

OpenQuake

calculate share explore

OPENQUAKE ENGINE

underlying hazard science

Version 0.9

An explanation of the scientific basis and the methodologies adopted in the implementation of the OpenQuake engine, an open source code for seismic hazard and physical risk calculation.



“OpenQuake: Calculate, share, explore”

OpenQuake Engine User Instruction Manual

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PART I

Introduction

OpenQuake engine background

1.1. OpenQuake-engine introduction

OpenQuake-engine (OQe) is the hazard and risk calculation engine developed by the Global Earthquake Model. OpenQuake-engine is an open source software developed using a test-driven development paradigm.

The OpenQuake-engine code is available on GitHub (a web repository) at the following address <http://github.com/gem/oq-engine>.

1.2. Running the OpenQuake-engine

The execution of an analysis using the OpenQuake-engine is launched from the command line of a terminal. A schematic list of the options that can be used for the execution of the **OQe** can be obtained with the following command:

```
user@ubuntu:~$ openquake --help
```

The result is the following:

```
usage: openquake [-h] [--version] [--log-file LOG_FILE]
                 [--log-level debug,info,progress,warn,error,critical]
                 [--no-distribute] [--list-inputs INPUT_TYPE] [--yes]
                 [--run-hazard CONFIG_FILE] [--list-hazard-calculations]
                 [--list-hazard-outputs HAZARD_CALCULATION_ID]
                 [--export-hazard OUTPUT_ID TARGET_DIR]
                 [--delete-hazard-calculation HAZARD_CALCULATION_ID]
                 [--run-risk CONFIG_FILE] [--hazard-output-id HAZARD_OUTPUT]
                 [--hazard-calculation-id HAZARD_CALCULATION_ID]
                 [--list-risk-calculations]
                 [--list-risk-outputs RISK_CALCULATION_ID]
                 [--export-risk OUTPUT_ID TARGET_DIR]
                 [--delete-risk-calculation RISK_CALCULATION_ID]
```

[--exports xml]

OpenQuake Seismic Hazard and Risk Analysis Engine

optional arguments:

-h, --help show this help message and exit

General:

--version Display version information
--log-file LOG_FILE, -L LOG_FILE Location to store log messages; if not specified, log messages will be printed to the console (to stderr)
--log-level debug,info,progress,warn,error,critical, -l debug,info,progress,warn,error,critical Defaults to "progress"
--no-distribute, --nd Disable calculation task distribution and run the computation in a single process. This is intended for use in debugging and profiling.
--list-inputs INPUT_TYPE, --li INPUT_TYPE List inputs of a specific input type
--yes, -y Automatically answer "yes" when asked to confirm an action

Hazard:

--run-hazard CONFIG_FILE, --rh CONFIG_FILE Run a hazard job with the specified config file
--list-hazard-calculations, --lhc List hazard calculation information
--list-hazard-outputs HAZARD_CALCULATION_ID, --lho HAZARD_CALCULATION_ID List outputs for the specified hazard calculation
--export-hazard OUTPUT_ID TARGET_DIR, --eh OUTPUT_ID TARGET_DIR Export the desired output to the specified directory
--delete-hazard-calculation HAZARD_CALCULATION_ID, --dhc HAZARD_CALCULATION_ID Delete a hazard calculation and all associated outputs

Risk:

--run-risk CONFIG_FILE, --rr CONFIG_FILE Run a risk job with the specified config file
--hazard-output-id HAZARD_OUTPUT, --ho HAZARD_OUTPUT Use the desired hazard output as input for the risk job
--hazard-calculation-id HAZARD_CALCULATION_ID, --hc HAZARD_CALCULATION_ID Use the desired hazard calculation as input for the risk job
--list-risk-calculations, --lrc List risk calculation information
--list-risk-outputs RISK_CALCULATION_ID, --lro RISK_CALCULATION_ID List outputs for the specified risk calculation
--export-risk OUTPUT_ID TARGET_DIR, --er OUTPUT_ID TARGET_DIR Export the desired risk output to the specified directory
--delete-risk-calculation RISK_CALCULATION_ID, --drc RISK_CALCULATION_ID Delete a risk calculation and all associated outputs

List and export:

--exports xml Automatically export all calculation results to the specifiedformat. Only "xml" is supported currently.

PART II

Hazard

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 calculation. The web repository of this library is available at the following address: <http://gitub.com/gem/oq-hazardlib>. In this chapter we briefly illustrate the main properties of the hazard component of the engine. In particular, we will describe the main typologies of sources supported and the main calculation workflows available.

2.1. Source typologies

A general **OQe seismic source input model** contains a list of seismic source inputs belonging to a finite set of possible typologies. Each source type is defined by a group of parameters essential for specifying source geometry and seismicity occurrence characteristics.

Currently the OpenQuake-engine supports the following source types:

- Sources for modelling distributed seismicity:
 - **Point source** - The elemental source type use to model distributed seismicity. Grid and area sources described below are basically two different containers of point sources.
 - **Area source** - So far, the most frequently adopted source type in national and regional PSHA models.
 - Grid sources - Can be considered a replacement for area sources since they both model distributed seismicity.
- Fault sources with floating ruptures:

2. Introduction to the hazard module

- **Simple fault source** - The simplest fault model in OpenQuake. This typology 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.

