxonomy for which the function is being defined. This string is used to relate the *Consequence Function* with the relevant asset in the *Exposure Model*. This string can contain letters (a–z; A–Z), numbers (0–9), dashes (-), and underscores (_), with a maximum of 100 characters.

- `dist`: mandatory; for vulnerability function which use a continuous distribution to model the uncertainty in the conditional loss ratios, this attribute should be set to either “LN” if using the lognormal distribution, or to “BT” if using the Beta distribution³.
- `params`: mandatory; this field is used to define the parameters of the continuous distribution used for modelling the uncertainty in the loss ratios for each limit state for this *Consequence Function*. For a lognormal distribution, the two parameters required to specify the function are the mean and standard deviation of the consequence ratio. These parameters are defined for each limit state using the attributes `mean` and `stddev` respectively. The attribute `ls` specifies the limit state for which the parameters are being defined. The parameters for each limit state must be provided on a separate line. The number and names of the limit states in each *Consequence Function* must be equal to the number of limit states defined in the corresponding *Fragility Model* using the attribute `limitStates`.

3.2.4 Vulnerability Models

In order to perform probabilistic or scenario risk calculations, it is necessary to define a *Vulnerability Function* for each building typology present in the *Exposure Model*. In this section, the schema for the *Vulnerability Model* is described in detail. A graphical representation of a *Vulnerability Model* (mean loss ratio for a set of intensity measure levels) is illustrated in Fig. 3.15.

Note that although the uncertainty for each loss ratio is not represented in Fig. 3.15, it can be considered in the input file, by means of a coefficient of variation per loss ratio and a probabilistic distribution, which can currently be set to lognormal (LN), Beta (BT); or by specifying a discrete probability mass (PM)⁴ distribution of the loss ratio at a set of intensity levels. An example of a *Vulnerability Function* that models the uncertainty in the loss ratio at different intensity levels using a lognormal distribution is illustrated in Fig. 3.16.

In general, defining vulnerability functions requires the user to specify the distribution of the loss ratio for a set of intensity levels. The loss ratio distributions can be defined using either a discrete or a continuous format, and the *Vulnerability Model* file can include a mix of both types of vulnerability functions. It is also possible to define a *Vulnerability Function* using a set of deterministic loss ratios corresponding to a set of intensity levels (i.e., ignoring the uncertainty in the conditional loss ratios).

An example *Vulnerability Model* comprising three vulnerability functions is shown in [the listing](#) below. This *Vulnerability Model* contains one function that uses the lognormal distribution to represent the uncertainty in the loss ratio at different intensity levels, one function that uses the Beta distribution, and one function that is defined using a discrete probability mass distribution.

³ Note that as of OpenQuake engine v1.8, the uncertainty in the consequence ratios is ignored, and only the mean consequence ratios for the set of limit states is considered when computing the consequences from the damage distribution. Consideration of the uncertainty in the consequence ratios is planned for future releases of the OpenQuake engine.

⁴ As of OpenQuake engine v1.8, the “PM” option for defining vulnerability functions is supported by the Scenario Risk and the Stochastic Event-Based Probabilistic Risk Calculators, but not by the Classical Probabilistic Risk Calculator.

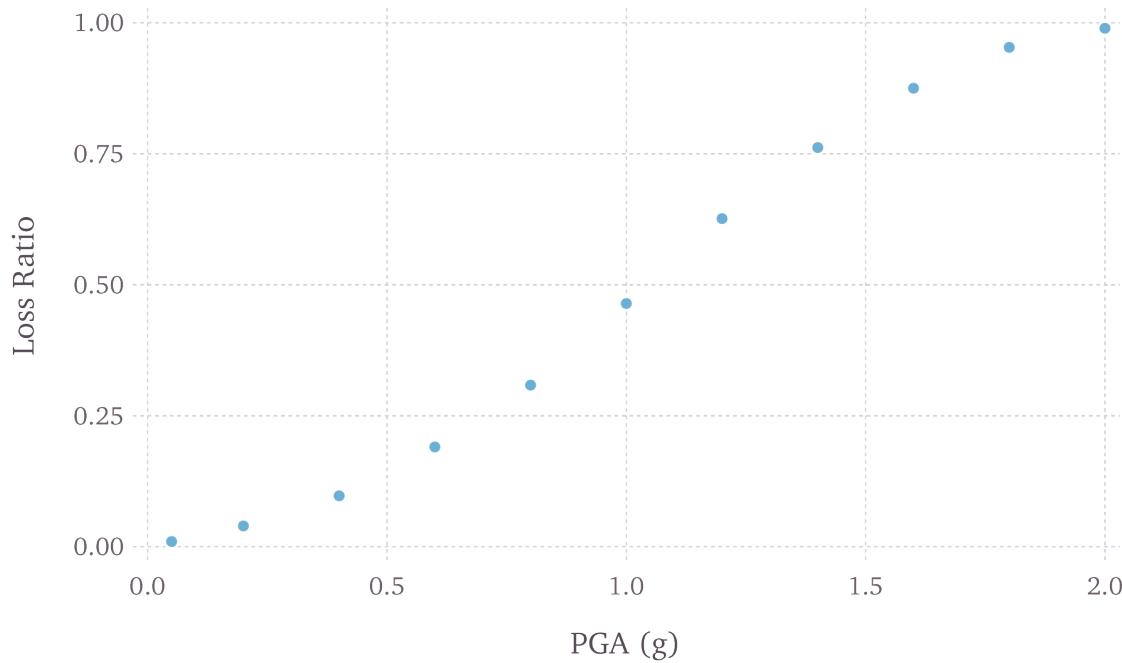


Fig. 3.15: Graphical representation of a vulnerability model

```

1  <?xml version="1.0" encoding="UTF-8"?>
2  <nrmrl xmlns="http://openquake.org/xmlns/nrml/0.5">
3
4  <vulnerabilityModel id="vulnerability_example"
5      assetCategory="buildings"
6      lossCategory="structural">
7
8      <description>vulnerability model</description>
9
10     <vulnerabilityFunction id="W1_Res_LowCode" dist="LN">
11         <imls imt="PGA">0.005 0.15 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0</imls>
12         <meanLRs>0.01 0.04 0.10 0.20 0.33 0.50 0.67 0.80 0.90 0.96 0.99</
13             meanLRs>
14             <covLRs>0.03 0.12 0.24 0.32 0.38 0.40 0.38 0.32 0.24 0.12 0.03</covLRs>
15
16     </vulnerabilityFunction>
17
18     <vulnerabilityFunction id="S1_Res_HighCode" dist="BT">
19         <imls imt="SA(0.3)">0.05 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0</imls>
20         <meanLRs>0.01 0.03 0.07 0.15 0.24 0.37 0.50 0.60 0.67 0.72 0.75</
21             meanLRs>

```

(continues on next page)

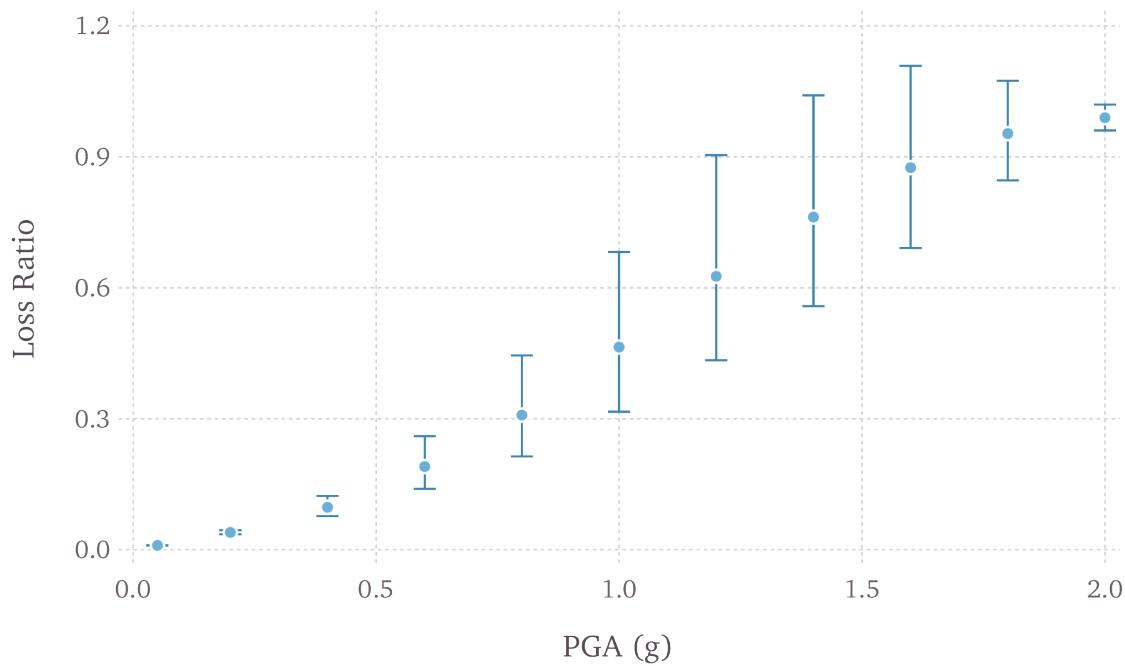


Fig. 3.16: Graphical representation of a vulnerability function that models the uncertainty in the loss ratio using a lognormal distribution. The mean loss ratios and coefficients of variation are illustrated for a set of intensity levels.

(continued from previous page)

```

20 <covLRs>0.03 0.12 0.24 0.32 0.38 0.40 0.38 0.32 0.24 0.12 0.03</covLRs>
21 </vulnerabilityFunction>
22
23
24 <vulnerabilityFunction id="ATC13_URM_Res" dist="PM">
25   <imls imt="MMI">6 7 8 9 10 11 12</imls>
26   <probabilities lr="0.000">0.95 0.49 0.30 0.14 0.03 0.01 0.00</
27   <probabilities lr="0.005">0.03 0.38 0.40 0.30 0.10 0.03 0.01</
28   <probabilities lr="0.050">0.02 0.08 0.16 0.24 0.30 0.10 0.01</
29   <probabilities lr="0.200">0.00 0.02 0.08 0.16 0.26 0.30 0.03</
30   <probabilities lr="0.450">0.00 0.02 0.03 0.10 0.18 0.30 0.18</
31   <probabilities lr="0.800">0.00 0.01 0.02 0.04 0.10 0.18 0.39</
32   <probabilities lr="1.000">0.00 0.01 0.01 0.02 0.03 0.08 0.38</
33   </probabilities>
34 </vulnerabilityFunction>
35 </vulnerabilityModel>
36
37 </nrml>
```

The initial portion of the schema contains general information that describes some general aspects of the *Vulnerability Model*. The information in this metadata section is common to all of the functions in the *Vulnerability Model* and needs to be included at the beginning of every *Vulnerability Model* file. The parameters are illustrated in the snippet shown and described below:

```

4 <vulnerabilityModel id="vulnerability_example"
5   assetCategory="buildings"
6   lossCategory="structural">
7
8   <description>vulnerability model</description>
```

- **id**: a unique string (ASCII) used to identify the *Vulnerability Model*. This string can contain letters (a–z; A–Z), numbers (0–9), dashes (-), and underscores (_), with a maximum of 100 characters.
- **assetCategory**: an optional string (ASCII) used to specify the type of assets for which vulnerabilityfunctions will be defined in this file (e.g: buildings, lifelines).
- **lossCategory**: mandatory; valid strings for this attribute are “structural”, “nonstructural”,

“contents”, “business_interruption”, and “occupants”.

- **description:** mandatory; a brief string with further information about the *Vulnerability Model*, for example, which building typologies are covered or the source of the functions in the *Vulnerability Model*.

The following snippet from the above *Vulnerability Model* example file defines a *Vulnerability Function* modelling the uncertainty in the conditional loss ratios using a (continuous) lognormal distribution:

```

10 <vulnerabilityFunction id="W1_Res_LowCode" dist="LN">
11   <imls imt="PGA">0.005 0.15 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0</imls>
12   <meanLRs>0.01 0.04 0.10 0.20 0.33 0.50 0.67 0.80 0.90 0.96 0.99</
13   meanLRs>
14   <covLRs>0.03 0.12 0.24 0.32 0.38 0.40 0.38 0.32 0.24 0.12 0.03</covLRs>
</vulnerabilityFunction>
```

The following attributes are needed to define a *Vulnerability Function* which uses a continuous distribution to model the uncertainty in the conditional loss ratios:

- **id:** a unique string (ASCII) used to identify the taxonomy for which the function is being defined. This string is used to relate the *Vulnerability Function* with the relevant asset in the *Exposure Model*. This string can contain letters (a–z; A–Z), numbers (0–9), dashes (-), and underscores (_), with a maximum of 100 characters.
- **dist:** mandatory; for vulnerabilityfunctions which use a continuous distribution to model the uncertainty in the conditional loss ratios, this attribute should be set to either “LN” if using the lognormal distribution, or to “BT” if using the Beta distribution.
- **imls:** mandatory; this attribute specifies the list of intensity levels for which the parameters of the conditional loss ratio distributions will be defined. In addition, it is also necessary to define the intensity measure type (imt).
- **meanLRs:** mandatory; this field is used to define the mean loss ratios for this *Vulnerability Function* for each of the intensity levels defined by the attribute **imls**. The number of mean loss ratios defined by the **meanLRs** attribute must be equal to the number of intensity levels defined by the attribute **imls**.
- **covLRs:** mandatory; this field is used to define the coefficient of variation for the conditional distribution of the loss ratios for this *Vulnerability Function* for each of the intensity levels defined by the attribute **imls**. The number of coefficients of variation of loss ratios defined by the **covLRs** attribute must be equal to the number of intensity levels defined by the attribute **imls**. The uncertainty in the conditional loss ratios can be ignored by setting all of the **covLRs** for a given *Vulnerability Function* to zero.

The next snippet from the *Vulnerability Model* example file of the *Vulnerability Function listing* above defines a *Vulnerability Function* which models the uncertainty in the conditional loss ratios using a (discrete) probability mass distribution:

```

24 <vulnerabilityFunction id="ATC13_URM_Res" dist="PM">
25   <imls imt="MMI">6 7 8 9 10 11 12</imls>
26   <probabilities lr="0.000">0.95 0.49 0.30 0.14 0.03 0.01 0.00</
27   </probabilities>
28   <probabilities lr="0.005">0.03 0.38 0.40 0.30 0.10 0.03 0.01</
29   </probabilities>
30   <probabilities lr="0.050">0.02 0.08 0.16 0.24 0.30 0.10 0.01</
31   </probabilities>
32   <probabilities lr="0.200">0.00 0.02 0.08 0.16 0.26 0.30 0.03</
33   </probabilities>
     <probabilities lr="0.450">0.00 0.02 0.03 0.10 0.18 0.30 0.18</
   </probabilities>
     <probabilities lr="0.800">0.00 0.01 0.02 0.04 0.10 0.18 0.39</
   </probabilities>
     <probabilities lr="1.000">0.00 0.01 0.01 0.02 0.03 0.08 0.38</
   </probabilities>
</vulnerabilityFunction>
```

The following attributes are needed to define a *Vulnerability Function* which uses a discrete probability mass distribution to model the uncertainty in the conditional loss ratios:

- **id**: a unique string (ASCII) used to identify the taxonomy for which the function is being defined. This string is used to relate the *Vulnerability Function* with the relevant asset in the *Exposure Model*. This string can contain letters (a–z; A–Z), numbers (0–9), dashes (-), and underscores (_), with a maximum of 100 characters.
- **dist**: mandatory; for vulnerabilityfunctions which use a discrete probability mass distribution to model the uncertainty in the conditional loss ratios, this attribute should be set to “PM”.
- **imls**: mandatory; this attribute specifies the list of intensity levels for which the parameters of the conditional loss ratio distributions will be defined. In addition, it is also necessary to define the intensity measure type (**imt**).
- **probabilities**: mandatory; this field is used to define the probability of observing a particular loss ratio (specified for each row of **probabilities** using the attribute **lr**), conditional on the set of intensity levels specified using the attribute **imls**. for this *Vulnerability Function*. Thus, the number of probabilities defined by each **probabilities** attribute must be equal to the number of intensity levels defined by the attribute **imls**. On the other hand, there is no limit to the number of loss ratios for which **probabilities** can be defined. In the example shown here, notice that the set of probabilities conditional on any particular intensity level, say, *MMI* = 8, sum up to one.

Note that the schema for representing vulnerabilitymodels has changed between Natural hazards’ Risk Markup Language v0.4 (used prior to OpenQuake engine17) and Natural hazards’ Risk Markup Language v0.5 (introduced in OpenQuake engine17).

A deprecation warning is printed every time you attempt to use a *Vulnerability Model* in the old Natural hazards' Risk Markup Language v0.4 format in an OpenQuake engine¹⁷ (or later) risk calculation. To get rid of the warning you must upgrade the old vulnerabilitymodels files to Natural hazards' Risk Markup Language v0.5. You can use the command `upgrade_nrml` with `oq` to do this as follows:

```
user@ubuntu:~$ oq upgrade_nrml <directory-name>
```

The above command will upgrade all of your old *Vulnerability Model* files to Natural hazards' Risk Markup Language v0.5. The original files will be kept, but with a `.bak` extension appended. Notice that you will need to set the `lossCategory` attribute to its correct value manually. This is easy to do, since if you try to run a computation you will get a clear error message telling the expected value for the `lossCategory` for each file.

Several methodologies to derive vulnerabilityfunctions are currently being evaluated by GEM Foundation and have been included as part of the Risk Modeller's Toolkit, the code for which can be found on a public repository at GitHub at: <http://github.com/gemscientechnologies/rmtk>.

A web-based tool to build an *Vulnerability Model* in the Natural hazards' Risk Markup Language schema are also under development, and can be found at the OpenQuake platform at the following address: <https://platform.openquake.org/ipt/>.

3.3 Using the Risk Module

This Chapter summarises the structure of the information necessary to define the different input data to be used with the OpenQuake engine risk calculators. Input data for scenario-based and probabilistic seismic damage and risk analysis using the OpenQuake engine are organised into:

- An exposure model file in the NRML format, as described in Section [Exposure Models](#).
- A file describing the *Vulnerability Model* (Section [Vulnerability Models](#)) for loss calculations, or a file describing the *Fragility Model* (Section [Fragility Models](#)) for damage calculations. Optionally, a file describing the *Consequence Model* (Section [Consequence Models](#)) can also be provided in order to calculate losses from the estimated damage distributions.
- A general calculation configuration file.
- Hazard inputs. These include hazard curves for the classical probabilistic damage and risk calculators, ground motion fields for the scenario damage and risk calculators, or stochastic event sets for the probabilistic event based calculators. As of OpenQuake engine v2.1, in general, there are five different ways in which hazard calculation parameters or results can be provided to the OpenQuake engine in order to run the subsequent risk calculations:
 - Use a single configuration file for running the hazard and risk calculations sequentially (preferred)

- Use separate configuration files for running the hazard and risk calculations sequentially (legacy)
- Use a configuration file for the risk calculation along with all hazard outputs from a previously completed, compatible OpenQuake engine hazard calculation
- Use a configuration file for the risk calculation along with hazard input files in the OpenQuake NRML format

The file formats for *Exposure models*, *Fragility Models*, *Consequence Models*, and *Vulnerability models* have been described earlier in Chapter [Risk Input Models](#). The configuration file is the primary file that provides the OpenQuake engine information regarding both the definition of the input models (e.g. exposure, site parameters, fragility, consequence, or vulnerability models) as well as the parameters governing the risk calculation.

Information regarding the configuration file for running hazard calculations using the OpenQuake engine can be found in Section [Configuration file](#). Some initial mandatory parameters of the configuration file common to all of the risk calculators are presented in [the listing](#). The remaining parameters that are specific to each risk calculator are discussed in subsequent sections.

[general]

```
description = Example risk calculation
calculation_mode = scenario_risk
```

[exposure]

```
exposure_file = exposure_model.xml
```

[vulnerability]

```
structural_vulnerability_file = structural_vulnerability_model.xml
```

- **description:** a parameter that can be used to include some information about the type of calculations that are going to be performed.
- **calculation_mode:** this parameter specifies the type of calculation to be run. Valid options for the `calculation_mode` for the risk calculators are: `scenario_damage`, `scenario_risk`, `classical_damage`, `classical_risk`, `event_based_risk`, and `classical_bcr`.
- **exposure_file:** this parameter is used to specify the path to the *Exposure Model* file. Typically this is the path to the xml file containing the exposure, or the xml file containing the metadata sections for the case where the assets are listed in one or more csv files. For particularly large exposure models, it may be more convenient to provide the path to a single compressed zip file that contains the exposure xml file and the exposure csv files (if any).

Depending on the type of risk calculation, other parameters besides the aforementioned ones may need to be provided. We illustrate in the following sections different examples of the configuration file for the different risk calculators.

3.3.1 Scenario Damage Calculator

For this calculator, the parameter `calculation_mode` should be set to `scenario_damage`.

Example 1

This example illustrates a scenario damage calculation which uses a single configuration file to first compute the ground motion fields for the given rupture model and then calculate damage distribution statistics based on the ground motion fields. A minimal job configuration file required for running a scenario damage calculation is shown in *the listing* below.

```
[general]
description = Scenario damage using a single config file
calculation_mode = scenario_damage

[exposure]
exposure_file = exposure_model.xml

[rupture]
rupture_model_file = rupture_model.xml
rupture_mesh_spacing = 2.0

[site_params]
site_model_file = site_model.xml

[hazard_calculation]
random_seed = 42
truncation_level = 3.0
maximum_distance = 200.0
gsim = BooreAtkinson2008
number_of_ground_motion_fields = 1000

[fragility]
structural_fragility_file = structural_fragility_model.xml
```

The general parameters `description` and `calculation_mode`, and `exposure_file` have already been described earlier. The other parameters seen in the above example configuration file are described below:

- `rupture_model_file`: a parameter used to define the path to the earthquake *Rupture Model* file describing the scenario event.
- `rupture_mesh_spacing`: a parameter used to specify the mesh size (in km) used by the OpenQuake engine to discretize the rupture. Note that the smaller the mesh spacing, the greater will be (1) the precision in the calculation and (2) the computational demand.
- `structural_fragility_file`: a parameter used to define the path to the structural

Fragility Model file.

In this case, the ground motion fields will be computed at each of the locations of the assets in the exposure model. Ground motion fields will be generated for each of the intensity measure types found in the provided set of fragility models. The above calculation can be run using the command line:

```
user@ubuntu:~$ oq engine --run job.ini
```

After the calculation is completed, a message similar to the following will be displayed:

```
Calculation 2680 completed in 13 seconds. Results:  
id | name  
5069 | Average Asset Damages
```

Note that one or more of the following parameters can be used in the same job configuration file to provide the corresponding fragility model files:

- `structural_fragility_file`: a parameter used to define the path to a structural *Fragility Model* file
- `nonstructural_fragility_file`: a parameter used to define the path to a nonstructural *Fragility Model* file
- `contents_fragility_file`: a parameter used to define the path to a contents *Fragility Model* file
- `business_interruption_fragility_file`: a parameter used to define the path to a business interruption *Fragility Model* file

It is important that the `lossCategory` parameter in the metadata section for each provided fragility model file (“structural”, “nonstructural”, “contents”, or “business_interruption”) should match the loss type defined in the configuration file by the relevant keyword above.

Example 2

This example illustrates a scenario damage calculation which uses separate configuration files for the hazard and risk parts of a scenario damage assessment. The first configuration file shown in *the first listing* below contains input models and parameters required for the computation of the ground motion fields due to a given rupture. The second configuration file shown in *the second listing* contains input models and parameters required for the calculation of the damage distribution for a portfolio of assets due to the ground motion fields.

Scenario hazard example

```
[general]  
description = Scenario hazard example  
calculation_mode = scenario
```

(continues on next page)

(continued from previous page)

```
[rupture]
rupture_model_file = rupture_model.xml
rupture_mesh_spacing = 2.0

[sites]
sites_csv = sites.csv

[site_params]
site_model_file = site_model.xml

[hazard_calculation]
random_seed = 42
truncation_level = 3.0
maximum_distance = 200.0
gsim = BooreAtkinson2008
intensity_measure_types = PGA, SA(0.3)
number_of_ground_motion_fields = 1000
ground_motion_correlation_model = JB2009
ground_motion_correlation_params = {"vs30_clustering": True}
```

Scenario damage example

```
[general]
description = Scenario damage example
calculation_mode = scenario_damage

[exposure]
exposure_file = exposure_model.xml

[boundaries]
region = -123.0 38.3, -121.0 38.3, -121.0 36.5, -123.0 36.5

[hazard]
asset_hazard_distance = 20

[fragility]
structural_fragility_file = structural_fragility_model.xml

[risk_calculation]
time_event = night
```

In this example, the set of intensity measure types for which the ground motion fields should be generated is specified explicitly in the configuration file using the parameter `intensity_measure_types`. If the hazard calculation outputs are intended to be used as inputs

for a subsequent scenario damage or risk calculation, the set of intensity measure types specified here must include all intensity measure types that are used in the fragility or vulnerability models for the subsequent damage or risk calculation.

In *the hazard configuration file* illustrated above, the list of sites at which the ground motion values will be computed is provided in a CSV file, specified using the `sites_csv` parameter. The sites used for the hazard calculation need not be the same as the locations of the assets in the exposure model used for the following risk calculation. In such cases, it is recommended to set a reasonable search radius (in km) using the `asset_hazard_distance` parameter for the OpenQuake engine to look for available hazard values, as shown in the `job_damage.ini` example file above.

The only new parameters introduced in *the risk configuration file* for this example are the `region`, `asset_hazard_distance`, and `time_event` parameters, which are described below; all other parameters have already been described in earlier examples.

- `region`: this is an optional parameter which defines the polygon that will be used for filtering the assets from the exposure model. Assets outside of this region will not be considered in the risk calculations. This region is defined using pairs of coordinates that indicate the vertices of the polygon, which should be listed in the Well-known text (WKT) format:

```
region = lon_1 lat_1, lon_2 lat_2, ..., lon_n lat_n
```

For each point, the longitude is listed first, followed by the latitude, both in decimal degrees. The list of points defining the polygon can be provided either in a clockwise or counter-clockwise direction.

If the `region` is not provided, all assets in the exposure model are considered for the risk calculation.

This parameter is useful in cases where the exposure model covers a region larger than the one that is of interest in the current calculation.

- `asset_hazard_distance`: this parameter indicates the maximum allowable distance between an asset and the closest hazard input. Hazard inputs can include hazard curves or ground motion intensity values. If no hazard input site is found within the radius defined by the `asset_hazard_distance`, the asset is skipped and a message is provided mentioning the id of the asset that is affected by this issue.

If multiple hazard input sites are found within the radius defined by the `asset_hazard_distance` parameter, the hazard input site with the shortest distance from the asset location is associated with the asset. It is possible that the associated hazard input site might be located outside the polygon defined by the `region`.

- `time_event`: this parameter indicates the time of day at which the event occurs. The values that this parameter can be set to are currently limited to one of the three strings: `day`, `night`, and `transit`. This parameter will be used to compute the number of fatalities based on the number of occupants present in the various assets at that time of day, as specified in the exposure model.

Now, the above calculations described by the two configuration files “`job_hazard.ini`” and

“job_damage.ini” can be run separately. The calculation id for the hazard calculation should be provided to the OpenQuake engine while running the risk calculation using the option --hazard-calculation-id (or --hc). This is shown below:

```
user@ubuntu:~$ oq engine --run job_hazard.ini
```

After the hazard calculation is completed, a message similar to the one below will be displayed in the terminal:

```
Calculation 2681 completed in 4 seconds. Results:
```

id	name
5072	Ground Motion Fields

In the example above, the calculation id of the hazard calculation is 2681. There is only one output from this calculation, i.e., the Ground Motion Fields.

The risk calculation for computing the damage distribution statistics for the portfolio of assets can now be run using:

```
user@ubuntu:~$ oq engine --run job_damage.ini --hc 2681
```

After the calculation is completed, a message similar to the one listed above in Example 1 will be displayed.

In order to retrieve the calculation id of a previously run hazard calculation, the option --list-hazard-calculations (or --lhc) can be used to display a list of all previously run hazard calculations:

job_id	status	start_time	description
2609	successful	2015-12-01 14:14:14	Mid Nepal earthquake
...			
2681	successful	2015-12-12 10:00:00	Scenario hazard example

The option --list-outputs (or --lo) can be used to display a list of all outputs generated during a particular calculation. For instance,

```
user@ubuntu:~$ oq engine --lo 2681
```

will produce the following display:

id	name
5072	Ground Motion Fields

Example 3

The example shown in *the listing* below illustrates a scenario damage calculation which uses a file listing a precomputed set of Ground Motion Fields. These Ground Motion Fields can be computed using the OpenQuake engine or some other software. The Ground Motion Fields must be provided

in either the Natural hazards' Risk Markup Language schema or the csv format as presented in Section *Outputs from Scenario Hazard Analysis*. The damage distribution is computed based on the provided Ground Motion Fields.

```
[general]
description = Scenario damage using user-defined ground motion fields
↳(NRML)
calculation_mode = scenario_damage

[hazard]
gmfs_file = gmfs.xml

[exposure]
exposure_file = exposure_model.xml

[fragility]
structural_fragility_file = structural_fragility_model.xml
```

- `gmfs_file`: a parameter used to define the path to the Ground Motion Fields file in the Natural hazards' Risk Markup Language schema. This file must define Ground Motion Fields for all of the intensity measure types used in the *Fragility Model*.

The listing below shows an example of a Ground Motion Fields file in the Natural hazards' Risk Markup Language schema and [Table 2.4](#) shows an example of a Ground Motion Fields file in the csv format. If the Ground Motion Fields file is provided in the csv format, an additional csv file listing the site ids must be provided using the parameter `sites_csv`. See [Table 2.5](#) for an example of the sites csv file, which provides the association between the site ids in the Ground Motion Fields csv file with their latitude and longitude coordinates.

```
[general]
description = Scenario damage using user-defined ground motion fields
↳(CSV)
calculation_mode = scenario_damage

[hazard]
sites_csv = sites.csv
gmfs_csv = gmfs.csv

[exposure]
exposure_file = exposure_model.xml

[fragility]
structural_fragility_file = structural_fragility_model.xml
```

- `gmfs_csv`: a parameter used to define the path to the Ground Motion Fields file in the csv format. This file must define Ground Motion Fields for all of the intensity measure types

used in the *Fragility Model*. ([Download an example file here](#)).

- `sites_csv`: a parameter used to define the path to the sites file in the csv format. This file must define site id, longitude, and latitude for all of the sites for the Ground Motion Fields file provided using the `gmfs_csv` parameter. ([Download an example file here](#)).

The above calculation(s) can be run using the command line:

```
user@ubuntu:~$ oq engine --run job.ini
```

Example 4

This example illustrates a the hazard job configuration file for a scenario damage calculation which uses two Ground Motion Prediction Equations instead of only one. Currently, the set of Ground Motion Prediction Equations to be used for a scenario calculation can be specified using a logic tree file, as demonstrated in [The Ground Motion Logic Tree](#). As of OpenQuake engine v1.8, the weights in the logic tree are ignored, and a set of Ground Motion Fields will be generated for each Ground Motion Prediction Equation in the logic tree file. Correspondingly, damage distribution statistics will be generated for each set of Ground Motion Field.

The file shown in *the listing* below lists the two Ground Motion Prediction Equations to be used for the hazard calculation:

```

1  <?xml version="1.0" encoding="UTF-8"?>
2  <nrm1 xmlns:gml="http://www.opengis.net/gml"
3    xmlns="http://openquake.org/xmlns/nrml/0.5">
4
5  <logicTree logicTreeID="lt1">
6    <logicTreeBranchSet uncertaintyType="gmpeModel"
7      branchSetID="bs1"
8      applyToTectonicRegionType="Active Shallow Crust">
9
10   <logicTreeBranch branchID="b1">
11     <uncertaintyModel>BooreAtkinson2008</uncertaintyModel>
12     <uncertaintyWeight>0.75</uncertaintyWeight>
13   </logicTreeBranch>
14
15   <logicTreeBranch branchID="b2">
16     <uncertaintyModel>ChiouYoungs2008</uncertaintyModel>
17     <uncertaintyWeight>0.25</uncertaintyWeight>
18   </logicTreeBranch>
19
20   </logicTreeBranchSet>
21 </logicTree>
22
23 </nrm1>
```

The only change that needs to be made in the hazard job configuration file is to replace the `gsim` parameter with `gsim_logic_tree_file`, as demonstrated in *the listing* below.

```
[general]
description = Scenario hazard example using multiple GMPEs
calculation_mode = scenario

[rupture]
rupture_model_file = rupture_model.xml
rupture_mesh_spacing = 2.0

[sites]
sites_csv = sites.csv

[site_params]
site_model_file = site_model.xml

[hazard_calculation]
random_seed = 42
truncation_level = 3.0
maximum_distance = 200.0
gsim_logic_tree_file = gsim_logic_tree.xml
intensity_measure_types = PGA, SA(0.3)
number_of_ground_motion_fields = 1000
ground_motion_correlation_model = JB2009
ground_motion_correlation_params = {"vs30_clustering": True}
```

Example 5

This example illustrates a scenario damage calculation which specifies fragility models for calculating damage to structural and nonstructural components of structures, and also specifies *Consequence Model* files for calculation of the corresponding losses.

A minimal job configuration file required for running a scenario damage calculation followed by a consequences analysis is shown in *the listing* below.

```
[general]
description = Scenario damage and consequences
calculation_mode = scenario_damage

[exposure]
exposure_file = exposure_model.xml

[rupture]
rupture_model_file = rupture_model.xml
```

(continues on next page)

(continued from previous page)

```

rupture_mesh_spacing = 2.0

[site_params]
site_model_file = site_model.xml

[hazard_calculation]
random_seed = 42
truncation_level = 3.0
maximum_distance = 200.0
gsim = BooreAtkinson2008
number_of_ground_motion_fields = 1000
ground_motion_correlation_model = JB2009
ground_motion_correlation_params = {"vs30_clustering": True}

[fragility]
structural_fragility_file = structural_fragility_model.xml
nonstructural_fragility_file = nonstructural_fragility_model.xml

[consequence]
structural_consequence_file = structural_consequence_model.xml
nonstructural_consequence_file = nonstructural_consequence_model.xml

```

Note that one or more of the following parameters can be used in the same job configuration file to provide the corresponding *Consequence Model* files:

- `structural_consequence_file`: a parameter used to define the path to a structural *Consequence Model* file
- `nonstructural_consequence_file`: a parameter used to define the path to a nonstructural *Consequence Model* file
- `contents_consequence_file`: a parameter used to define the path to a contents *Consequence Model* file
- `business_interruption_consequence_file`: a parameter used to define the path to a business interruption *Consequence Model* file

It is important that the `lossCategory` parameter in the metadata section for each provided *Consequence Model* file (“structural”, “nonstructural”, “contents”, or “business_interruption”) should match the loss type defined in the configuration file by the relevant keyword above.

The above calculation can be run using the command line:

```
user@ubuntu:~$ oq engine --run job.ini
```

After the calculation is completed, a message similar to the following will be displayed:

```
Calculation 1579 completed in 37 seconds. Results:  
id | name  
8990 | Average Asset Losses  
8993 | Average Asset Damages
```

3.3.2 Scenario Risk Calculator

In order to run this calculator, the parameter `calculation_mode` needs to be set to `scenario_risk`.