There are some basic assumptions accepted in the definition of these source typologies such as:

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

2.1.1. Source typologies for modelling distributed seismicity

2.1.1.1. Point sources

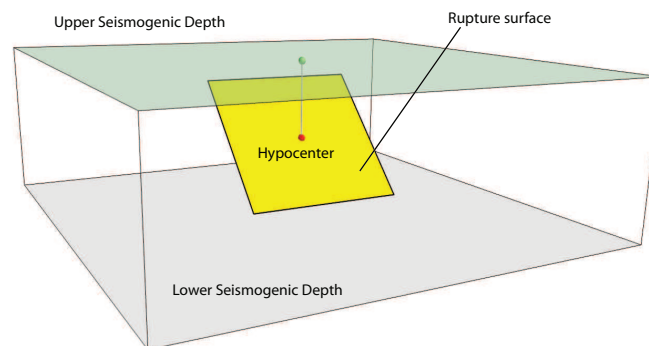


Figure 2.1. – *Single rupture*

Point source is the elemental source type adopted in the OpenQuake engine to model distributed seismicity. These are the basic assumptions used to generate finite ruptures with point sources:

- ruptures have a rectangular shape
- rupture's 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 topographic surface and placed at two characteristic depths named upper and lower seismogenic depths, respectively.

Source data

For each point source (i.e. grid node) the following parameters are requested (Figure 2.1 shows some of the parameters described below, together with an example of rupture):

- The coordinates of the point (i.e. Longitude and Latitude in decimal degrees)
- The upper and lower seismogenic depths;
- One **magnitude-frequency distribution** (see also Section 2.1.4 at page 23);
- 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**
 - **dip**
 - **rake**
- A magnitude independent depth distribution of hypocenters.

Figure 2.2 shows multiple ruptures of different magnitude centered on the single hypocentre allowed by this point source. Ruptures are created by conserving the area obtained from magnitude through a magnitude-area scaling relationship. Below we provide the excerpt of an .xml file used to describe the properties of a point source in a seismic source model. In this example, ruptures occur on two possible nodal planes and two hypocentral depths. Figure 2.3 shows all the possible ruptures generated by the point source specified in the inset.

```
1 <pointSource id="1" name="point" tectonicRegion="Stable Continental Crust">
2   <pointGeometry>
3     <gml:Point>
4       <gml:pos>-122.0 38.0</gml:pos>
5     </gml:Point>
6     <upperSeismoDepth>0.0</upperSeismoDepth>
```

2. Introduction to the hazard module

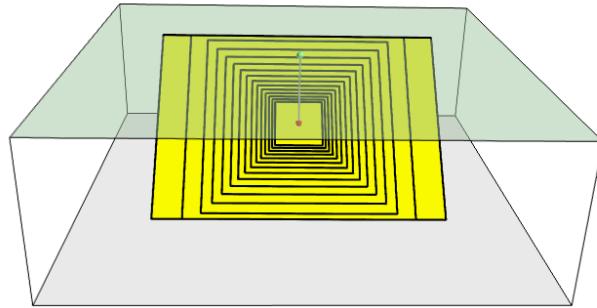


Figure 2.2. – *Point source with multiple ruptures. Note the change in the aspect ratio once the rupture width fills the entire seismogenic layer.*

```
7      <lowerSeismoDepth>10.0</lowerSeismoDepth>
8    </pointGeometry>
9    <magScaleRel>WC1994</magScaleRel>
10   <ruptAspectRatio>0.5</ruptAspectRatio>
11   <truncGutenbergRichterMFD aValue="-3.5" bValue="1.0" minMag="5.0"
12     maxMag="6.5" />
13   <nodalPlaneDist>
14     <nodalPlane probability="0.3" strike="0.0" dip="90.0" rake="0.0" />
15     <nodalPlane probability="0.7" strike="90.0" dip="45.0" rake="90.0" />
16   </nodalPlaneDist>
17   <hypoDepthDist>
18     <hypoDepth probability="0.5" depth="4.0" />
19     <hypoDepth probability="0.5" depth="8.0" />
20   </hypoDepthDist>
21 </pointSource>
```

2.1.1.2. 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 reproduce distributed seismicity usually incorporating events of low and intermediate magnitude. Grid sources usually are generated using seismicity smoothing algorithms [Frankel, 1995; Woo, 1996, amongst many others].

The use of this source type brings some advantages compared to area sources, since (1) it removes most of the unavoidable degree of subjectivity due to the

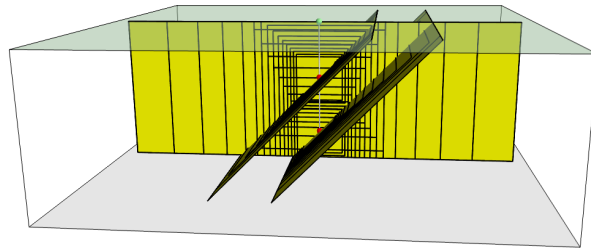


Figure 2.3. – *Ruptures produced by the source created using the information in the example .xml file described at page 15.*

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, some smoothing algorithms require an a-priori definition of some setup parameters that expose the calculation to a certain degree of partiality.

Grid sources are modelled in **OQe** simply as a set of point sources.

2.1.1.3. Area sources

Area sources describe the seismicity occurring over wide areas where 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. The **OQe** 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).

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. The current version of OQ doesn't support the definition of internal borders
- The upper and lower seismogenic depths;
- One **magnitude-frequency distribution** (see also Section 2.1.4 at page 23);
- One magnitude-scaling relationship;

2. Introduction to the hazard module

- The rupture aspect ratio;
- A distribution of nodal planes i.e. one (or several) instances of the following set of parameters:
 - strike
 - dip
 - rake
- A magnitude independent depth distribution of hypocenters.