Most of the job configuration parameters required for running a scenario risk calculation are the same as those described in the previous section for the scenario damage calculator. The remaining parameters specific to the scenario risk calculator are illustrated through the examples below.

Example 1

This example illustrates a scenario risk calculation which uses a single configuration file to first compute the ground motion fields for the given rupture model and then calculate loss statistics for structural losses and nonstructural losses, based on the ground motion fields. The job configuration file required for running this scenario risk calculation is shown in *the listing* below.

```
[general]  
description = Scenario risk using a single config file  
calculation_mode = scenario_risk  
  
[exposure]  
exposure_file = exposure_model.xml  
  
[rupture]  
rupture_model_file = rupture_model.xml  
rupture_mesh_spacing = 2.0  
  
[site_params]  
site_model_file = site_model.xml  
  
[hazard_calculation]  
random_seed = 42  
truncation_level = 3.0  
maximum_distance = 200.0  
gsim = BooreAtkinson2008  
number_of_ground_motion_fields = 1000  
ground_motion_correlation_model = JB2009  
ground_motion_correlation_params = {"vs30_clustering": True}
```

(continues on next page)

(continued from previous page)

[vulnerability]

```
structural_vulnerability_file = structural_vulnerability_model.xml
nonstructural_vulnerability_file = nonstructural_vulnerability_model.xml
```

[risk_calculation]

```
master_seed = 24
asset_correlation = 1
```

Whereas a scenario damage calculation requires one or more fragility and/or consequence models, a scenario risk calculation requires the user to specify one or more vulnerability model files. Note that one or more of the following parameters can be used in the same job configuration file to provide the corresponding vulnerability model files:

- **structural_vulnerability_file**: this parameter is used to specify the path to the structural *Vulnerability Model* file
- **nonstructural_vulnerability_file**: this parameter is used to specify the path to the nonstructuralvulnerabilitymodel file
- **contents_vulnerability_file**: this parameter is used to specify the path to the contents *Vulnerability Model* file
- **business_interruption_vulnerability_file**: this parameter is used to specify the path to the business interruption *Vulnerability Model* file
- **occupants_vulnerability_file**: this parameter is used to specify the path to the occupants *Vulnerability Model* file

It is important that the `lossCategory` parameter in the metadata section for each provided vulnerability model file (“structural”, “nonstructural”, “contents”, “business_interruption”, or “occupants”) should match the loss type defined in the configuration file by the relevant keyword above.

The remaining new parameters introduced in this example are the following:

- **master_seed**: this parameter is used to control the random number generator in the loss ratio sampling process. If the same `master_seed` is defined at each calculation run, the same random loss ratios will be generated, thus allowing reproducibility of the results.
- **asset_correlation**: if the uncertainty in the loss ratios has been defined within the *Vulnerability Model*, users can specify a coefficient of correlation that will be used in the Monte Carlo sampling process of the loss ratios, between the assets that share the same taxonomy. If the `asset_correlation` is set to one, the loss ratio residuals will be perfectly correlated. On the other hand, if this parameter is set to zero, the loss ratios will be sampled independently. If this parameter is not defined, the OpenQuake engine will assume zero correlation in the vulnerability. As of OpenQuake engine v1.8, `asset_correlation` applies only to continuous vulnerabilityfunctions using the lognormal or Beta distribution; it does not apply to vulnerabilityfunctions defined using the PMF distribution. Although partial correlation

was supported in previous versions of the engine, beginning from OpenQuake engine22, values between zero and one are no longer supported due to performance considerations. The only two values permitted are `asset_correlation = 0` and `asset_correlation = 1`.

In this case, the ground motion fields will be computed at each of the locations of the assets in the exposure model and for each of the intensity measure types found in the provided set of vulnerability models. The above calculation can be run using the command line:

```
user@ubuntu:~$ oq engine --run job.ini
```

After the calculation is completed, a message similar to the following will be displayed:

```
Calculation 2735 completed in 10 seconds. Results:  
id | name  
5328 | Aggregate Asset Losses  
5329 | Average Asset Losses  
5330 | Aggregate Event Losses
```

All of the different ways of running a scenario damage calculation as illustrated through the examples of the previous section are also applicable to the scenario risk calculator, though the examples are not repeated here.

A few additional parameters related to the event based risk calculator that may be useful for controlling specific aspects of the calculation are listed below:

- `ignore_covs`: this parameter controls the propagation of vulnerability uncertainty to losses. The vulnerability functions using continuous distributions (such as the lognormal distribution or beta distribution) to characterize the uncertainty in the loss ratio conditional on the shaking intensity level, specify the mean loss ratios and the corresponding coefficients of variation for a set of intensity levels. They are used to build the so called *Epsilon* matrix within the engine, which is how loss ratios are sampled from the distribution for each asset. There is clearly a performance penalty associated with the propagation of uncertainty in the vulnerability to losses. The *Epsilon* matrix has to be computed and stored, and then the worker processes have to read it, which involves large quantities of data transfer and memory usage. Setting `ignore_covs = true` in the job file will result in the engine using just the mean loss ratio conditioned on the shaking intensity and ignoring the uncertainty. This tradeoff of not propagating the vulnerability uncertainty to the loss estimates can lead to a significant boost in performance and tractability. The default value of `ignore_covs` is `false`.

3.3.3 Classical Probabilistic Seismic Damage Calculator

In order to run this calculator, the parameter `calculation_mode` needs to be set to `classical_damage`.

Most of the job configuration parameters required for running a classical probabilistic damage calculation are the same as those described in the section for the scenario damage calculator. The remaining parameters specific to the classical probabilistic damage calculator are illustrated through the examples below.

Example 1

This example illustrates a classical probabilistic damage calculation which uses a single configuration file to first compute the hazard curves for the given source model and ground motion model and then calculate damage distribution statistics based on the hazard curves. A minimal job configuration file required for running a classical probabilistic damage calculation is shown in *the listing* below.

```
[general]
description = Classical probabilistic damage using a single config file
calculation_mode = classical_damage

[exposure]
exposure_file = exposure_model.xml

[erf]
width_of_mfd_bin = 0.1
rupture_mesh_spacing = 2
area_source_discretization = 20

[site_params]
site_model_file = site_model.xml

[logic_trees]
source_model_logic_tree_file = source_model_logic_tree.xml
gsim_logic_tree_file = gsim_logic_tree.xml
number_of_logic_tree_samples = 0

[hazard_calculation]
random_seed = 42
investigation_time = 1
truncation_level = 3.0
maximum_distance = 200.0

[fragility]
structural_fragility_file = structural_fragility_model.xml
```

The general parameters `description` and `calculation_mode`, and `exposure_file` have already been described earlier in Section [Scenario Damage Calculator](#). The parameters related to the hazard curves computation have been described earlier in Section [Classical PSHA](#).

In this case, the hazard curves will be computed at each of the locations of the assets in the exposure model, for each of the intensity measure types found in the provided set of fragilitymodels. The above calculation can be run using the command line:

```
user@ubuntu:~$ oq engine --run job.ini
```

After the calculation is completed, a message similar to the following will be displayed:

```
Calculation 2741 completed in 12 seconds. Results:  
id | name  
5359 | Asset Damage Distribution
```

Example 2

This example illustrates a classical probabilistic damage calculation which uses separate configuration files for the hazard and risk parts of a classical probabilistic damage assessment. The first configuration file shown in *the listing* below contains input models and parameters required for the computation of the hazard curves.

```
[general]  
description = Classical probabilistic hazard  
calculation_mode = classical  
  
[sites]  
region = -123.0 38.3, -121.0 38.3, -121.0 36.5, -123.0 36.5  
region_grid_spacing = 0.5  
  
[erf]  
width_of_mfd_bin = 0.1  
rupture_mesh_spacing = 2  
area_source_discretization = 20  
  
[site_params]  
site_model_file = site_model.xml  
  
[logic_trees]  
source_model_logic_tree_file = source_model_logic_tree.xml  
gsim_logic_tree_file = gsim_logic_tree.xml  
number_of_logic_tree_samples = 0  
  
[hazard_calculation]  
random_seed = 42
```

(continues on next page)

(continued from previous page)

```
investigation_time = 1
truncation_level = 3.0
maximum_distance = 200.0
intensity_measure_types_and_levels = {
    "PGA": logscale(0.05, 3.0, 30),
    "SA(1.0)": logscale(0.05, 3.0, 30)}
```

The second configuration file shown in *the listing* below contains input models and parameters required for the calculation of the probabilistic damage distribution for a portfolio of assets based on the hazard curves and fragility models.

```
[general]
description = Classical probabilistic damage example
calculation_mode = classical_damage

[exposure]
exposure_file = exposure_model.xml

[hazard]
asset_hazard_distance = 20

[fragility]
structural_fragility_file = structural_fragility_model.xml

[risk_calculation]
risk_investigation_time = 50
steps_per_interval = 4
```

Now, the above calculations described by the two configuration files “job_hazard.ini” and “job_damage.ini” can be run sequentially or separately, as illustrated in Example 2 in Section *Scenario Damage Calculator*. The new parameters introduced in the above example configuration file are described below:

- **risk_investigation_time**: an optional parameter that can be used in probabilistic damage or risk calculations where the period of interest for the risk calculation is different from the period of interest for the hazard calculation. If this parameter is not explicitly set, the OpenQuake engine will assume that the risk calculation is over the same time period as the preceding hazard calculation.
- **steps_per_interval**: an optional parameter that can be used to specify whether discrete fragility functions in the fragility models should be discretized further, and if so, how many intermediate steps to use for the discretization. Setting

`steps_per_interval = n`

will result in the OpenQuake engine discretizing the discrete fragility models using $(n - 1)$

linear interpolation steps between each pair of intensity level, poe points.

The default value of this parameter is one, implying no interpolation.

3.3.4 Classical Probabilistic Seismic Risk Calculator

In order to run this calculator, the parameter `calculation_mode` needs to be set to `classical_risk`.

Most of the job configuration parameters required for running a classical probabilistic risk calculation are the same as those described in the previous section for the classical probabilistic damage calculator. The remaining parameters specific to the classical probabilistic risk calculator are illustrated through the examples below.

Example 1

This example illustrates a classical probabilistic risk calculation which uses a single configuration file to first compute the hazard curves for the given source model and ground motion model and then calculate loss exceedance curves based on the hazard curves. An example job configuration file for running a classical probabilistic risk calculation is shown in *the listing* below.

```
[general]
description = Classical probabilistic risk using a single config file
calculation_mode = classical_risk

[exposure]
exposure_file = exposure_model.xml

[erf]
width_of_mfd_bin = 0.1
rupture_mesh_spacing = 2
area_source_discretization = 20

[site_params]
site_model_file = site_model.xml

[logic_trees]
source_model_logic_tree_file = source_model_logic_tree.xml
gsim_logic_tree_file = gsim_logic_tree.xml
number_of_logic_tree_samples = 0

[hazard_calculation]
random_seed = 42
investigation_time = 1
truncation_level = 3.0
```

(continues on next page)

(continued from previous page)

```
maximum_distance = 200.0
```

[vulnerability]

```
structural_vulnerability_file = structural_vulnerability_model.xml
nonstructural_vulnerability_file = nonstructural_vulnerability_model.xml
```

Apart from the calculation mode, the only difference with the example job configuration file shown in Example 1 of Section *Classical Probabilistic Seismic Damage Calculator* is the use of a vulnerability model instead of a fragility model.

As with the Scenario Risk calculator, it is possible to specify one or more *Vulnerability Model* files in the same job configuration file, using the parameters:

- `structural_vulnerability_file`,
- `nonstructural_vulnerability_file`,
- `contents_vulnerability_file`,
- `business_interruption_vulnerability_file`, and/or
- `occupants_vulnerability_file`

It is important that the `lossCategory` parameter in the metadata section for each provided vulnerability model file (“structural”, “nonstructural”, “contents”, “business_interruption”, or “occupants”) should match the loss type defined in the configuration file by the relevant keyword above.

In this case, the hazard curves will be computed at each of the locations of the assets in the *Exposure Model*, for each of the intensity measure types found in the provided set of vulnerability models. The above calculation can be run using the command line:

```
user@ubuntu:~$ oq engine --run job.ini
```

After the calculation is completed, a message similar to the following will be displayed:

```
Calculation 2749 completed in 24 seconds. Results:
  id | name
3980 | Asset Loss Curves Statistics
3981 | Asset Loss Maps Statistics
3983 | Average Asset Loss Statistics
```

Example 2

This example illustrates a classical probabilistic risk calculation which uses separate configuration files for the hazard and risk parts of a classical probabilistic risk assessment. The first configuration file shown in *the listing* contains input models and parameters required for the computation of the hazard curves.

```
[general]
description = Classical probabilistic hazard
calculation_mode = classical

[sites]
region = -123.0 38.3, -121.0 38.3, -121.0 36.5, -123.0 36.5
region_grid_spacing = 0.5

[erf]
width_of_mfd_bin = 0.1
rupture_mesh_spacing = 2
area_source_discretization = 20

[site_params]
site_model_file = site_model.xml

[logic_trees]
source_model_logic_tree_file = source_model_logic_tree.xml
gsim_logic_tree_file = gsim_logic_tree.xml
number_of_logic_tree_samples = 0

[hazard_calculation]
random_seed = 42
investigation_time = 1
truncation_level = 3.0
maximum_distance = 200.0
intensity_measure_types_and_levels = {
    "PGA": logscale(0.05, 3.0, 30),
    "SA(1.0)": logscale(0.05, 3.0, 30)}
```

The second configuration file shown in *the listing* below contains input models and parameters required for the calculation of the loss exceedance curves and probabilistic loss maps for a portfolio of assets based on the hazard curves and vulnerability models.

```
[general]
description = Classical probabilistic risk
calculation_mode = classical_risk

[exposure]
exposure_file = exposure_model.xml

[hazard]
asset_hazard_distance = 20
```

(continues on next page)

(continued from previous page)

```

[vulnerability]
structural_vulnerability_file = structural_vulnerability_model.xml
nonstructural_vulnerability_file = nonstructural_vulnerability_model.xml

[risk_calculation]
risk_investigation_time = 50
lrem_steps_per_interval = 2

[risk_outputs]
quantiles = 0.15, 0.50, 0.85
conditional_loss_poes = 0.02, 0.10

```

Now, the above calculations described by the two configuration files “job_hazard.ini” and “job_risk.ini” can be run sequentially or separately, as illustrated in Example 2 in Section *Scenario Damage Calculator*. The new parameters introduced in *the above risk configuration file example* are described below:

- `lrem_steps_per_interval`: this parameter controls the number of intermediate values between consecutive loss ratios (as defined in the *Vulnerability Model*) that are considered in the risk calculations. A larger number of loss ratios than those defined in each *Vulnerability Function* should be considered, in order to better account for the uncertainty in the loss ratio distribution. If this parameter is not defined in the configuration file, the OpenQuake engine assumes the `lrem_steps_per_interval` to be equal to 5. More details are provided in the OpenQuake Book (Risk).
- `quantiles`: this parameter can be used to request the computation of quantile loss curves for computations involving non-trivial logic trees. The quantiles for which the loss curves should be computed must be provided as a comma separated list. If this parameter is not included in the configuration file, quantile loss curves will not be computed.
- `conditional_loss_poes`: this parameter can be used to request the computation of probabilistic loss maps, which give the loss levels exceeded at the specified probabilities of exceedance over the time period specified by `risk_investigation_time`. The probabilities of exceedance for which the loss maps should be computed must be provided as a comma separated list. If this parameter is not included in the configuration file, probabilistic loss maps will not be computed.

3.3.5 Stochastic Event Based Seismic Damage

Calculator The parameter `calculation_mode` needs to be set to `event_based_damage` in order to use this calculator.

Most of the job configuration parameters required for running a stochastic event based damage calculation are the same as those described in the previous sections for the scenario damage calculator and the classical probabilistic damage calculator. The remaining parameters specific to the stochastic event based damage calculator are illustrated through the example below.

Example 1

This example illustrates a stochastic event based damage calculation which uses a single configuration file to first compute the Stochastic Event Sets and Ground Motion Fields for the given source model and ground motion model, and then calculate event loss tables, loss exceedance curves and probabilistic loss maps for structural losses, nonstructural losses and occupants, based on the Ground Motion Fields. The job configuration file required for running this stochastic event based damage calculation is shown in *the listing* below.

```
[general]
description = Stochastic event based damage using a single job file
calculation_mode = event_based_damage

[exposure]
exposure_file = exposure_model.xml

[site_params]
site_model_file = site_model.xml

[erf]
width_of_mfd_bin = 0.1
rupture_mesh_spacing = 2.0
area_source_discretization = 10.0

[logic_trees]
source_model_logic_tree_file = source_model_logic_tree.xml
gsim_logic_tree_file = gsim_logic_tree.xml
number_of_logic_tree_samples = 0

[correlation]
ground_motion_correlation_model = JB2009
ground_motion_correlation_params = {"vs30_clustering": True}

[hazard_calculation]
random_seed = 24
```

(continues on next page)

(continued from previous page)

```

truncation_level = 3
maximum_distance = 200.0
investigation_time = 1
ses_per_logic_tree_path = 10000

[fragility]
structural_fragility_file = structural_fragility_model.xml

[consequence]
structural_consequence_file = structural_consequence_model.xml

[risk_calculation]
master_seed = 42
risk_investigation_time = 1
return_periods = 5, 10, 25, 50, 100, 250, 500, 1000

```

Similar to that the procedure described for the Scenario Damage calculator, a Monte Carlo sampling process is also employed in this calculator to take into account the uncertainty in the conditional loss ratio at a particular intensity level. Hence, the parameters `asset_correlation` and `master_seed` may be defined as previously described for the Scenario Damage calculator in Section [Scenario Damage Calculator](#). The parameter “`risk_investigation_time`” specifies the time period for which the average damage values will be calculated, similar to the Classical Probabilistic Damage calculator. If this parameter is not provided in the risk job configuration file, the time period used is the same as that specified in the hazard calculation using the parameter “`investigation_time`”.