Below we provide the excerpt of an .xml file used to describe the properties of an area source of a seismic source model. The ruptures generated inside this area source follow to possible nodal planes and have hypocenters at two 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
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   </nodalPlaneDist>
28   <hypoDepthDist>
29     <hypoDepth probability="0.5" depth="4.0" />
30     <hypoDepth probability="0.5" depth="8.0" />
31   </hypoDepthDist>
32 </areaSource>
```

2.1.2. Fault source with floating ruptures

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

- Faults where ruptures with a surface smaller than the whole fault surface are floated so as to cover - as much as possible - homogeneously the fault surface. This model is compatible with almost all the possible magnitude-frequency distributions.
- Faults where ruptures always fill the entire fault surface. This model is compatible with **Magnitude-Frequency Distributions (MFDs)** admitting a limited range of magnitudes (e.g. characteristic models à la **Schwartz and Coppersmith [1984]**).

In this Section we discuss fault source types that support floating ruptures.

2.1.2.1. 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 basically obtained by projecting a 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 **fault trace** (usually a polyline);
- A **magnitude-frequency distribution** (see also Section 2.1.4 at page 23);
- A representative value of the dip angle (specified following the Aki-Richards convention; see **Aki and Richards [2002]**);
- Rake angle (specified following the Aki-Richards convention; see **Aki and Richards [2002]**);
- Upper and lower depth values limiting the seismogenic interval;

Below we provide the excerpt of an .xml file used to describe the properties of a simple fault source.

2. Introduction to the hazard module

```
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>
20    <rake>30.0</rake>
21 </simpleFaultSource>
```

2.1.2.2. Complex faults

Complex faults differ from simple fault just by the way the geometry of the fault surface is defined and, consequently by the way 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 case of complex faults the dip angle is not requested while the fault trace is substituted by two fault edges limiting at the top and bottom the fault surface. Additional curves lying over the fault surface can be specified to complement and refine the description of the fault surface geometry.

Usually, we use complex faults to model interface faults such as the big subduction structures active in the Pacific (i.e. Sumatra, South America, Japan).

Below we provide the excerpt of a seismic source model .xml file containing a complex fault source.

```
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>
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>2.0</ruptAspectRatio>
43 <truncGutenbergRichterMFD aValue="-3.5" bValue="1.0" minMag="5.0"
44     maxMag="6.5" />
45 <rake>30.0</rake>
46 </complexFaultSource>

```

2.1.3. Fault source types without floating ruptures

2.1.3.1. Characteristic faults

Characteristic fault source has been created to support faults which conceptually follow a pure characteristic model (a la [Schwartz and Coppersmith \[1984\]](#)).

2. Introduction to the hazard module

Source data

- A fault surface (it always coincides with the rupture surface). Note that the fault surface in this case is defined by more than one elementary fault geometry (e.g. simple fault, complex fault).
- A **magnitude-frequency distribution** (see also Section 2.1.4 at page 23);
- Rake angle (specified following the Aki-Richards convention; see [Aki and Richards \[2002\]](#))

Below we provide the excerpt of an .xml file used to describe the properties of a characteristic fault source.