The new parameters introduced in this example are described below:

- `minimum_intensity`: this optional parameter specifies the minimum intensity levels for each of the intensity measure types in the risk model. Ground motion fields where each ground motion value is less than the specified minimum threshold are discarded. This helps speed up calculations and reduce memory consumption by considering only those ground motion fields that are likely to contribute to losses. It is also possible to set the same threshold value for all intensity measure types by simply providing a single value to this parameter. For instance: “`minimum_intensity = 0.05`” would set the threshold to 0.05 g for all intensity measure types in the risk calculation. If this parameter is not set, the OpenQuake engine extracts the minimum thresholds for each intensity measure type from the vulnerability models provided, picking the lowest intensity value for which a mean loss ratio is provided.
- `return_periods`: this parameter specifies the list of return periods (in years) for computing the asset / aggregate damage curves. If this parameter is not set, the OpenQuake engine uses a default set of return periods for computing the loss curves. The default return periods used are from the list: [5, 10, 25, 50, 100, 250, 500, 1000, …], with its upper bound limited by

$$\begin{aligned} & (\text{ses_per_logic_tree_path} \times \text{investigation_time}) \\ & \quad \text{average_damages} = \sum(\text{event_damages}) \\ & \quad \div (\text{hazard_investigation_time} \times \text{ses_per_logic_tree_path}) \\ & \quad \times \text{risk_investigation_time} \end{aligned}$$

The above calculation can be run using the command line:

```
user@ubuntu:~$ oq engine --run job.ini
```

Computation of the damage curves, and average damages for each individual asset in the *Exposure Model* can be resource intensive, and thus these outputs are not generated by default.

3.3.6 Stochastic Event Based Seismic Risk Calculator

The parameter `calculation_mode` needs to be set to `event_based_risk` in order to use this calculator.

Most of the job configuration parameters required for running a stochastic event based risk calculation are the same as those described in the previous sections for the scenario risk calculator and the classical probabilistic risk calculator. The remaining parameters specific to the stochastic event based risk calculator are illustrated through the example below.

Example 1

This example illustrates a stochastic event based risk calculation which uses a single configuration file to first compute the Stochastic Event Sets and Ground Motion Fields for the given source model and ground motion model, and then calculate event loss tables, loss exceedance curves and probabilistic loss maps for structural losses, nonstructural losses and occupants, based on the Ground Motion Fields. The job configuration file required for running this stochastic event based risk calculation is shown in *the listing* below.

```
[general]
description = Stochastic event based risk using a single job file
calculation_mode = event_based_risk

[exposure]
exposure_file = exposure_model.xml

[site_params]
site_model_file = site_model.xml

[erf]
width_of_mfd_bin = 0.1
rupture_mesh_spacing = 2.0
```

(continues on next page)

(continued from previous page)

```

area_source_discretization = 10.0

[logic_trees]
source_model_logic_tree_file = source_model_logic_tree.xml
gsim_logic_tree_file = gsim_logic_tree.xml

[correlation]
ground_motion_correlation_model = JB2009
ground_motion_correlation_params = {"vs30_clustering": True}

[hazard_calculation]
random_seed = 24
truncation_level = 3
maximum_distance = 200.0
investigation_time = 1
number_of_logic_tree_samples = 0
ses_per_logic_tree_path = 100000
minimum_intensity = {"PGA": 0.05, "SA(0.4)": 0.10, "SA(0.8)": 0.12}

[vulnerability]
structural_vulnerability_file = structural_vulnerability_model.xml
nonstructural_vulnerability_file = nonstructural_vulnerability_model.xml

[risk_calculation]
master_seed = 42
risk_investigation_time = 1
asset_correlation = 0
return_periods = [5, 10, 25, 50, 100, 250, 500, 1000]

[risk_outputs]
avg_losses = true
quantiles = 0.15, 0.50, 0.85
conditional_loss_poes = 0.02, 0.10

```

Similar to that the procedure described for the Scenario Risk calculator, a Monte Carlo sampling process is also employed in this calculator to take into account the uncertainty in the conditional loss ratio at a particular intensity level. Hence, the parameters `asset_correlation` and `master_seed` may be defined as previously described for the Scenario Risk calculator in Section [Scenario Risk Assessment](#). The parameter “`risk_investigation_time`” specifies the time period for which the event loss tables and loss exceedance curves will be calculated, similar to the Classical Probabilistic Risk calculator. If this parameter is not provided in the risk job configuration file, the time period used is the same as that specified in the hazard calculation using the parameter “`investigation_time`”.

The new parameters introduced in this example are described below:

- `minimum_intensity`: this optional parameter specifies the minimum intensity levels for each of the intensity measure types in the risk model. Ground motion fields where each ground motion value is less than the specified minimum threshold are discarded. This helps speed up calculations and reduce memory consumption by considering only those ground motion fields that are likely to contribute to losses. It is also possible to set the same threshold value for all intensity measure types by simply providing a single value to this parameter. For instance: “`minimum_intensity = 0.05`” would set the threshold to 0.05 g for all intensity measure types in the risk calculation. If this parameter is not set, the OpenQuake engine extracts the minimum thresholds for each intensity measure type from the vulnerability models provided, picking the lowest intensity value for which a mean loss ratio is provided.
- `return_periods`: this parameter specifies the list of return periods (in years) for computing the aggregate loss curve. If this parameter is not set, the OpenQuake engine uses a default set of return periods for computing the loss curves. The default return periods used are from the list: [5, 10, 25, 50, 100, 250, 500, 1000, ...], with its upper bound limited by (`ses_per_logic_tree_path` × `investigation_time`)
- `avg_losses`: this boolean parameter specifies whether the average asset losses over the time period “`risk_investigation_time`” should be computed. The default value of this parameter is `true`.

$$\begin{aligned} \text{average_loss} &= \text{sum}(\text{event_losses}) \\ &\div (\text{hazard_investigation_time} \times \text{ses_per_logic_tree_path}) \\ &\times \text{risk_investigation_time} \end{aligned}$$

The above calculation can be run using the command line:

```
user@ubuntu:$ oq engine --run job.ini
```

Computation of the loss tables, loss curves, and average losses for each individual asset in the *Exposure Model* can be resource intensive, and thus these outputs are not generated by default, unless instructed to by using the parameters described above.

Users may also begin an event based risk calculation by providing a precomputed set of Ground Motion Fields to the OpenQuake engine. The following example describes the procedure for this approach.

Example 2

This example illustrates a stochastic event based risk calculation which uses a file listing a pre-computed set of Ground Motion Fields. These Ground Motion Fields can be computed using the OpenQuake engine or some other software. The Ground Motion Fields must be provided in the csv format as presented in Section [Event based PSHA](#). Table 2.2 shows an example of a Ground Motion Fields file in the csv format.

An additional csv file listing the site ids must also be provided using the parameter `sites_csv`. See [Table 2.5](#) for an example of the sites csv file, which provides the association between the site ids in the Ground Motion Fields csv file with their latitude and longitude coordinates.

Starting from the input Ground Motion Fields, the OpenQuake engine can calculate event loss tables, loss exceedance curves and probabilistic loss maps for structural losses, nonstructural losses and occupants. The job configuration file required for running this stochastic event based risk calculation starting from a precomputed set of Ground Motion Fields is shown in *the listing* below.

```
[general]
description = Stochastic event based risk using precomputed gmfs
calculation_mode = event_based_risk

[hazard]
sites_csv = sites.csv
gmfs_csv = gmfs.csv
investigation_time = 50

[exposure]
exposure_file = exposure_model.xml

[vulnerability]
structural_vulnerability_file = structural_vulnerability_model.xml

[risk_calculation]
risk_investigation_time = 1
return_periods = [5, 10, 25, 50, 100, 250, 500, 1000]

[risk_outputs]
avg_losses = true
quantiles = 0.15, 0.50, 0.85
conditional_loss_poes = 0.02, 0.10
```

Additional parameters

A few additional parameters related to the event based risk calculator that may be useful for controlling specific aspects of the calculation are listed below:

- **individual_curves**: this boolean parameter is used to specify if the asset loss curves for each *Branch* realization should be saved to the datastore. For the asset loss curves output, by default the engine only saves and exports statistical results, i.e. the mean and quantile asset loss curves. If you want the asset loss curves for each of the individual *Branch* realizations, you must set `individual_curves=true` in the job file. Please take care: if you have hundreds of realizations, the data transfer and disk space requirements will be orders of magnitude larger than just returning the mean and quantile asset loss curves, and the calculation might fail. The default value of `individual_curves` is `false`.
- **asset_correlation**: if the uncertainty in the loss ratios has been defined within the *Vulnerability Model*, users can specify a coefficient of correlation that will be used in the Monte Carlo sampling process of the loss ratios, between the assets that share the same taxonomy.

If the `asset_correlation` is set to one, the loss ratio residuals will be perfectly correlated. On the other hand, if this parameter is set to zero, the loss ratios will be sampled independently. If this parameter is not defined, the OpenQuake engine will assume zero correlation in the vulnerability. As of OpenQuake engine v1.8, `asset_correlation` applies only to continuous vulnerability functions using the lognormal or Beta distribution; it does not apply to vulnerability functions defined using the PMF distribution. Although partial correlation was supported in previous versions of the engine, beginning from OpenQuake engine 2.2, values between zero and one are no longer supported due to performance considerations. The only two values permitted are `asset_correlation = 0` and `asset_correlation = 1`.

- `ignore_covs`: this parameter controls the propagation of vulnerability uncertainty to losses. The vulnerability functions using continuous distributions (such as the lognormal distribution or beta distribution) to characterize the uncertainty in the loss ratio conditional on the shaking intensity level, specify the mean loss ratios and the corresponding coefficients of variation for a set of intensity levels. They are used to build the so called *Epsilon* matrix within the engine, which is how loss ratios are sampled from the distribution for each asset. There is clearly a performance penalty associated with the propagation of uncertainty in the vulnerability to losses. The *Epsilon* matrix has to be computed and stored, and then the worker processes have to read it, which involves large quantities of data transfer and memory usage. Setting `ignore_covs = true` in the job file will result in the engine using just the mean loss ratio conditioned on the shaking intensity and ignoring the uncertainty. This tradeoff of not propagating the vulnerability uncertainty to the loss estimates can lead to a significant boost in performance and tractability. The default value of `ignore_covs` is `false`.

3.3.7 Retrofit Benefit-Cost Ratio Calculator

As previously explained, this calculator uses loss exceedance curves which are calculated using the Classical Probabilistic risk calculator. In order to run this calculator, the parameter `calculation_mode` needs to be set to `classical_bcr`.

Most of the job configuration parameters required for running a classical retrofit benefit-cost ratio calculation are the same as those described in the previous section for the classical probabilistic risk calculator. The remaining parameters specific to the classical retrofit benefit-cost ratio calculator are illustrated through the examples below.

Example 1

This example illustrates a classical probabilistic retrofit benefit-cost ratio calculation which uses a single configuration file to first compute the hazard curves for the given source model and ground motion model, then calculate loss exceedance curves based on the hazard curves using both the original vulnerability model and the vulnerability model for the retrofitted structures, then calculate the reduction in average annual losses due to the retrofits, and finally calculate the benefit-cost ratio for each asset. A minimal job configuration file required for running a classical probabilistic retrofit benefit-cost ratio calculation is shown in *the listing* below.

```

[general]
description = Classical cost-benefit analysis using a single config file
calculation_mode = classical_bcr

[exposure]
exposure_file = exposure_model.xml

[erf]
width_of_mfd_bin = 0.1
rupture_mesh_spacing = 2
area_source_discretization = 20

[site_params]
site_model_file = site_model.xml

[logic_trees]
source_model_logic_tree_file = source_model_logic_tree.xml
gsim_logic_tree_file = gsim_logic_tree.xml
number_of_logic_tree_samples = 0

[hazard_calculation]
random_seed = 42
investigation_time = 1
truncation_level = 3.0
maximum_distance = 200.0

[vulnerability]
structural_vulnerability_file = structural_vulnerability_model.xml
structural_vulnerability_retrofitted_file = retrofit_vulnerability_model.
    ↪xml

[risk_calculation]
interest_rate = 0.05
asset_life_expectancy = 50
lrem_steps_per_interval = 1

```

The new parameters introduced in the above example configuration file are described below:

- **vulnerability_retrofitted_file**: this parameter is used to specify the path to the *Vulnerability Model* file containing the vulnerability functions for the retrofitted asset
- **interest_rate**: this parameter is used in the calculation of the present value of potential future benefits by discounting future cash flows
- **asset_life_expectancy**: this variable defines the life expectancy or design life of the

assets, and is used as the time-frame in which the costs and benefits of the retrofit will be compared

The above calculation can be run using the command line:

```
user@ubuntu:~$ oq engine --run job.ini
```

After the calculation is completed, a message similar to the following will be displayed:

```
Calculation 2776 completed in 25 seconds. Results:  
id | name  
5422 | Benefit-cost ratio distribution | BCR Map. type=structural,  
↪hazard=5420
```

3.3.8 Exporting Risk Results

To obtain a list of all risk calculations that have been previously run (successfully or unsuccessfully), or that are currently running, the following command can be employed:

```
user@ubuntu:~$ oq engine --list-risk-calculations
```

or simply:

```
user@ubuntu:~$ oq engine --lrc
```

Which will display a list of risk calculations as presented below.

```
job_id | status | start_time | description  
1 | complete | 2015-12-02 08:50:30 | Scenario damage example  
2 | failed | 2015-12-03 09:56:17 | Scenario risk example  
3 | complete | 2015-12-04 10:45:32 | Scenario risk example  
4 | complete | 2015-12-04 10:48:33 | Classical risk example  
5 | complete | 2020-07-09 13:47:45 | Event based risk aggregation  
↪example
```

Then, in order to display a list of the risk outputs from a given job which has completed successfully, the following command can be used:

```
user@ubuntu:~$ oq engine --list-outputs <risk_calculation_id>
```

or simply:

```
user@ubuntu:~$ oq engine --lo <risk_calculation_id>
```

which will display a list of outputs for the calculation requested, as presented below:

Calculation 5 results:

```

id | name
11 | Aggregate Event Losses
1 | Aggregate Loss Curves
2 | Aggregate Loss Curves Statistics
3 | Aggregate Losses
4 | Aggregate Losses Statistics
5 | Average Asset Losses Statistics
13 | Earthquake Ruptures
6 | Events
7 | Full Report
10 | Input Files
12 | Realizations
14 | Source Loss Table
15 | Total Loss Curves
16 | Total Loss Curves Statistics
17 | Total Losses
18 | Total Losses Statistics

```

Then, in order to export all of the risk calculation outputs in the default file format (csv for most outputs), the following command can be used:

```
user@ubuntu:~$ oq engine --export-outputs <risk_calculation_id> <output_directory>
```

or simply:

```
user@ubuntu:~$ oq engine --eos <risk_calculation_id> <output_directory>
```

If, instead of exporting all of the outputs from a particular calculation, only particular output files need to be exported, this can be achieved by using the `--export-output` option and providing the id of the required output:

```
user@ubuntu:~$ oq engine --export-output <risk_output_id> <output_directory>
```

or simply:

```
user@ubuntu:~$ oq engine --eo <risk_output_id> <output_directory>
```

3.4 Risk Results

This following sections describe the different output files produced by the risk calculators.

3.4.1 Scenario Damage Outputs

The Scenario Damage Calculator produces the following output file for all loss types (amongst “structural”, “nonstructural”, “contents”, or “business_interruption”) for which a fragility model file was provided in the configuration file:

1. **Event Damages:** this file contains the damage distribution statistics for each individual events generated by the scenario, for each event and for every GMPE specified in the job file. For each event, the total number of buildings in each damage state are listed in this file.
2. **Average Asset Damages:** this file contains the damage distribution statistics for each of the individual assets defined in the *Exposure Model* that fall within the `region` and have a computed Ground Motion Field value available within the defined `asset_hazard_distance`. For each asset, the mean number of buildings (`mean`) in each damage state are listed in this file.

In addition, if the OpenQuake-QGIS plugin is used for visualizing or exporting the results from a Scenario Damage Calculation, the following additional outputs can be exported:

2. **dmg_by_tag:** this file contains the aggregated damage distribution statistics for each of the tags defined in the *Exposure Model*. For each tag, the mean number of buildings (`mean`) in each damage state are listed in this file.
3. **dmg_total:** this file contains the aggregated damage distribution statistics for the entire portfolio of assets defined in the *Exposure Model*. The mean (`mean`) and associated standard deviation (`stddev`) of the total number of buildings in each damage state are listed in this file.

In addition to the above asset-level damage output file which is produced for all Scenario Damage calculations, the following output file is also produced for all loss types (amongst “structural”, “nonstructural”, “contents”, or “business_interruption”) for which a *Consequence Model* file was also provided in the configuration file:

4. **Event Losses:** this file contains the scenario consequence statistics for each of the individual events generated by the scenario for every GMPE specified in the job file. For each event, the total consequences considering the entire portfolio of assets are listed in this file.
5. **Average Asset Losses:** this file contains the scenario consequence statistics for each of the individual assets defined in the *Exposure Model* that fall within the `region` and have a computed Ground Motion Field value available within the defined `asset_hazard_distance`. For each asset, the mean consequences (`mean`) and associated standard deviation (`stddev`) are listed in this file.