```
1 <characteristicFaultSource tectonicRegion="Subduction Interface" id="1"
2   name="Example Characteristic Source" >
3   <surface>
4     <complexFaultGeometry>
5       <faultTopEdge>
6         <gml:LineString>
7           <gml:posList>
8             -124.704 40.363 0.5493260E+01
9             -124.977 41.214 0.4988560E+01
10            -125.140 42.096 0.4897340E+01
11          </gml:posList>
12        </gml:LineString>
13      </faultTopEdge>
14      <faultBottomEdge>
15        <gml:LineString>
16          <gml:posList>
17            -123.829 40.347 0.2038490E+02
18            -124.137 41.218 0.1741390E+02
19            -124.252 42.115 0.1752740E+02
20          </gml:posList>
21        </gml:LineString>
22      </faultBottomEdge>
23    </complexFaultGeometry>
24  </surface>
25  <incrementalMFD>
26    <occurRates>50</occurRates>
27  </incrementalMFD>
28  <rake>0</rake>
29 </characteristicFaultSource>
```


2.1.4. Supported magnitude-frequency distributions

The magnitude-frequency distributions currently supported by the **OQe** are the following:

A discrete incremental magnitude-frequency distribution

It's the simplest distribution offered. It's defined by a 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 (centered on increasing values of magnitude). Below we show an example of the xml used to describe an incremental **MFDs** for a seismic source input of a **Seismic Source Input Model (SSIM)**.

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

This is the magnitude-frequency distribution obtained with the above settings:

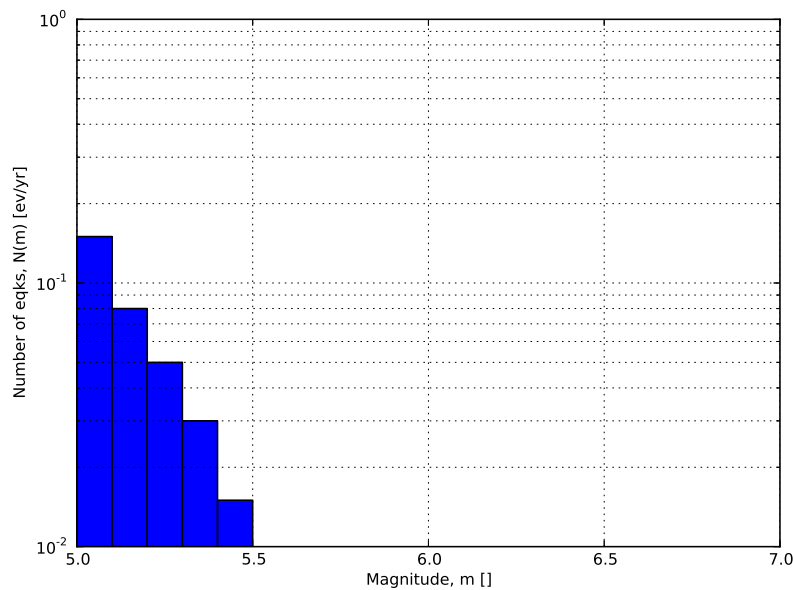


Figure 2.4. – *Incremental magnitude-frequency distribution.*

2. Introduction to the hazard module

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 is rather compact as shown below

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

This is the magnitude-frequency distribution obtained using the parameters of the considered example:

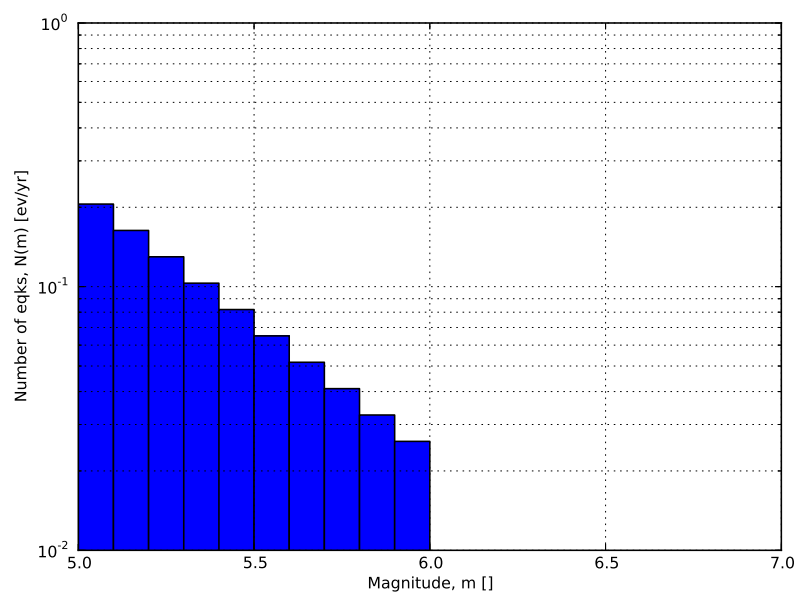


Figure 2.5. – *Double truncated Gutenberg-Richter magnitude-frequency distribution.*

Characteristic earthquake model (à la [Youngs and Coppersmith \[1985\]](#)) The

AA

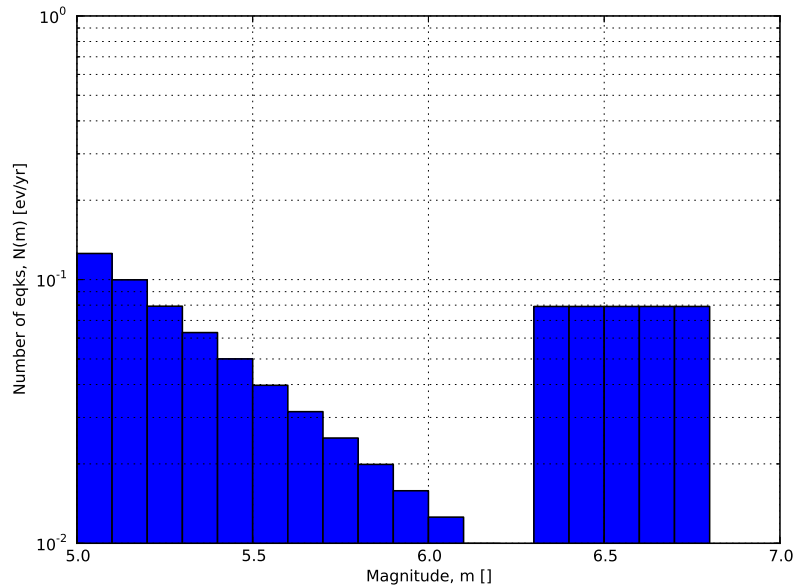


Figure 2.6. – *Yongs and Coppersmith [1985] magnitude-frequency distribution.*

2.2. Calculation workflows

The hazard component of the OpenQuake-engine can compute seismic hazard following 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 et al. \[2003\]](#).
- *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 (SSHA)*, allowing the calculation of ground motion fields from a single earthquake rupture scenario taking into account ground-motion aleatory variability.

Each workflow has a modular structure, so that intermediate results can be exported and analysed. 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. Introduction to the hazard module

2.2.1. Classical Probabilistic Seismic Hazard Analysis

Input data for the classical PSHA consist of an Input Model provided together with a set of calculation settings.

The main calculators used to perform this analysis are:

1. *Logic Tree Processor*

The Logic Tree Processor (LTP) takes as an input the **Probabilistic Seismic Hazard Analysis (PSHA)** Input Model and creates a Seismic Source Model. The LTP uses the information in the Initial Seismic Source Models and by 'harvesting' the information contained in the Seismic Source Logic Tree - that is to sample the epistemic uncertainties - it creates a Seismic Source Model (i.e. a model describing geometry and activity rates of each source without any epistemic uncertainty). Following the procedure 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 (GMPE)**).

2. *Earthquake Rupture Forecast Calculator*

The produced Seismic Source Model is then used as input for the Earthquake Rupture Forecast (ERF) calculator which computes the probability of occurrence, over a specified time span, for each earthquake rupture produced by the source model.