In addition, if the OpenQuake-QGIS plugin is used for visualizing or exporting the results from a Scenario Damage Calculation, the following additional outputs can be exported:

5. `losses_by_tag`: this file contains the aggregated scenario consequence statistics for each of the tags defined in the *Exposure Model*. For each tag, the mean consequences (`mean`) and associated standard deviation (`stddev`) are listed in this file.
6. `losses_total`: this file contains the aggregated scenario consequence statistics for the entire portfolio of assets defined in the *Exposure Model*. The mean consequences (`mean`) and associated standard deviation (`stddev`) are listed in this file.

If the calculation involves multiple Ground Motion Prediction Equations as described in Example 4 in Section [Scenario Damage Calculator](#), separate output files are generated for each of the above outputs, for each of the different Ground Motion Prediction Equations used in the calculation.

These different output files for Scenario Damage calculations are described in more detail in the following subsections.

3.4.1.1 Scenario damage statistics

Event damage statistics

This output contains the total damage distribution statistics for each of the individual events generated for the scenario. An example output file for structural damage is shown in the file snippet in [Table 3.2](#).

Table 3.2: Example of a scenario event damage distribution output file

event_id	rlz_id	ds0	ds1	ds2	ds3	ds4	...
0	0	5	1	0	0	1	...
1	0	4	1	1	1	0	...
2	0	6	0	0	0	1	...
...
100	1	5	0	1	0	1	...
101	1	4	1	1	1	0	...
102	1	5	1	0	0	1	...
...

The output file lists the total number of buildings in each damage state for each simulated event for the scenario, for each GMPE specified in the job file.

Asset damage statistics

This output contains the damage distribution statistics for each of the individual assets defined in the *Exposure Model* that fall within the `region` and have a computed Ground Motion Field value available within the defined `asset_hazard_distance`. An example output file for structural damage is shown in the file snippet in [Table 3.3](#).

Table 3.3: Example of a scenario asset damage distribution output file

as-set_ref	taxon-omy	lon	lat	ds0_mean	ds1_mean	ds2_mean	ds3_mean	...
a1	tax1	- 122.000	38.113	2.43E-01	6.60E-01	3.00E-02	0.00E+00	...
a2	tax2	- 122.114	38.113	8.18E-01	1.00E-01	8.00E-02	2.50E-03	...
a3	tax1	- 122.570	38.113	9.90E-01	1.00E-02	0.00E+00	0.00E+00	...
a4	tax3	- 122.000	38.000	3.93E-01	2.35E-01	2.95E-01	7.25E-02	...
a5	tax1	- 122.000	37.910	9.90E-01	0.00E+00	0.00E+00	0.00E+00	...
a6	tax2	- 122.000	38.225	4.08E-01	2.35E-01	1.73E-01	1.28E-01	...
a7	tax1	- 121.886	38.113	9.70E-01	2.00E-02	0.00E+00	0.00E+00	...

The output file lists the mean of the number of buildings in each damage state for each asset in the exposure model for all loss types (amongst ‘structural’, “nonstructural”, “contents”, or “business_interruption”) for which a *Consequence Model* file was also provided in the configuration file in addition to the corresponding *Fragility Model* file.

Damage statistics by tag

If the OpenQuake-QGIS plugin is used for visualizing or exporting the results, the Scenario Damage calculator can also estimate the expected total number of buildings of a certain combination of tags in each damage state and made available for export as a csv file. This distribution of damage per building tag is depicted in the example output file snippet in [Table 3.4](#).

Table 3.4: Example of a scenario damage distribution per tag output file

taxonomy	structural ds0_mean	structural ds1_mean	structural ds2_mean	structural ds3_mean	...
taxo nomy=wood	3,272.48	592.55	479.19	422.34	...
taxonomy =concrete	1,241.94	389.94	272.69	91.63	...
taxon omy=steel	460.72	279.44	152.18	57.43	...

The output file lists the mean of the total number of buildings in each damage state for each tag found in the exposure model for all loss types (amongst “structural”, “nonstructural”, “contents”, or “business_interruption”).

Total damage statistics

Finally, a total damage distribution output file can also be generated if the OpenQuake-QGIS plugin is used for visualizing or exporting the results from a Scenario Damage Calculation, which will contain the mean and standard deviation of the total number of buildings in each damage state, as illustrated in the example file in [Table 3.5](#).

Table 3.5: Example of a scenario total damage distribution output file

loss_type	damage_state	damage_value
structural	no_damage_mean	4,975.13
structural	ds1_mean	904.06
structural	ds2_mean	564.35
structural	ds3_mean	246.44
structural	ds4_mean	310.03

3.4.1.2 Scenario consequence statistics

Asset consequence statistics

This output contains the consequences statistics for each of the individual assets defined in the *Exposure Model* that fall within the `region` and have a computed Ground Motion Field value available within the defined `asset_hazard_distance`. An example output file for structural damage consequences is shown in [Table 3.6](#).

Table 3.6: Example of a scenario asset consequences output file

asset_ref	lon	lat	nonstructural-mean	nonstructural-stddev
a3	-122.57000	38.11300	428.29	281.49
a2	-122.11400	38.11300	1220.84	1111.4
a5	-122.00000	37.91000	1390.59	859.10
a4	-122.00000	38.00000	2889.04	1663.33
a1	-122.00000	38.11300	3191.30	1707.41
a6	-122.00000	38.22500	3310.62	2069.87
a7	-121.88600	38.11300	1415.19	845.83

The output file lists consequence statistics for all loss types (amongst “structural”, “nonstructural”, “contents”, or “business_interruption”) for which a *Consequence Model* file was also provided in the configuration file in addition to the corresponding *Fragility Model* file.

Total consequence statistics

Finally, if the OpenQuake-QGIS plugin is used for visualizing or exporting the results from a Scenario Damage Calculation, a total consequences output file can also be generated, which will contain the mean and standard deviation of the total consequences for the selected scenario, as illustrated in the example shown in [Table 3.7](#).

Table 3.7: Example of a scenario total consequences output file

contents-mean	contents-stddev	structural-mean	structural-stddev
13845.87	6517.61	2270.29	2440.90

3.4.2 Scenario Risk Outputs

The Scenario Risk Calculator produces the following set of output files:

1. **Aggregate Asset Losses:** this file contains the aggregated scenario loss statistics for the entire portfolio of assets defined in the *Exposure Model*. The mean (`mean`) and standard deviation (`stddev`) of the total loss for the portfolio of assets are listed in this file.
2. **Average Asset Losses:** this file contains mean (`mean`) and associated standard deviation (`stddev`) of the scenario loss for all assets at each of the unique locations in the *Exposure Model*.
3. **Aggregate Event Losses:** this file contains the total loss for the portfolio of assets defined in the *Exposure Model* for each realization of the scenario generated in the Monte Carlo simulation process.

In addition, if the OpenQuake-QGIS plugin is used for visualizing or exporting the results from a Scenario Risk Calculation, the following additional outputs can be exported:

4. **losses_by_tag:** this file contains the scenario loss statistics for each of the tags defined in the *Exposure Model*. For each tag, the mean (`mean`) and associated standard deviation (`stddev`) of the losses for each tag are listed in this file.

If the calculation involves multiple Ground Motion Prediction Equations, separate output files are generated for each of the above outputs, for each of the different Ground Motion Prediction Equations used in the calculation.

These different output files for Scenario Risk calculations are described in more detail in the following subsections.

3.4.2.1 Scenario loss statistics

Asset loss statistics

This output is always produced for a Scenario Risk calculation and comprises a mean total loss and associated standard deviation for each of the individual assets defined in the *Exposure Model* that fall within the `region` and have a computed Ground Motion Field value available within the defined `asset_hazard_distance`. These results are stored in a comma separate value (.csv) file as illustrated in the example shown in Table 3.8.

Table 3.8: Example of a scenario asset loss distribution output file

asset_ref	taxonomy	lon	lat	mean	structural	structural	...
a3	wood	-122.57000	38.11300	686,626	1,070,680	...	
a2	concrete	-122.11400	38.11300	1,496,360	2,121,790	...	
a5	wood	-122.00000	37.91000	3,048,910	4,339,480	...	
a4	steel	-122.00000	38.00000	9,867,070	15,969,600	...	
a1	wood	-122.00000	38.11300	12,993,800	22,136,700	...	
a6	concrete	-122.00000	38.22500	5,632,180	9,508,760	...	
a7	wood	-121.88600	38.11300	2,966,190	5,270,480	...	

Tag loss statistics

If the OpenQuake-QGIS plugin is used for visualizing or exporting the results from a Scenario Risk Calculation, the total expected losses for assets of each tag will be computed and made available for export as a csv file. This distribution of losses per asset tag is depicted in the example output file snippet in [Table 3.9](#).

Table 3.9: Example of a scenario loss distribution per tag output file

tag	contents	nonstructural	structural
taxonomy=wood	526,754.0	759,653.0	393,912.0
taxonomy=concrete	587,773.0	1,074,620.0	142,571.0
taxonomy=steel	407,821.0	923,281.0	197,341.0

The output file lists the mean loss aggregated for each tags present in the exposure model and selected by the for all loss types (amongst “structural”, “nonstructural”, “contents”, or “business_interruption”) for which a *Vulnerability Model* file was provided in the configuration file.

Total loss statistics

If the OpenQuake-QGIS plugin is used for visualizing or exporting the results from a Scenario Risk Calculation, the mean total loss and associated standard deviation for the selected earthquake rupture will be computed and made available for export as a csv file, as illustrated in the example shown in [Table 3.10](#).

Table 3.10: Example of a scenario total loss output file

LossType	Unit	Mean	Standard Deviation
structural	USD	8717775315.66	2047771108.36

3.4.2.2 Scenario losses by event

The losses by event output lists the total losses for each realization of the scenario generated in the Monte Carlo simulation process for all loss types for which a *Vulnerability Model* file was provided in the configuration file. These results are exported in a comma separate value (.csv) file as illustrated in the example shown in Table 3.11.

Table 3.11: Example of a scenario losses by event output file

event	structural	nonstructural
1	2,194.74	20,767.00
2	4,037.57	20,905.70
3	2,950.80	18,635.50
4	7,787.75	19,041.40
5	3,964.19	30,982.80
6	19,394.60	40,274.60
...

3.4.3 Probabilistic Damage Outputs

3.4.3.1 Probabilistic damage distribution

The Classical Probabilistic Damage calculator provides the expected damage distribution per asset as a csv file, an example of which is shown in Table 3.12.

Table 3.12: Example of a probabilistic damage distribution output file

asset_ref	no_damage	slight	moderate	extreme	complete
a1	4.4360E-06	6.3482E-03	3.4851E-01	4.7628E-01	1.6884E-01
a2	1.0391E-05	9.1856E-03	3.7883E-01	4.6140E-01	1.5056E-01
...
a998	6.9569E-02	6.4106E+00	7.4108E+01	5.7563E+01	1.7848E+01
a999	1.2657E-01	8.1294E+00	7.6249E+01	5.4701E+01	1.6792E+01

This file lists the expected number of structural units in each damage state for each asset, for the time period specified by the parameter `risk_investigation_time`.

3.4.4 Probabilistic Risk Outputs

Probabilistic risk calculations can be run using either the Classical Probabilistic Risk Calculator or the Stochastic Event-Based Probabilistic Risk Calculator. The following set of outputs is generated by both calculators:

1. `loss_curves`: loss exceedance curves describe the probabilities of exceeding a set of loss ratios or loss values, within a given time span (or investigation interval).
2. `loss_maps`: loss maps describe the loss (`value`) that is exceeded at the selected probability of exceedance (`poE`) within the specified time period for all assets at each of the unique locations in the *Exposure Model*.
3. `avg_losses`: the average losses output describes the expected loss (`value`) within the time period specified by `risk_investigation_time` for all assets in the *Exposure Model*.

In addition, with the Stochastic Event-Based Probabilistic Risk Calculator, it is also possible to calculate the following types of outputs:

1. `agg_curves`: aggregate loss curves describe the exceedance probabilities for a set of loss values for the entire portfolio of assets defined in the *Exposure Model*.
2. `losses_by_event`: an event loss table contains the aggregate loss across all assets in the *Exposure Model* for each of the simulated ruptures in the Stochastic Event Set.

3.4.4.1 Loss exceedance curves

Loss exceedance curves describe the probabilities of exceeding a set of loss ratios or loss values, within a given time span (or investigation interval). Depending upon the type of calculator used and the options defined before running a probabilistic risk calculation, one or more of the sets of loss exceedance curves described in the following subsections will be generated for all loss types (amongst “structural”, “nonstructural”, “contents”, “occupants”, or “business_interruption”) for which a vulnerability model file was provided in the configuration file.

Asset loss exceedance curves

Individual asset loss exceedance curves for ground-up losses are always generated for the Classical Probabilistic Risk Calculator. On the other hand, individual asset loss exceedance curves are not generated for the Stochastic Event-Based Probabilistic Risk Calculator. These results are stored in a comma separate value (.csv) file as illustrated in the example shown in Table 3.13.

Table 3.13: Example of an asset loss curve output file

asset	loss_type	loss	poe
asset	loss_type	loss	poe
a1	structural	0	1.00E+00
a1	structural	100	1.00E+00
a1	structural	400	8.43E-01
a1	structural	1000	4.70E-01
a1	structural	2000	1.78E-01
a1	structural	3300	7.31E-02
a1	structural	5000	3.30E-02
a1	structural	6700	1.68E-02
a1	structural	8000	1.01E-02
a1	structural	9000	6.62E-03
a1	structural	9600	4.95E-03
a1	structural	9900	4.12E-03
a1	structural	10000	3.86E-03

Mean loss exceedance curves

For calculations involving multiple hazard branches, mean asset loss exceedance curves are also generated for both the Classical Probabilistic Risk Calculator and the Stochastic Event-Based Probabilistic Risk Calculator (if the parameter “loss_ratios” is defined in the configuration file). The structure of the file is identical to that of the individual asset loss exceedance curve output file.

Quantile loss exceedance curves

For calculations involving multiple hazard branches, quantile asset loss exceedance curves can also be generated for both the Classical Probabilistic Risk Calculator and the Stochastic Event-Based Probabilistic Risk Calculator (if the parameter “loss_ratios” is defined in the configuration file). The quantiles for which loss curves will be calculated should have been defined in the job configuration file for the calculation using the parameter `quantiles`. The structure of the file is identical to that of the individual asset loss exceedance curve output file.

Aggregate loss exceedance curves

Aggregate loss exceedance curves are generated only by the Stochastic Event- Based Probabilistic Risk Calculator and describe the probabilities of exceedance of the total loss across the entire portfolio for a set of loss values within a given time span (or investigation interval). These results are exported in a comma separate value (.csv) file as illustrated in the example shown in [Table 3.14](#).

Table 3.14: Example of an aggregate loss curve

annual frequency_o f f of exceedence	_fre-	return _period	structural	nonstructural
1E+00	1	•	1,440.07	
5E-01	2	246.95	2,122.25	
2E-01	5	506.42	2,714.08	
1E-01	10	740.06	3,226.47	
5E-02	20	1,040.54	4,017.06	
2E-02	50	1,779.61	6,610.49	
1E-02	100	2,637.58	9,903.82	
5E-03	200	3,742.73	14,367.00	
2E-03	500	5,763.20	21,946.50	
1E-03	1,000	7,426.77	25,161.00	
5E-04	2,000	9,452.61	28,937.50	
2E-04	5,000	12,021.00	35,762.20	
1E-04	10,000	14,057.90	38,996.60	
...

Same as described previously for individual assets, mean aggregate loss exceedance curves and quantile aggregate loss exceedance curves will also be generated when relevant.

3.4.4.2 Probabilistic loss maps

A probabilistic loss map contains the losses that have a specified probability of exceedance within a given time span (or investigation interval) throughout the region of interest. This result can be generated using either the Stochastic Event-Based Probabilistic Risk Calculator or the Classical Probabilistic Risk Calculator.

The file snippet included in [Table 3.15](#) shows an example probabilistic loss map output file.

Table 3.15: Example of a probabilistic loss map output file

asset_ref	taxonomy	lon	lat	structural poe-0.02	structural poe-0.1
a1	wood	-122.000	38.113	6,686.10	3,241.80
a2	concrete	-122.114	38.113	597.59	328.07
a3	wood	-122.570	38.113	251.73	136.64
a4	steel	-122.000	38.000	3,196.66	1,610.98
a5	wood	-122.000	37.910	949.26	431.26
a6	concrete	-122.000	38.225	1,549.72	577.30
a7	wood	-121.886	38.113	1,213.54	677.16

3.4.4.3 Stochastic event loss tables

The Stochastic Event-Based Probabilistic Risk Calculator will also produce an aggregate event loss table. Each row of this table contains the rupture id, and aggregated loss (sum of the losses from the collection of assets within the region of interest), for each event in the stochastic event sets. The rupture id listed in this table is linked with the rupture ids listed in the stochastic event sets files.

The file snippet included in [Table 3.16](#) shows an example stochastic event loss table output file.

Table 3.16: Example aggregate event loss table

event_id	rup_id	year	structural
0	486	8	•
1	486	8	•
2	486	8	375.12
3	486	8	177.71
4	486	12	173.75
5	486	12	200.51
6	486	12	267.50
7	486	12	196.72
8	785	12	4,720.67
9	785	12	1,002.59
10	785	12	6,693.98
11	785	12	1,135.40
12	483	13	111.85
...

Asset event loss tables provide calculated losses for each of the assets in the exposure model, for each event within the stochastic event sets. Considering that the amount of data usually contained

in an asset event loss table is substantial, this table is not generated by default and even when it is generated it cannot be exported: it can only be accessed programmatically from the datastore. It is there for debugging purposes only.

3.4.5 Benefit-Cost Ratio Outputs

3.4.5.1 Retrofitting benefit/cost ratio maps

Ratio maps from the Retrofitting Benefit/Cost Ratio calculator require loss exceedance curves, which can be calculated using the Classical Probabilistic Risk calculator. For this reason, the parameters `sourceModelTreePath` and `gsimTreePath` are also included in this NRML schema, so the whole calculation process can be traced back. The results for each asset are stored as depicted in Table 3.17.

Table 3.17: Example benefit-cost ratio map output

lon	lat	asset_ref	aal_original	aal_retrofitted	bcr
80.0888	28.8612	a1846	966,606	53,037	1.72
80.0888	28.8612	a4119	225,788	26,639	1.46
80.0888	28.8612	a6444	444,595	16,953	1.33
80.0888	28.8612	a8717	106,907	10,086	0.39
80.0888	28.9362	a1784	964,381	53,008	1.92
80.0888	28.9362	a4057	225,192	26,597	1.64
80.0888	28.9362	a6382	443,388	16,953	1.49
80.0888	28.9362	a8655	106,673	10,081	0.44
80.1292	29.0375	a2250	1,109,310	60,989	2.08
80.1292	29.0375	a4523	2,785,790	329,083	1.78
...

- `interestRate`: this parameter represents the interest rate used in the time-value of money calculations
- `assetLifeExpectancy`: this parameter specifies the life expectancy (or design life) of the assets considered for the calculations
- `node`: this schema follows the same `node` structure already presented for the loss maps, however, instead of losses for each asset, the benefit/cost ratio (`ratio`), the average annual loss considering the original vulnerability (`aalOrig`) and the average annual loss for the retrofitted (`aalRetr`) configuration of the assets are provided.

3.5 Demonstrative Examples

The following sections describe the set of demos that have been compiled to demonstrate some of the features and usage of the risk calculators of the OpenQuake engine. These demos can be found in a public repository on GitHub at the following link: <https://github.com/gem/oq-engine/tree/master/demos/risk>.

These examples are purely demonstrative and are not intended to represent accurately the seismicity, vulnerability or exposure characteristics of the region selected, but simply to provide example input files that can be used as a starting point for users planning to employ the OpenQuake engine in seismic risk and loss estimation studies.

It is also noted that in the demonstrative examples presented in this section, illustrations about the various messages from the engine displayed in the command line interface are presented. These messages often contain information about the calculation id and output id, which will certainly be different for each user.

Following is the list of demos which illustrate how to use the OpenQuake engine for various scenario-based and probabilistic seismic damage and risk analyses:

- ClassicalBCR
- ClassicalDamage
- ClassicalRisk
- EventBasedDamage
- EventBasedRisk
- ScenarioDamage
- ScenarioRisk

These seven demos use Nepal as the region of interest. An example *Exposure Model* has been developed for this region, comprising 9,063 assets distributed amongst 2,221 locations (due to the existence of more than one asset at the same location). A map with the distribution of the number of buildings throughout Nepal is presented in Fig. 3.17.

The building portfolio was organised into four classes for the rural areas (adobe, dressed stone, unreinforced fired brick, wooden frames), and five classes for the urban areas (the aforementioned typologies, in addition to reinforced concrete buildings). For each one of these building typologies, vulnerabilityfunctions and fragilityfunctions were collected from the published literature available for the region. These input models are only for demonstrative purposes and for further information about the building characteristics of Nepal, users are advised to contact the National Society for Earthquake Technology of Nepal (NSET - <http://www.nset.org.np/>).

The following sections include instructions not only on how to run the risk calculations, but also on how to produce the necessary hazard inputs. Thus, each demo comprises the configuration file,

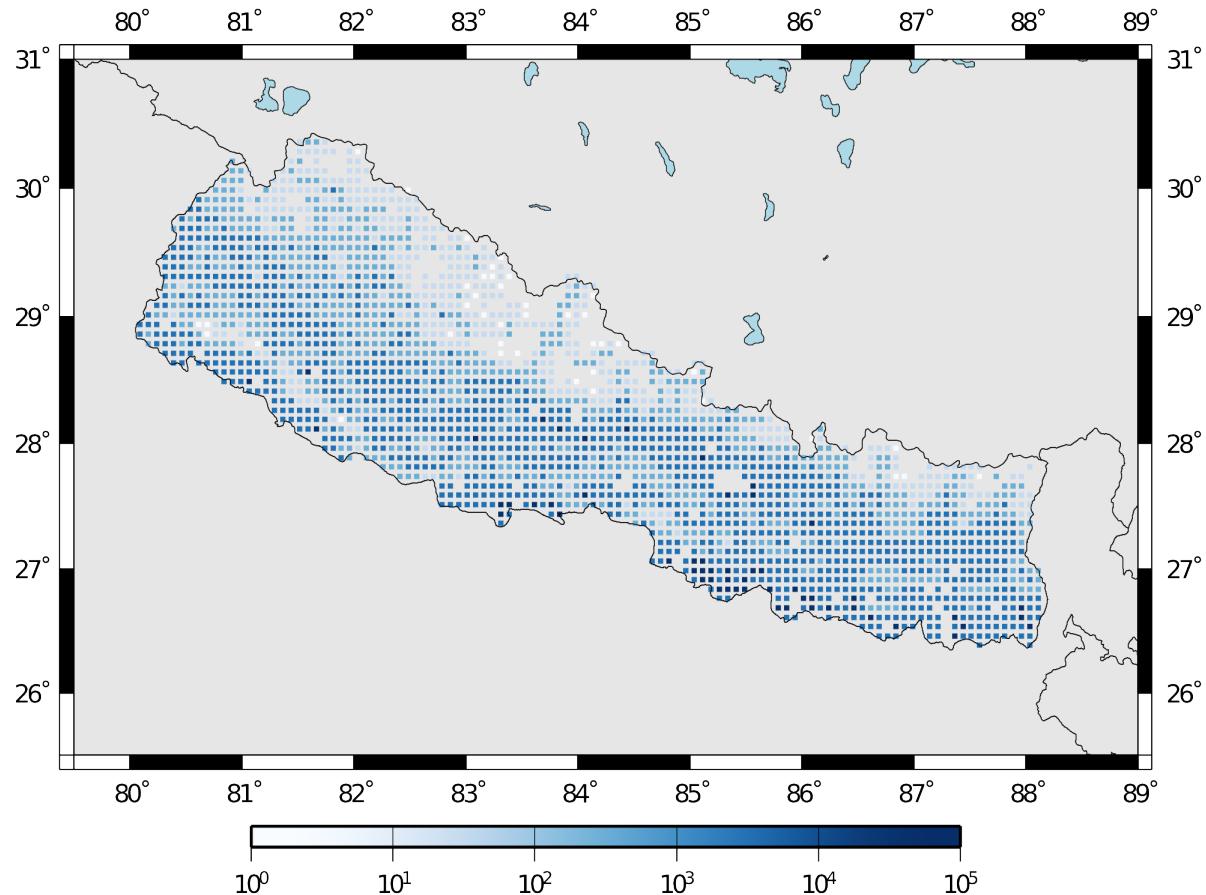


Fig. 3.17: Distribution of number of buildings in Nepal

Exposure Model and fragility or vulnerability models fundamental for the risk calculations. Each demo folder also a configuration file and the input models to produce the relevant hazard inputs.

3.5.1 Scenario Damage

Demos A rupture of magnitude Mw 7 in the central part of Nepal is considered in this demo. The characteristics of this rupture (geometry, dip, rake, hypocentre, upper and lower seismogenic depth) are defined in the `fault_rupture.xml` file, and the hazard and risk calculation settings are specified in the `job.ini` file.

To run the Scenario Damage demo, users should navigate to the folder where the required files have been placed and employ following command:

```
user@ubuntu:~$ oq engine --run job_hazard.ini && oq engine --run job_risk.  
→ini --hc=-1
```

The hazard calculation should produce the following outputs:

```
Calculation 8967 completed in 4 seconds. Results:  
id | name  
9060 | Ground Motion Fields  
9061 | Realizations
```

and the following outputs should be produced by the risk calculation:

```
Calculation 8968 completed in 16 seconds. Results:  
id | name  
9062 | Average Asset Damages  
9063 | Average Asset Losses
```

3.5.2 Scenario Risk Demos

The same rupture described in the Scenario Damage demo is also used for this demo. In this case, a combined job file, `job.ini`, is used to specify the configuration parameters for the hazard and risk calculations.

To run the Scenario Risk demo, users should navigate to the folder where the required files have been placed and employ following command:

```
user@ubuntu:~$ oq engine --run job.ini
```

and the following outputs should be produced:

```
Calculation 8970 completed in 16 seconds. Results:
```

id	name
9071	Aggregate Asset Losses
9072	Full Report
9073	Ground Motion Fields
9074	Average Asset Losses
9075	Aggregate Event Losses
9076	Realizations

3.5.3 Classical Probabilistic Seismic Damage Demos

The seismic source model developed within the Global Seismic Hazard Assessment Program (GSHAP) is used with the (B. S.-J. Chiou and Youngs 2008) ground motion prediction equation to produce the hazard input for this demo. No uncertainties are considered in the seismic source model and since only one GMPE is being considered, there will be only one possible path in the logic tree. Therefore, only one set of seismic hazard curves will be produced. To run the hazard calculation, the following command needs to be employed:

```
user@ubuntu:~$ oq engine --run job_hazard.ini
```

which will produce the following sample hazard output:

```
Calculation 8971 completed in 34 seconds. Results:
```

id	name
9074	Hazard Curves
9075	Realizations

The risk job calculates the probabilistic damage distribution for each asset in the *Exposure Model* starting from the above generated hazard curves. The following command launches the risk calculations:

```
user@ubuntu:~$ oq engine --run job_risk.ini --hc 8971
```

and the following sample outputs are obtained:

```
Calculation 8972 completed in 16 seconds. Results:
```

id	name
9076	Asset Damage Distribution
9077	Asset Damage Statistics

3.5.4 Classical Probabilistic Seismic Risk Demos

The same hazard input as described in the Classical Probabilistic Damage demo is used for this demo. Thus, the workflow to produce the set of hazard curves described in Section *Classical Probabilistic Seismic Damage Demos* is also valid herein. Then, to run the Classical Probabilistic Risk demo, users should navigate to the folder containing the demo input models and configuration files and employ the following command:

```
user@ubuntu:~$ oq engine --run job_hazard.ini
```

which will produce the following hazard output:

```
Calculation 8971 completed in 34 seconds. Results:
id | name
9074 | Hazard Curves
9075 | Realizations
```

In this demo, loss exceedance curves for each asset and two probabilistic loss maps (for probabilities of exceedance of 1% and 10%) are produced. The following command launches these risk calculations:

```
user@ubuntu:~$ oq engine --run job_risk.ini --hc 8971
```

and the following outputs are expected:

```
Calculation 8973 completed in 16 seconds. Results:
id | name
9077 | Asset Loss Curves Statistics
9078 | Asset Loss Maps Statistics
9079 | Average Asset Loss Statistics
```

3.5.5 Event Based Probabilistic Seismic Damage Demos

This demo uses the same probabilistic seismic hazard assessment (PSHA) model described in the previous examples in Section *Classical Probabilistic Seismic Damage Demos* and Section *Classical Probabilistic Seismic Risk Demos*. However, instead of hazard curves, sets of ground motion fields will be generated by the hazard calculation of this demo. Again, since there is only one *Branch* in the logic tree, only one set of ground motion fields will be used in the risk calculations. The hazard and risk jobs are defined in a single configuration file for this demo. To trigger the hazard and risk calculations the following command needs to be used:

```
user@ubuntu:~$ oq engine --run job.ini
```

and the following results are expected:

```
Calculation 2 completed in 29 seconds. Results:
```

id	name
24	Aggregate Event Damages
30	Aggregate Event Losses
20	Average Asset Damages
21	Average Asset Damages Statistics
22	Average Asset Losses
23	Average Asset Losses Statistics
32	Earthquake Ruptures
25	Events
26	Full Report
27	Ground Motion Fields
28	Hazard Curves
29	Input Files
31	Realizations

3.5.6 Event Based Probabilistic Seismic Risk Demos

This demo uses the same probabilistic seismic hazard assessment (PSHA) model described in the previous examples in Section [Classical Probabilistic Seismic Damage Demos](#) and Section [Classical Probabilistic Seismic Risk Demos](#). However, instead of hazard curves, sets of ground motion fields will be generated by the hazard calculation of this demo. Again, since there is only one *Branch* in the logic tree, only one set of ground motion fields will be used in the risk calculations. The hazard and risk jobs are defined in a single configuration file for this demo. To trigger the hazard and risk calculations the following command needs to be used:

```
user@ubuntu:~$ oq engine --run job.ini
```

and the following results are expected:

```
Calculation 8974 completed in 229 seconds. Results:
```

id	name
1820	Total Loss Curves
1821	Total Loss Curves Statistics
1822	Aggregate Loss Table
1823	Average Asset Losses
1824	Average Asset Loss Statistics
1826	Asset Loss Maps
1827	Asset Loss Maps Statistics
1828	Average Asset Losses
1829	Average Asset Losses Statistics
1830	Earthquake Ruptures

(continues on next page)

(continued from previous page)

1831		Events
1832		Realizations

The number and the name of the outputs can change between different versions of the engine.

3.5.7 Retrofit Benefit-Cost Ratio Demos

The loss exceedance curves used within this demo are produced using the Classical Probabilistic Risk calculator. Thus, the process to produce the seismic hazard curves described in Section [Classical Probabilistic Seismic Risk Demos](#) can be employed here. Then, the risk calculations can be initiated using the following command:

```
user@ubuntu:~$ oq engine --run job_risk.ini --hc 8971
```

which should produce the following output:

```
Calculation 8976 completed in 14 seconds. Results:
id | name
9087 | Benefit Cost Ratios
```

3.6 Bibliography

Aki, K., and P. G. Richards. 2002. *Quantitative Seismology*. Sausalito, California: University Science Books.

Chiou, B. S.-J., and R. R. Youngs. 2008. “An NGA Model for the Average Horizontal Component of Peak Ground Motion and Response Spectra.” *Earthquake Spectra* 24: 173–215.

Chiou, Brian S.-J., and Robert R. Youngs. 2014. “Update of the Chiou and Youngs NGA Model for the Average Horizontal Component of Peak Ground Motion and Response Spectra.” *Earthquake Spectra* 30 (3): 1117–53.

Cornell, C. A. 1968. “Engineering Seismic Risk Analysis.” *Bulletin of the Seismological Society of America* 58: 1583–1606.

EPRI, Electric Power Research Institute. 2011. “Technical Report: Central and Eastern United States Seismic Source Characterisation for Nuclear Facilities.” Report. EPRI, Palo Alto, CA. U. S. DoE.; U. S. NERC.

Field, E. H., T. H. Jordan, and C. A. Cornell. 2003. “OpenSHA - a Developing Community-Modeling Environment for Seismic Hazard Analysis.” *Seismological Research Letters* 74: 406–19.

- Frankel, A. 1995. “Mapping Seismic Hazard in the Central and Eastern United States.” *Seismological Research Letters* 66 (4): 8–21.
- McGuire, K. K. 1976. “FORTRAN Computer Program for Seismic Risk Analysis.” Open-File report 76-67. United States Department of the Interior, Geological Survey.
- Petersen, M. D., A. D. Frankel, S. C. Harmsen, C. S. Mueller, K. M. Haller, R. L. Wheeler, R. L. Wesson, et al. 2008. “Documentation for the 2008 Update of the United States National Seismic Hazard Maps.” Open File Report 2008-1128. U.S. Department of the Interior, U.S. Geological Survey.
- Schwartz, D. P., and K. J. Coppersmith. 1984. “Fault Behaviour and Characteristic Earthquakes: Examples from the Wasatch and San Andreas Fault Zones.” *Journal of Geophysical Research* 89 (B7): 5681–98.
- Strasser, F. O., M. C. Arango, and J. J. Bommer. 2010. “Scaling of the Source Dimensions of Interface and Intraslab Subduction-zone Earthquakes with Moment Magnitude.” *Seismological Research Letters* 81: 941–50.
- Thingbaijam, K. K. S., P. M. Mai, and K. Goda. 2017. “New Empirical Earthquake Source-Scaling Laws.” *Bulletin of the Seismological Society of America* 107 (5): 2225–2946. <https://doi.org/10.1785/0120170017>.
- Wells, D. L., and K. J. Coppersmith. 1994. “New Empirical Relationships Among Magnitude, Rupture Length, Rupture Width, Rupture Area, and Surface Displacement.” *Bulletin of the Seismological Society of America* 84 (4): 974–1002.
- Woo, G. 1996. “Kernel Estimation Methods for Seismic Hazard Area Source Modeling.” *Bulletin of the Seismological Society of America* 86 (2): 353–62.
- Youngs, R. R., and K. J. Coppersmith. 1985. “Implications of Fault Slip Rates and Earthquake Recurrence Models to Probabilistic Seismic Hazard Estimates.” *Bulletin of the Seismological Society of America* 75 (April): 939–64.

**CHAPTER
FOUR**

SECONDARY PERILS ANALYSIS

Landslides and liquefaction are well-known perils that accompany earthquakes. Basic models to describe their occurrence have been around for decades and are constantly improving. However, these models have rarely been incorporated into PSHA.

The tools presented here are implementations of some of the more common and appropriate secondary perils models. The intention is seamless incorporation of these models into PSH(R)A calculations done through the OpenQuake Engine, though the incorporation is a work in progress.

Tools for preparing the data for these models are also presented. This can be a non-trivial challenge, and consistent and correct data preparation is necessary for accurate secondary peril hazard and risk calculations.