3. *Classical PSHA Calculator*

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

2.2.2. Event-Based Probabilistic Seismic Hazard Analysis

Input data for the Event-Based **PSHA** - as in the case of the Classical **PSHA** calculator - consist of a PSHA Input Model supplied to OQ together with a set of calculation settings. The main calculators used to perform this analysis are:

1. *Logic Tree Processor*

The Logic Tree Processor was already introduced in the description of the Classical **PSHA** workflow (see section 2.2.1 at page 26).

2. *Earthquake Rupture Forecast Calculator*

The Earthquake Rupture Forecast Calculator was already introduced in the description of the PSHA workflow (see section 2.2.1 at page 26).

3. *Stochastic Event Set Calculator*

The Stochastic Event Set Calculator generates a Stochastic Event set by sampling each rupture contained in the ERF according to its probability of occurrence. Usually a Stochastic Event Set (SES) contains a large number of seismicity histories each one representative of a possible collection of events that can be produced by the seismic source considered in an analysis during the time span fixed for the calculation of hazard (normally corresponding to 50 years).

4. *Ground Motion Field Calculator*

The Ground Motion Field Calculator computes for each event contained in a Stochastic Event Set - provided as an input - a realization of the ground shaking 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 GMF.

5. *Event-based PSHA Calculator*

The event-based PSHA calculator takes a (large) set of ground-motion fields representative of the possible shaking that the investigated area can eventually experience over a (large) time span and for each grid node in a ground-motion fields computes the corresponding hazard curve. This procedure is computationally intensive and is not recommended for investigating the hazard over large areas.

The Logic Tree Processor and the Earthquake rupture forecast were already introduced during the description of the PSHA workflow (see section 2.2.1 at page 26).

2.2.3. Scenario based Seismic Hazard Analysis

For **SSHA**, the input data consist of a single earthquake rupture model and a single ground-motion model. 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 calculators used to perform this analysis are:

1. *Ground Motion Field Calculator*

The Ground Motion Field Calculator was already introduced during the description of the event based PSHA workflow (see section 2.2.2 at page 26).

Using the hazard module

This Chapter summarises the structure of the information necessary to define the OpenQuake-engine PSHA input model.

3.1. Input Data definition

Input data for probabilistic based seismic hazard analysis (Classical, Event based, Disaggregation, and UHS) 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.

Figure 3.1 summarises the structure of a PSHA input model for the OpenQuake-engine and the relationships between the files.

3.1.1. The Seismic Source System

The Seismic Source System contains 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.

3. Using the hazard module

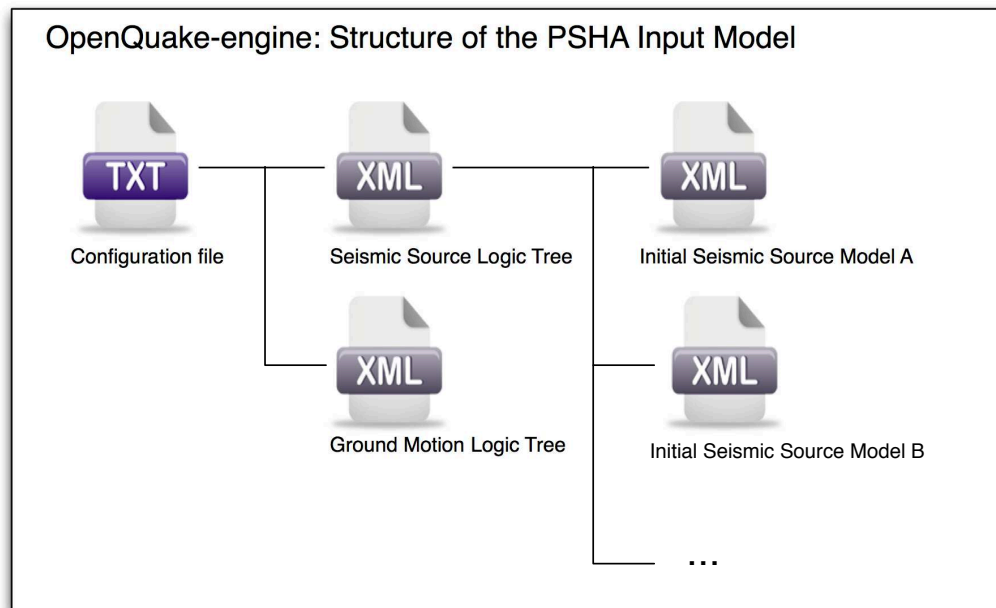


Figure 3.1. – PSHA Input Model structure

3.1.1.1. The Seismic Source Logic Tree

The structure of the Seismic Source Logic Tree consists of at least one branching level. The first - and mandatory - branching level is the one used to define one (or several) **initial seismic source input models** (see Figure 3.1). The successive branching levels can be used to account for epistemic uncertainties in the parameters characterizing the **initial seismic source input models**

The example provided below shows the simplest Seismic Source Logic Tree structure that can be defined in a PSHA Input model for OQ. This consists of a logic tree with one initial seismic source model (with weight equal to one) and no epistemic uncertainties.