4.1 Liquefaction and Landslide models

4.1.1 Liquefaction models

Several liquefaction models are implemented in the OpenQuake engine. One of them is the method developed for the HAZUS software by the US Federal Emergency Management Agency. This model involves categorization of sites into liquefaction susceptibility classes based on geotechnical characteristics, and a quantitative probability model for each susceptibility class. The remaining models are the academic geospatial models, i.e., statistical models that uses globally available input variables as first-order proxies to characterise saturation and density properties of the soil. The shaking component is expressed either in terms of Peak Ground Acceleration (PGA) or Peak Ground Velocity (PGV).

4.1.1.1 HAZUS

The HAZUS model classifies each site into a liquefaction susceptibility class (LSC) based on the geologic and geotechnical characteristics of the site, such as the sedimentological type and the deposition age of the unit. In addition to the LSC and the local ground acceleration at each site, the depth to groundwater at the site and the magnitude of the causative earthquake will affect the probability that a given site will experience liquefaction.

The equation that describes this probability is:

$$P(L) = \frac{P(L|PGA = a) \cdot P_{ml}}{K_m K_w} \quad (1)$$

$P(L|PGA = a)$ is the conditional probability that a site will fail based on the PGA and the LSC. P_{ml} is the fraction of the total mapped area that will experience liquefaction if $P(L|PGA = a)$ reaches 1. These terms both have LSC-specific coefficients; these are shown in Table 1.

K_m is a magnitude-correction factor that scales $P(L)$ for earthquake magnitudes other than $M=7.5$, potentially to account for the duration of shaking (longer shaking increases liquefaction probability). K_w is a groundwater depth correction factor (shallower groundwater increases liquefaction probability).

LSC	PGA min	PGA slope	PGA int	P_{ml}
very high	0.09	9.09	0.82	0.25
high	0.12	7.67	0.92	0.2
moderate	0.15	6.67	1.0	0.1
low	0.21	5.57	1.18	0.05
very low	0.26	4.16	1.08	0.02
none	∞	0.0	0.0	0.0

Table 1: Liquefaction values for different liquefaction susceptibility categories (LSC). $PGA\ min$ is the minimum ground acceleration required to initiate liquefaction. $PGA\ slope$ is the slope of the liquefaction probability curve as a function of PGA, and $PGA\ int$ is the y-intercept of that curve. P_{ml} is the Map Area Proportion, which gives the area of liquefaction within each map unit conditional on liquefaction occurring in the map unit.

4.1.1.2 Geospatial models

Zhu et al. (2015)

The model by Zhu et al. (2015) is a logistic regression model requiring specification of the $V_{s30}[m/s]$, the Compound Topographic Index (CTI), a proxy for soil wetness or groundwater depth $gwd[m]$, the $PGA_{M,SM}[g]$ experienced at a site, and the magnitude of the causative earthquake.

The model is quite simple. An explanatory variable X is calculated as:

$$X = 24.1 + 2.067 \ln PGA_{M,SM} + 0.355 CTI - 4.784 \ln Vs30(2)$$

and the final probability is the logistic function

$$P(L) = \frac{1}{1 + e^X}(3)$$

The term $PGA_{M,SM}$ is the PGA corrected by magnitude scaling factor (MSF) that serves as proxy for earthquake duration. The MSF is calculated as per Idriss et al. (1991):

$$MSF = 10^2 \cdot 24M^2 \cdot 56(4)$$

Both the CTI and the $Vs30$ may be derived from digital elevation data. The $Vs30$ may be estimated from the topographic slope through the equations of Wald and Allen (2007), which uses a very low resolution DEM compared to modern offerings. As topographic slope tends to increase with increased DEM resolution, the estimated $Vs30$ does too; therefore a low-resolution DEM (i.e., a 1 km resolution) must be used to calculate $Vs30$, rather than the 30 m DEM that is the current standard. This results in a more accurate $Vs30$ for a given slope measurement, but it also means that in an urban setting, sub-km-scale variations in slope are not accounted for.

The CTI (Moore et al., 1991) is a proxy for soil wetness that relates the topographic slope of a point to the upstream drainage area of that point, through the relation

$$CTI = \ln(d_a / \tan \delta)(4)$$

where d_a is the upstream drainage area per unit width through the flow direction (i.e. relating to the DEM resolution). It was developed for hillslopes, and is not meaningful in certain very flat areas such as the valley floors of major low-gradient rivers, where the upstream drainage areas are very large. Unfortunately, this is exactly where liquefaction is most expected away from coastal settings.

Model's prediction can be transformed into binary class (liquefaction occurrence or nonoccurrence) via probability threshold value. The authors proposed a threshold of 0.2.

Bozzoni et al. (2021)

The parametric model developed by Bozzoni et al. (2021), keeps the same input variables (i.e., $PGA_{M,SM}$, CTI , $Vs30$) and functional form as in Zhu et al. (2015). Regression parameters are calibrated based on the liquefaction case histories observed during seismic events in Europe. The implemented model is associated with the ADASYN sampling algorithm. The explanatory variable X is computed as:

$$X = -11.489 + 3.864 \ln PGA_M + 2.328 CTI - 0.091 \ln Vs30(5)$$

and the probability of liquefaction is calculated using equation (3).

The adopted probability threshold of 0.57 converts the probability of liquefaction into binary outcome.

Zhu et al. (2017)

Two parametric models are proposed by Zhu and others (2017), a coastal model (Model 1), and a more general model (Model 2). A coastal event is defined as one where the liquefaction occurrences are, on average, within 20 km of the coast; or, for earthquakes with insignificant or no liquefaction, epicentral distances less than 50 km. The implemented geospatial models are for global use. An extended set of input parameters is used to describe soil properties (its density and wetness). The ground shaking is characterised by $PGV[cm/s]$. Soil density is described by $Vs30[m/s]$. Soil wetness in Model 1 is characterised by a set of features: mean annual precipitation $precip[mm]$, distance to the coast $d_c[km]$, and distance to the river $d_r[km]$. Distance to the coast also indicates the geologic age - younger deposits are found near the coast. Soil wetness in Model 2 is characterised by closest distance to the water body $d_w[km]$ which is determined as $\min(d_c, d_r)$, and the water table depth $wtd[m]$. Mean annual precipitation is from a global layer developed by Hijmans et al. (2005). Distance to the nearest river is calculated based on the HydroSHEDS database (Lehner et al. 2008). Water table depth is retrieved from a global dataset by Fan et al (2013). Distance to the nearest coastline data was computed from <https://oceancolor.gsfc.nasa.gov>.

The explanatory variable X is calculated as:

Model 1: .. math:: X = 12.435 + 0.301, \ln, PGV - 2.615, \ln, Vs30 + 0.0005556, precip .. math:: -0.0287, \sqrt{d_c} + 0.0666, d_r - 0.0369, \sqrt{d_c} \cdot d_r \quad (6)

Model 2: .. math:: X = 8.801 + 0.334, \ln, PGV - 1.918, \ln, Vs30 + 0.0005408, precip .. math:: -0.2054, d_w - 0.0333, wtd \quad (7)

and the probability of liquefaction is calculated using equation (3). Zero probability is heuristically assigned if $PGV < 3cm/s$ or :math: ' $Vs30 > 620m/s$ '.

The proposed probability threshold to convert to class outcome is 0.4.

Another model's outcome is liquefaction spatial extent (LSE). After an earthquake LSE is the spatial area covered by surface manifestations of liquefaction reported as a percentage of liquefied material within that pixel. Logistic regression with the same form was fit for the two models, with only difference in squaring the denominator to improve the fit. The regression coefficients are given in Table 2.

$$L(P) = \frac{a}{1 + b e^{(-cP)}}^2 \quad (8)$$

Parameters	Model 1	Model 2
a	42.08	49.15
b	62.59	42.40
c	11.43	9.165

Table 2: Parameters for relating probabilities to areal liquefaction percent.

Rashidian et al. (2020)

The model proposed by Rashidian et al. (2020) keeps the same functional form as the general model (Model 2) proposed by Zhu et al. (2017); however, introducing two constraints to address the overestimation of liquefaction extent. The mean annual precipitation has been capped to 1700 mm. No liquefaction is heuristically assigned when $pga < 0.1g$ as an additional measure to decrease the overestimation of liquefaction. Additional novelty introduced in this model is the magnitude scaling factor MSF to multiply the PGV to mitigate the potential over-prediction in earthquake with low magnitude.

The explanatory variable X is evaluated using the equation (7) that corresponds to the general model of Zhu et al. (2017). The spatial extent is evaluated identically using the equation (8).

The proposed probability threshold to convert to class outcome is 0.4.

Akhlagi et al. (2021)

Expanding the liquefaction inventory to include 51 earthquake, Akhlagi et al. (2021) proposed two candidate models to predict probability of liquefaction. Shaking is expressed in terms of $PGV [cm/s]$. Soil saturation is characterised using the set of proxies: distance to the nearest coastline $d_c[m]$, distance to the closest river $d_r[m]$, elevation from the closest water body $Z_{wb}[m]$. Soil density is characterised either by $Vs30[cm/s]$ or topographic roughness index TRI which is defined as the mean difference between a central pixel and its eight surrounding cells. The explanatory variables of two candidate models are:

Model 1: .. math:: X = 4.925 + 0.694, \ln, PGV - 0.459, \sqrt{TRI} - 0.403, \ln, d_c + 1 .. math:: -0.309, \ln, d_r + 1 - 0.164, \sqrt{Z_{wb}} \quad (10)

Model 2: .. math:: X = 9.504 + 0.706, \ln, PGV - 0.994, \ln, Vs30 - 0.389, \ln, d_c + 1 .. math:: -0.291, \ln, d_r + 1 - 0.205, \sqrt{Z_{wb}} \quad (11)

and the probability of liquefaction is calculated using equation (3). Zero probability is heuristically assigned if $PGV < 3cm$ or $Vs30 > 620m/s$.

The proposed probability threshold to convert to class outcome is 0.4.

Allstadth et al. (2022)

The model proposed by Allstadth et al. (2022) uses the model proposed by Rashidian et al. (2020) as a base with slight changes to limit unrealistic extrapolations. The authors proposed capping the mean annual precipitation at 2500 mm, and PGV at 150 cm/s. The magnitude scaling factor MSF , explanatory variables X , probability of liquefaction $P(L)$, and liquefaction spatial extent LSE are calculated using the set of equations previously shown. The proposed probability threshold to convert to class outcome is 0.4.

Todorovic et al. (2022)

A non-parametric model was proposed to predict liquefaction occurrence and the associated probabilities. The general model was trained on the dataset including inventories from over 40 events. A set of candidate variables were considered and the ones that correlate the best with liquefaction occurrence are identified as: strain proxy, a ratio between $pgv[cm/s]$ and $Vs30[m/s]$; distance to the closest water body $d_w[km]$, water table depth $gwd[m]$, average precipitation $precip[mm]$.

4.1.1.3 Permanent ground displacements due to liquefaction

Evaluation of the liquefaction induced permanent ground deformation is conducted using the methodology developed for the HAZUS software by the US Federal Emergency Management Agency. Lateral spreading and vertical settlements can have detrimental effects on the built environment.

Lateral spreading (Hazus)

The expected permanent displacement due to lateral spreading given the susceptibility category can be determined as:

Where: $E[PGD|(PGA/PL_{SC}) = a]$ is the expected ground displacement given the susceptibility category under a specified level of normalised shaking, and is calculated as: .. :math:: 12, x - 12 text{for} 1 < PGA/PGA(t) < 2 .. :math:: 18, x - 24 text{for} 2 < PGA/PGA(t) < 3 .. :math:: 70, x - 180 text{for} 3 < PGA/PGA(t) < 4

($PGA/PGA(t)$) $PGA(t)$ is the minimum shaking level to induce liquefaction (see Table 1) K_Δ is the displacement correction factor given that modify the displacement term for magnitudes other than $M7.5$: .. :math:: K_{\Delta} = 0.0086, M^3 - 0.0914, M^2 + 0.4698, M - 0.9835 (13)

Vertical settlements (Hazus)

Ground settlements are assumed to be related to the area's susceptibility category. The ground settlement amplitudes are given in Table 3 for the portion of a soil deposit estimated to experience liquefaction at a given ground motion level. The expected settlements at the site is the product of the probability of liquefaction (equation 1) and the characteristic settlement amplitude corresponding to the liquefaction susceptibility category (LSC).

LSC	Settlements (inches)
very high	12
high	6
moderate	2
low	1
very low	0
none	0

Table 3: Ground settlements amplitudes for liquefaction susceptibility categories.

4.1.2 Landslide models

Landslides are considered as one of the most damaging secondary perils associated with earthquakes. Earthquake-induced landslides occurs when the static and inertia forces within the sliding mass reduces the factor of safety below 1. Factors contributing to a slope failure are rather complex. The permanent-displacement analysis developed by Newmark (1965) is used to model the dynamic performance of slopes (Jibson 2020, 2007). It considers a slope as a rigid block resting on an inclined plane at an angle α (derived from Digital Elevation Model, DEM). When the input motion which is expressed in terms of acceleration exceeds the critical acceleration a_c , the block starts to move. The critical acceleration accounts for the shear strength and geometrical characteristics of the sliding surface, and is calculated as:

The lower bound of a_c is set to 0.05 to avoid unrealistically large displacements. The static factor of safety is calculated as:

where: $c' [Pa]$ is the effective cohesion with typical values ranging from 20 kPa for soils up to 20 MPa for unfaulted rocks. $\alpha [^\circ]$ is the slope angle. $\phi' [^\circ]$ is the effective friction angle with typical values ranging from 30 to 40 degrees. $\gamma [kg/m^3]$ is the dry density of the soil or rock. It ranges from $\sim 1500 kg/m^3$ for soils to $\sim 2500 - 3200 kg/m^3$. $t[m]$ is the slope-normal thickness of a failure slab with the default value of 2.5 meters. m is the proportion of slab thickness that is saturated with default value of 0.1. $\gamma_w [kg/m^3]$ is the unit weight of water which equals to $1000 kg/m^3$.

Note that the units of the input parameters reported in this document corresponds to the format required by the Engine to produce correct results. The first and second term of the equation (15) corresponds to the cohesive and frictional components of the strength, while the third component accounts for the strength reduction due to pore pressure.

A variety of regression equations can be used to estimate the Newmark displacements, and within the engine, Newmark displacement as a function of critical acceleration ratio and moment magnitude is implemented. The displacement is in units of meters.

The computed displacements do not necessarily correspond directly to measurable slope movements in the field, but the modeled displacements provide an index to correlate with field performance. Jibson (2000) compared the predicted displacements with observations from 1994

Northridge earthquake and fit the data with Weibull curve. The following equation can be used to estimate the probability of slope failure as a function of Newmark displacement.

The rock-slope failures are the other common effect observed in earthquakes. The methodology proposed by Grant et al., (2016) captures the brittle behavior associated with rock-slope failures and discontinuities common in rock masses. The static factor of safety is computed as:

where: $c[Pa]$ is the cohesion with typical values ranging from 20 kPa for soils up to 20 MPa for unfaulted rocks. c_r is the cohesion provided by the root systems of vegetated hillslopes. Here, we adopted the default value of 0 root cohesion. $\alpha[^{\circ}]$ is the slope angle. $\gamma[kg/m^3]$ is the dry_density of the soil or rock. It ranges from $\sim 1500 kg/m^3$ for soils to $\sim 2500 - 3200 kg/m^3$. $h[m]$ is the vertical height of the failure mass and it corresponds to 1/4 of the local relief H calculated based on the moving window analysis. $\phi'[^{\circ}]$ is the effective friction angle with typical values ranging from 30 to 40 degrees. β is the slope's critical angle calculated as: ... :math:: beta = frac{alpha + phi}{0.5}

(19)

The critical acceleration is computed similarly to equation (14). For rock- slope failures, the α term is replaced with β .

Finally, the coseismic displacements are estimated using Jibson's (2007) sliding block displacement regression equation:

4.1.3 Reference

- [1] HAZUS-MH MR5 Earthquake Model Technical Manual (<https://www.hSDL.org/?view&did=12760>)
- [2] Youd, T. L., & Idriss, I. M. (2001). **Liquefaction Resistance of Soils: Summary Report** from the 1996 NCEER and 1998 NCEER/NSF Workshops on Evaluation of Liquefaction Resistance of Soils. Journal of Geotechnical and Geoenvironmental Engineering, 127(4), 297–313. [https://doi.org/10.1061/\(asce\)1090-0241\(2001\)127:4\(297\)](https://doi.org/10.1061/(asce)1090-0241(2001)127:4(297))
- [3] I. D. Moore, R. B. Grayson & A. R. Ladson (1991). **Digital terrain modelling: A review of hydrological, geomorphological, and biological applications.** Journal of Hydrological Processes, 5(1), 3-30. <https://doi.org/10.1002/hyp.3360050103>
- [4] Wald, D.J., Allen, T.I., (2007). **Topographic Slope as a Proxy for Seismic Site Conditions and Amplification.** Bull. Seism. Soc. Am. 97 (5), 1379–1395.
- [5] Zhu et al., 2015, ‘**A Geospatial Liquefaction Model for Rapid Response and Loss Estimation**’, Earthquake Spectra, 31(3), 1813-1837.
- [6] Bozzoni, F., Bonì, R., Conca, D., Lai, C. G., Zuccolo, E., & Meisina, C. (2021). Megazonation of earthquake-induced soil liquefaction hazard in continental Europe. Bulletin of Earthquake Engineering, 19(10), 4059–4082. <https://doi.org/10.1007/s10518-020-01008-6>
- [7] Zhu, J., Baise, L. G., & Thompson, E. M. (2017). **An updated geospatial liquefaction model for global application.** Bulletin of the Seismological Society of America, 107(3),

1365–1385. <https://doi.org/10.1785/0120160198>

- [8] Rashidian, V., & Baise, L. G. (2020). **Regional efficacy of a global geospatial liquefaction model.** Engineering Geology, 272, 105644. <https://doi.org/10.1016/j.enggeo.2020.105644>
- [9] Allstadt, K. E., Thompson, E. M., Jibson, R. W., Wald, D. J., Hearne, M., Hunter, E. J., Fee, J., Schovanec, H., Slosky, D., & Haynie, K. L. (2022). The US Geological Survey ground failure product: Near-real-time estimates of earthquake-triggered landslides and liquefaction. Earthquake Spectra, 38(1), 5–36. <https://doi.org/10.1177/87552930211032685>
- [10] Baise, L. G., Akhlaghi, A., Chansky, A., Meyer, M., & Moeveni, B. (2021). **USGS Award #G20AP00029.** Updating the Geospatial Liquefaction Database and Model. Tufts University. Medford, Massachusetts, United States.
- [11] Todorovic, L., Silva, V. (2022). **A liquefaction occurrence model for regional analysis.** Soil Dynamics and Earthquake Engineering, 161, 1–12. <https://doi.org/10.1016/j.soildyn.2022.107430>
- [12] Newmark, N.M., 1965. Effects of earthquakes on dams and embankments. Geotechnique 15, 139–159.
- [13] Jibson, R.W., Harp, E.L., & Michael, J.A. (2000). **A method for producing digital probabilistic seismic landslide hazard maps.** Engineering Geology, 58(3-4), 271-289. [https://doi.org/10.1016/S0013-7952\(00\)00039-9](https://doi.org/10.1016/S0013-7952(00)00039-9)
- [14] Jibson, R.W. (2007). **Regression models for estimating coseismic landslide displacement.** Engineering Geology, 91(2-4), 209-218. <https://doi.org/10.1016/j.enggeo.2007.01.013>
- [15] Grant, A., Wartman, J., & Grace, A.J. (2016). **Multimodal method for coseismic landslide hazard assessment.** Engineering Geology, 212, 146-160. <https://doi.org/10.1016/j.enggeo.2016.08.005>

4.2 Tutorials for running secondary perils analysis

Tutorials are available for preparing data and performing calculations relating to secondary perils (liquefaction) in your own scripts.