```
1 <?xml version="1.0" encoding="UTF-8"?>
2 <nrml xmlns:gml="http://www.opengis.net/gml"
3     xmlns="http://openquake.org/xmlns/nrml/0.4">
4   <logicTree logicTreeID="lt1">
5     <logicTreeBranchingLevel branchingLevelID="b1">
6       <logicTreeBranchSet uncertaintyType="sourceModel"
7         branchSetID="bs1">
8         <logicTreeBranch branchID="b1">
9           <uncertaintyModel>seismic_source_model.xml
10          </uncertaintyModel>
```


3.1. Input Data definition

```
11         <uncertaintyWeight>1.0</uncertaintyWeight>
12     </logicTreeBranch>
13 </logicTreeBranchSet>
14 </logicTreeBranchingLevel>
15 </logicTree>
16 </nrml>
```

The optional branching levels will contain rules that modify specific parameters of the sources in the initial seismic source model so as to take into account the epistemic uncertainties.

For example, if the principal epistemic uncertainties to be considered are source geometry and maximum magnitude, the modeller can create a logic tree structure with three initial seismic source models (each one exploring a different definition of the geometry of sources and, an assigned weight) and one branching level accounting for the epistemic uncertainty on the maximum magnitude. Below we provide an example of such logic tree structure.

```
1 <?xml version="1.0" encoding="UTF-8"?>
2 <nrml xmlns:gml="http://www.opengis.net/gml"
3     xmlns="http://openquake.org/xmlns/nrml/0.4">
4     <logicTree logicTreeID="lt1">
5
6         <logicTreeBranchingLevel branchingLevelID="bl1">
7             <logicTreeBranchSet uncertaintyType="sourceModel"
8                 branchSetID="bs1">
9                 <logicTreeBranch branchID="b1">
10                     <uncertaintyModel>seismic_source_model_A.xml
11                     </uncertaintyModel>
12                     <uncertaintyWeight>0.2</uncertaintyWeight>
13                 </logicTreeBranch>
14                 <logicTreeBranch branchID="b2">
15                     <uncertaintyModel>seismic_source_model_B.xml
16                     </uncertaintyModel>
17                     <uncertaintyWeight>0.3</uncertaintyWeight>
18                 </logicTreeBranch>
19                 <logicTreeBranch branchID="b3">
20                     <uncertaintyModel>seismic_source_model_C.xml
21                     </uncertaintyModel>
22                     <uncertaintyWeight>0.5</uncertaintyWeight>
23                 </logicTreeBranch>
24             </logicTreeBranchSet>
25         </logicTreeBranchingLevel>
26     </logicTree>
```

3. Using the hazard module

```
27     <logicTreeBranchingLevel branchingLevelID="bl2">
28         <logicTreeBranchSet branchSetID="bs21"
29             uncertaintyType="maxMagGRRRelative">
30             <logicTreeBranch branchID="b211">
31                 <uncertaintyModel>+0.0</uncertaintyModel>
32                 <uncertaintyWeight>0.6</uncertaintyWeight>
33             </logicTreeBranch>
34             <logicTreeBranch branchID="b212">
35                 <uncertaintyModel>+0.5</uncertaintyModel>
36                 <uncertaintyWeight>0.4</uncertaintyWeight>
37             </logicTreeBranch>
38         </logicTreeBranchSet>
39     </logicTreeBranchingLevel>
40
41 </logicTree>
42 </nrml>
```

Note that the uncertainty on the maximum magnitude is specified in terms of relative increments with respect to the initial maximum magnitude defined in the initial seismic source models.

3.1.1.2. 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 typologies currently supported:

```
<sourceModel gml:id="ID">
    ...
    <areaSource gml:id="SOURCE_ID">
        <gml:name>SOURCE_NAME</gml:name>
        <tectonicRegion>TECT_REGION_TYPE</tectonicRegion>
        ...
    </areaSource>
    ...
    <pointSource gml:id="SOURCE_ID">
        <gml:name>SOURCE_NAME</gml:name>
        <tectonicRegion>TECT_REGION_TYPE</tectonicRegion>
        ...
    </pointSource>
    ...
    <simpleFaultSource gml:id="SOURCE_ID">
        <gml:name>SOURCE_NAME</gml:name>
```

```
        <tectonicRegion>TECT_REGION_TYPE</tectonicRegion>
        ...
    </simpleFaultSource>
    ...
    <complexFaultSource gml:id="SOURCE_ID">
        <gml:name>SOURCE_NAME</gml:name>
        <tectonicRegion>TECT_REGION_TYPE</tectonicRegion>
        ...
    </complexFaultSource>
    ...
</sourceModel>
```

3.1.2. The Ground Motion System

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

3.1.2.1. 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 fairly 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 **Chiou and Youngs [2008] GMPE**.

```
1 <?xml version="1.0" encoding="UTF-8"?>
2 <nrml xmlns:gml="http://www.opengis.net/gml"
3   xmlns="http://openquake.org/xmlns/nrml/0.4">
4   <logicTree logicTreeID='lt1'>
5     <logicTreeBranchingLevel branchingLevelID="b1">
6       <logicTreeBranchSet uncertaintyType="gmpeModel" 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>
```

3. Using the hazard module

```
15         </logicTreeBranchSet>
16     </logicTreeBranchingLevel>
17 </logicTree>
18 </nrml>
```

3.1.3. Configuration file

The configuration file is the primary file controlling both the input model as well as parameters governing the calculation.

In this section we will illustrate different examples of the configuration file addressing different typologies of seismic hazard calculation.

3.1.3.1. Calculation of a hazard map and hazard curves using the classical PSHA methodology

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 describe the type of calculation defined
- **calculation_mode:** sets the kind of calculation.
- **random_seed:** is used to control the random generator so that when montecarlo procedures are used calculations are replicable (if the same random_seed is used).

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

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

The first one consists on the defining a polygon (usually a rectangle) and a distance (in km) used to discretize the polygon area. An example is provided below.

3.1. Input Data definition

```
5 [geometry]
6 region = 10.0 43.0, 12.0 43.0, 12.0 46.0, 10.0 46.0
7 # km
8 region_grid_spacing = 10.0
```

The second option allows the definition of a number of sites where the hazard will be computed. An example is provided below.

```
5 [geometry]
6 sites = 10.0 43.0, 12.0 43.0, 12.0 46.0, 10.0 46.0
7
8
```

- **Logic tree sampling**

The **OQe** provides two options for processing the full logic tree structure. The first option uses Montecarlo sampling; the user in this case specifies a number of realisations. In the second option all the possible realisations are created. Below we provide an example for the latter option.

```
9 [logic_tree]
10 number_of_logic_tree_samples = 0
```

In this example we set the `number_of_logic_tree_samples` to 0. **OQe** will perform a complete enumeration of all the possible paths from the roots to the leaves of the logic tree structure. 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.

- **Parameters controlling the construction of the earthquake rupture forecast**

```
11 [erf]
12 # km
13 rupture_mesh_spacing = 5
14 width_of_mfd_bin = 0.1
15 # km
16 area_source_discretization = 10
```

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

3. Using the hazard module

- **Parameters describing site conditions**

```
17 [site_params]
18 reference_vs30_type = measured
19 reference_vs30_value = 760.0
20 reference_depth_to_2pt5km_per_sec = 5.0
21 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 soil conditions). Alternatively it's possible to define spatially variable soil properties in a separate file; the engine will then assign to each investigation site the appropriate characteristics.

```
17 [site_params]
18 site_model_file = ../_site_model/site_model.xml
19
20
21
```

The file containing the site model has the following structure:

```
<?xml version="1.0" encoding="utf-8"?>
<nrml xmlns:gml="http://www.opengis.net/gml"
      xmlns="http://openquake.org/xmlns/nrml/0.4">
  <siteModel>
    <site lon="10.0" lat="40.0" vs30="800.0"
          vs30Type="inferred"
          z1pt0="19.367196734" z2pt5="0.588625072259" />
    <site lon="10.1" lat="40.0" vs30="800.0"
          vs30Type="inferred"
          z1pt0="19.367196734" z2pt5="0.588625072259" />
    <site lon="10.2" lat="40.0" vs30="800.0"
          vs30Type="inferred"
          z1pt0="19.367196734" z2pt5="0.588625072259" />
    <site lon="10.3" lat="40.0" vs30="800.0"
          vs30Type="inferred"
          z1pt0="19.367196734" z2pt5="0.588625072259" />
    <site lon="10.4" lat="40.0" vs30="800.0"
          vs30Type="inferred"
          z1pt0="19.367196734" z2pt5="0.588625072259" />
    ...
  </siteModel>
</nrml>
```

- **Calculation configuration**

```
22 [calculation]
23 source_model_logic_tree_file = source_model_logic_tree.xml
24 gsim_logic_tree_file = gmpe_logic_tree.xml
25 # years
26 investigation_time = 50.0
27 intensity_measure_types = PGA, SA(0.1)
28 intensity_measure_types_and_levels = {"PGA": [0.005, 0.007, ..., 2.13]}
29 truncation_level = 3
30 # km
31 maximum_distance = 200.0
```

This section of the OQ configuration file specifies the parameters that are relevant for the calculation of hazard. These include the names of the two files with 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 in the computation of the hazard).

- **Output**

```
32 [output]
33 export_dir = out/
34 # given the specified 'intensity_measure_types_and_levels'
35 quantile_hazard_curves =
36 poes_hazard_maps = 0.1
```

The final section of the configuration file is the one that contains the parameters controlling the typology of output to be produced.

3.1.3.2. 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'll use the description give in [Section 3.1.3.1](#) at page 34 as a reference.

- **Calculation type and model info**

3. Using the hazard module

```
[general]
description = A demo OpenQuake-engine .ini file for PSHA disaggregation
calculation_mode = disaggregation
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**

```
[geometry]
sites = 11.0 44.5
```

In the section it will be necessary to specify the geographic coordinates of the site (or the sites) where the disaggregation will be performed.

- **Disaggregation parameters**

```
[disaggregation]
poes_disagg = 0.02, 0.1
mag_bin_width = 1.0
distance_bin_width = 25.0
# decimal degrees
coordinate_bin_width = 1.5
num_epsilon_bins = 3
```

With the disaggregation settings above we'll disaggregate the intensity measure levels with 10% and 2% probability of exceedance in the investigation_time defined in the "Calculation configuration" section of the OpenQuake configuration file (see page 37).

3.1.3.3. Event based PSHA

In the following we describe the sections of the logic tree that are specific for event based PSHA calculations (the remaining sections

1. **Calculation type and model info** This part is almost identical to the corresponding one describe in section 3.1.3.1. Note the setting of the calculation_mode parameter.