These tutorials are given as Jupyter Notebooks:

Tutorial: Preparing site data for liquefaction analysis with the OpenQuake engine

Tutorial: Single earthquake liquefaction assessment

CHAPTER FIVE

THANKS

The OpenQuake Engine is developed by the [Global Earthquake Model Foundation \(GEM\)](#) with the support of

5.1 Public Partners



Australian Government
Geoscience Australia



Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra





5.2 Private Partners

5.2.1 Governors

EUCENTRE





5.2.2 Advisors



DESCARTES



PumerRe

safehub

LPPW
Willis
Towers
Watson

5.3 Associate Partners







5.4 Project Partners



Empower Results®



5.5 Products Distribution Partners





If you would like to help support development of OpenQuake, please contact us at partnership@globalquakemodel.org. For more info visit the GEM website at <https://www.globalquakemodel.org/partners>

GLOSSARY

6.1 Area Source

A source type usually adopted to model distributed seismicity. In an area source the seismicity occurrence rate is assumed uniform over the source area; this produces an hazard pattern with a plateau of constant hazard inside the polygon delimiting the area source and values of hazard that tend to decrease as we move away from the border of the source

6.2 Asset

An asset is an element with a certain value, which can include buildings or population. For example, an asset can include an individual building at a given location, or a number of buildings that are grouped, co-located at a single location and classified with the same *Taxonomy*

6.3 Branch

The simplest element in a logic tree; it belongs to a *Branch Set* where it represents one possible option among a finite number of alternatives. A branch is associated with a weight value if the *Branch Set* represents the epistemic uncertainty on a parameter or a model when the *Branch Set* is used to specify alternative models (e.g. district *Magnitude-Frequency Distribution*)

6.4 Branch Set

The structure describing the epistemic uncertainty on a specific parameter or model included in a logic tree structure. It ensembles a number of *Branch*, each one representing a discrete alternative

6.5 Configuration File

The file (usually .ini) containing the information necessary to run a calculation in OpenQuake

6.6 Consequence Function

the distribution of the consequence (or loss) ratio conditional on a set of discrete limit states, defined for a particular *Taxonomy*

6.7 Consequence Model

A set of *Consequence Function* used to model the consequence ratios of all the *Taxonomy* in the *Exposure Model*

6.8 Characteristic Fault Source

A fault source typology where ruptures always cover the entire fault surface

6.9 Complex Fault Source

A source typology usually adopted to model subduction interface faults

6.10 Deductible

A parameter used in the calculation of insured losses that establishes the economic value that needs to be deducted from the ground-up losses

6.11 Seismic Hazard Disaggregation

A methodology to investigate the contributions to a specific level of hazard in terms of fundamental variables commonly used to characterize seismic sources and ground motion models (e.g. magnitude, source-site distance, *Epsilon*)

6.12 Dip

The dip is the steepest angle of descent of the fault plane relative to a horizontal plane; it is measured in degrees [0,90]

6.13 Disaggregation Matrix

A multi-dimensional matrix used to systematically store the contributions to a level of hazard to be disaggregated and that is specified by the user. See also *Seismic Hazard Disaggregation*

6.14 Earthquake Rupture Forecast

A list of all possible ruptures generated by all the sources included in a seismic source model. Each element in the list contains: the rupture geometry and the rupture probability of occurrence in a given time span. See also the definition available on the [OpenSHA website](#)

6.15 Earthquake Rupture Forecast Calculator

Calculator producing a *Seismic Source Model* from a *Seismic Source Logic Tree*

6.16 Epsilon

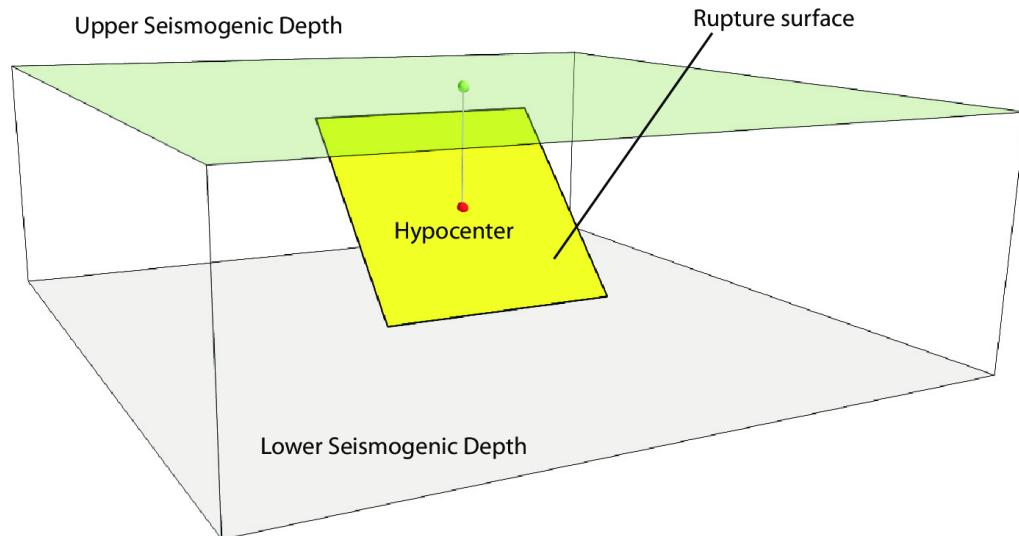
normalized residual of the ground motion

6.17 Exposure Model

A set of *Asset* grouped according to their geographical location, *Taxonomy* and value

6.18 Fault Trace

A curve representing the intersection between the surface containing the fault surface (or its prolongation) and the topographic surface



6.19 Fragility Function

the probability of exceeding a set of limit states, given an intensity measure level. These functions can be discrete or continuous

6.20 Fragility Model

A set of *Vulnerability Function* used to model the fragility of all the *Asset* in the *Exposure Model*

6.21 Frequency-Magnitude Distribution

A distribution describing the frequency of earthquakes with a specific magnitude. It can be continuous or discrete. One frequency-magnitude distribution frequently adopted in PSHA is the double truncated Gutenberg-Richter distribution

6.22 Grid Source

A source typology usually adopted to model distributed seismicity. It is routinely produced by a seismicity smoothing algorithm (one of the most famous algorithm is the one proposed by Frankel 1995)

6.23 Ground-Motion Field (GMF)

An object describing the geographic distribution around a rupture of a ground motion intensity measure

6.24 Ground-Motion Field Calculator

An OpenQuake engine calculator that given a rupture computes the geographic distribution of a ground motion intensity parameter. Currently OQ can generate ground motion fields using a *Ground-Motion Prediction Equation*

6.25 Ground-Motion Logic Tree

A method used to systematically describe the epistemic uncertainties related to the ground motion models used in the computation of hazard using a specific *PSHA Input Model*

6.26 Ground-Motion Model

An object that given a rupture with specific properties computes the expected ground motion at the given site. In simplest case a ground motion model corresponds to a *Ground-Motion Prediction Equation*. In case of complex PSHA input models, the produced ground motion models contains a set of *Ground-Motion Prediction Equations*, one for each tectonic region considered

6.27 Ground-Motion Parameter

A scalar or vector quantity describing a relevant property of the shaking such as intensity (e.g. PGA or Spectral Acceleration) or duration, equivalent number of cycles. See for example Hancock 2005.

6.28 Ground-Motion Prediction Equation (GMPE)

An equation that - given some fundamental parameters characterizing the source, the propagation path and the site (in the simplest case magnitude, distance and VS30) - computes the value GM of a (scalar) ground motion intensity parameter

6.29 Ground-Motion System

An object containing a list of *Ground-Motion Logic Trees*

6.30 Initial Seismic Source Input Model

It is the ensemble of information needed to fully describe the seismic sources composing a seismic source input model. The initial seismic source input model is included in the first branching level of a seismic source logic tree

6.31 Insured Losses

Fraction of the ground-up losses that can be covered by the insurance industry, according to a certain policy

6.32 Integrated Risk Modelling Toolkit

A plugin for QGIS which includes tools to run the OpenQuake Engine, to visualize hazard and risk results, to develop composite indicators and integrate them with physical risk estimations, and to predict building recovery times following an earthquake. This plugin was designed as a collaborative effort between the GEM Foundation and the Center for Disaster Management and Risk Reduction Technology, and it has been developed by the GEM Foundation.

6.33 Investigation Time

The time interval considered to calculate hazard; usually it corresponds to 50 years

6.34 Limit

A parameter used in the calculation of insured losses that establishes the maximum economic amount that can be covered by the insurance industry, according to a certain insurance policy

6.35 Logic Tree

Data structure used to systematically describe uncertainties on parameters and models used in a PSHA study

6.36 Logic Tree Processor

An OQ calculator that takes the PSHA Input Model and creates many realisations of a *Seismic Source Model* and of a *Ground-Motion Model*

6.37 Magnitude-Scaling Relationship

An empirical relationship linking the magnitude with a parameter describing the size of the corresponding rupture (e.g. the area of the rupture or the rupture length)

6.38 Magnitude-Frequency Distribution

A distribution describing the frequency of earthquakes with a specific magnitude. It can be continuous or discrete. One frequency-magnitude distribution frequently adopted in *PSHA* is the double truncated Gutenberg-Richter distribution

6.39 Non-Parametric Source

A source typology in which the earthquake rupture forecast is described explicitly by a set of ruptures and the corresponding probabilities of occurrence

6.40 Natural Hazards' Risk Markup Language

A markup language similar to XML, which specifies a number of standardised schemas to represent various input models used for OpenQuake engine calculations and output files generated by the OpenQuake engine

6.41 OpenSHA

OpenSHA is an open-source, advanced Java-based platform for conducting Seismic Hazard Analysis - (see the [OpenSHA website](#))

6.42 Point Source

The elemental source typology used in the OpenQuake Engine to model distributed seismicity

6.43 PSHA Input Model

An object containing the information necessary to describe the seismic source and the ground motion models - plus the related epistemic uncertainties

6.44 Probabilistic Seismic Hazard Analysis (PSHA)

A methodology to compute seismic hazard by taking into account the potential contributions coming from all the sources of engineering importance for a specified site

6.45 Earthquake Rupture

A 3D surface - representing a portion or the entire fault surface - over which a slip event (i.e. an earthquake) occurs

6.46 Rupture Model

An object containing the information necessary to describe a *Rupture*, such as magnitude, hypocenter location, strike, dip, rake, and seismogenic depths

6.47 Rupture Aspect Ratio

The ratio between the length and the width of an earthquake rupture

6.48 Rake

The rake is the direction in which a hanging wall block moves during a rupture, measured relative to fault strike on the plane of the fault

6.49 Scenario Based Seismic Hazard Analysis

An analysis of seismic hazard based on the selection of one or a few ruptures and the computation of the expected ground motion at a set of sites using a *GMPE* accounting ground motion variability

6.50 Seismicity History

An object containing a set ruptures representative of the possible seismicity generated by the sources in a *Seismic Source Model* during the investigation time t

6.51 Seismicity Rate

Number of events per unit of time (if not better specified, the definition of a seismicity rate generally presumes a time independent

6.52 Seismic Source Data

An object containing the information necessary to completely describe a *PSHA* seismic source i.e. seismic source type, position, geometry and seismicity occurrence model

6.53 Seismic Source Logic Tree

Logic tree structure defined to describe in a structured and systematic way the epistemic uncertainties characterizing the seismic source model. The first branching level in the logic tree by definition contains one or several alternative *Initial Seismic Source Input Model*

6.54 Seismic Source Input Model

An object containing a list of *Seismic Source Data*. In the OpenQuake Engine a seismic source model does not contain epistemic uncertainty

6.55 Seismic Source

An object that can generate

6.56 Seismic Source Model (SSM)

An object containing a list of *Seismic Source* objects

6.57 Seismic Source System

An object containing a list of *Initial Seismic Source Input Model* and the *Seismic Source Logic Tree*

6.58 Simple Fault Source

A source typology usually adopted to model shallow structures with an uncomplicated geometry

6.59 Stochastic Event Set

An object containing one or many *Seismicity History*

6.60 Strike

The strike direction correspond to the angle between thenorth and the direction you take so that when you walk along the *Fault Trace* the fault dips on your right

6.61 Tag

Scheme used to specify attributes for the *Asset*. Attributes for an *Asset* could include the state, county, zip-code, city, occupancy, CRESTA ID, or other such markers that could be used in the post-processing stage of a risk calculation to aggregate results for each tag.

6.62 Taxonomy

Scheme used to classify the *Asset*. For buildings, a classification scheme has been proposed by the GEM Foundation which considers a number of attributes including lateral load resisting system and its material, height, year of construction. The taxonomy is currently used to link the *Asset* in the *Exposure Model* to the relevant *Vulnerability Function* or *Fragility Function*

6.63 Tectonic Region

A area on the topographic surface that can be considered homogeneous in terms of tectonic properties such as the prevalent seismogenic properties and/or the seismic wave propagation properties

6.64 Temporal Occurrence Model

Usually a probabilistic model giving the probability of occurrence of an event in a specified *Investigation Time*

6.65 Vulnerability Function

A function that describes the probability distribution of loss ratio, conditioned on an intensity measure level. Currently only discrete vulnerability functions are supported

6.66 Vulnerability Model

A set of *Vulnerability Function* used to model the physical vulnerability of all the *Asset* in the *Exposure Model*

6.67 VS30

Average shear wave velocity of the materials in the uppermost 30m of the soil column
globalquakemodel.org/openquake

Authors

Marco Pagani¹, Vitor Silva¹, Anirudh Rao¹, Michele Simionato¹, Kendra Johnson¹

Authors on previous versions

Helen Crowley², Damiano Monelli³, Graeme Weatherill⁴, Robin Gee⁵

¹ GEM Foundation, via Ferrata 1, 27100 Pavia, Italy

² EUCENTRE, via Ferrata 1, 27100 Pavia, Italy

³ RenRe, Beethovenstrasse 33, CH-8002 Zürich, Switzerland

⁴ GFZ, Helmholtzstraße 6/7, 14473 Potsdam, Germany

⁵ PartnerRe, Hardstrasse 301, CH-8002 Zürich, Switzerland

Email address for all current authors:

<firstname.lastname>@globalquakemodel.org

Citation

Please cite this document as: GEM (2022). The OpenQuake-engine User Manual. Global Earthquake Model (GEM) OpenQuake Manual for Engine version 3.18.0. doi: 10.13117/GEM.OPENQUAKE.MAN.ENGINE.3.18.0

Disclaimer

The OpenQuake-engine User Manual is distributed in the hope that it will be useful, but without any warranty: without even the implied warranty of merchantability or fitness for a particular purpose. While every precaution has been taken in the preparation of this document, in no event shall the authors of the Manual and the GEM Foundation be liable to any party for direct, indirect, special, incidental, or consequential damages, including lost profits, arising out of the use of information contained in this document or from the use of programs and source code that may accompany it, even if the authors and GEM Foundation have been advised of the possibility of such damage. The Manual provided hereunder is on as “as is” basis, and the authors and GEM Foundation have no obligations to provide maintenance, support, updates, enhancements, or modifications.

License

This Manual is distributed under the Creative Commons License Attribution-NonCommercial-ShareAlike 4.0 International ([CC BY-NC-SA 4.0](#)). You can download this Manual and share it with others as long as you provide proper credit, but you cannot change it in any way or use it commercially.

RST format manual

This manual was adapted from LaTeX to reStructured Text format as part of the TREQ project by Paul Henshaw¹ and Sandra Giacomini¹.

The RSTformat manual is made possible by the support of the American People through the United States Agency for International Development (USAID.) The contents of this study are the sole responsibility of the GEM Foundation and do not necessarily reflect the views of USAID or the United States Government.



© 2013–2022 GEM Foundation

April 2022