```
1 [general]
2 description = A demo OpenQuake-engine .ini file for classical PSHA
```


3.1. Input Data definition

```
3 calculation_mode = event_based
4 random_seed = 1024
```

2. Event based

This is an additional part used to specify the number of stochastic event sets (each one representing a potential realisation of seismicity during the investigation_time specified in the calculation_configuration part.

```
[event_based_params]
ses_per_logic_tree_path = 5
ground_motion_correlation_model = JB2009
ground_motion_correlation_params = "vs30_clustering": true
```

3. Output

This part substitutes the Output part described in configuration file example described in section [3.1.3.1](#) at page [34](#).

```
[output]
export_dir = /tmp/xxx
complete_logic_tree_ses = true
complete_logic_tree_gmf = true
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_hazard_curves = true
quantile_hazard_curves = 0.15, 0.5, 0.85
poes_hazard_maps = 0.1, 0.2
```


Hazard calculation and results provided

A general introduction to the use of OpenQuake is provided in Section 1.2 at page 9. The reader is invited to consult this part before moving into the details of this section.

4.1. 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 which consists in the invocation of `openquake` together with the `--rh` option which stands for “run hazard” and requires the name of a configuration file (in the example below it corresponds to `job.ini`):

```
user@ubuntu:~$ openquake --rh job.ini
```

The amount of information prompted during the execution of the analysis is controlled by means of the `--log-level` flag as shown in the example below:

```
user@ubuntu:~$ openquake --rh job.ini --log-level debug
```

There are two alternative ways to get results from OpenQuake engine. The first one is activated at the OpenQuake invocation the flag `--exports xml` as shown in the example below

```
user@ubuntu:~$ openquake --rh job.ini --exports xml
```

4. Hazard calculation and results provided

With the second option, it's possible to export from the database incorporated into the OpenQuake-engine the results produced by any of the calculations completed.

The list of the hazard calculations is obtained with the following command:

```
user@ubuntu:~$ openquake --lhc
```

The execution of this command will produce a list of the hazard calculations performed with OpenQuake.

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

4.2. Description of 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 'distribution' of results (hazard curves, ground motion fields, disaggregation matrices, UHS) which is specular to the 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 included in the hazard module of the OpenQuake-engine calculators (the only exception being disaggregation).

4.2.1. Output from Classical PSHA

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

4.2. Description of outputs

When the PSHA input model doesn't contain epistemic uncertainties the results will consist on a set of hazard curves (one for each investigated site).

```
user@ubuntu:~$ openquake --lho <calc_id>
id | output_type | name
3 | hazard_curve | hc-rlz-6
```

If number_of_logic_tree_samples, then N hazard curves files are generated:

```
user@ubuntu:~$ openquake --lho <calc_id>
id | output_type | name
5 | hazard_curve | hc-rlz-10
6 | hazard_curve | hc-rlz-7
7 | hazard_curve | hc-rlz-8
8 | hazard_curve | hc-rlz-9
9 | hazard_curve | hc-rlz-11
10 | hazard_curve | hc-rlz-12
```

If we export from the database the hazard curves contained in one of the items above through this command below

```
user@ubuntu:~$ openquake --eh <output_id> <output_directory>
```

we will obtain a nrml formatted file as represented in the example above.

```
<?xml version='1.0' encoding='UTF-8'?>
<nrml xmlns:gml="http://www.opengis.net/gml"
      xmlns="http://openquake.org/xmlns/nrml/0.4">
  <hazardCurves sourceModelTreePath="b1|b212"
    gsimTreePath="b2" IMT="PGA" investigationTime="50.0">
    <IMLs>0.005 0.007 0.0098 ... 1.09 1.52 2.13</IMLs>
    <hazardCurve>
      <gml:Point>
        <gml:pos>10.0 45.0</gml:pos>
      </gml:Point>
      <poEs>1.0 1.0 1.0 ... 0.000688359310522 0.0 0.0</poEs>
    </hazardCurve>
    ...
    <hazardCurve>
      <gml:Point>
        <gml:pos>lon lat</gml:pos>
      </gml:Point>
      <poEs>poe1 poe2 ... poeN</poEs>
```

4. Hazard calculation and results provided

```
</hazardCurve>
</hazardCurves>
</nrml>
```

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 which can be either the single PSHA input model (if epistemic uncertainties are not accounted) or one possible realisation of the complete logic tree structure.

The attributes of the hazardCurves element (see text in red in the example file above) specify the path used to create the seismic source model (source-ModelTreePath) and the ground motion model (gsimTreePath) plus the intensity measure type and the investigation time used to compute the probability of exceedance. The IMLs element (in green in the example above) contains the values of shaking for which OpenQuake computed the probability of exceedance in the investigation time. For each site this file contains a hazardCurve element which includes the coordinates (longitude and latitude in decimal degrees) of the site and the values of the probability of exceedance for all the intensity measure levels specified in the IMLs element.

If together with hazard curves the calculation of hazard curves have been selected in the configuration file this is the kind of output we should expect from OpenQuake:

```
user@ubuntu:~$ openquake --lho <calc_id>
id | output_type | name
17 | hazard_curve | hc-rlz-17
18 | hazard_curve | hc-rlz-18
19 | hazard_curve | hc-rlz-13
20 | hazard_curve | hc-rlz-14
21 | hazard_curve | hc-rlz-15
22 | hazard_curve | hc-rlz-16
23 | hazard_curve | quantile(0.5)-curves-PGA
24 | hazard_map | hazard-map(0.1)-PGA-rlz-17
25 | hazard_map | hazard-map(0.1)-PGA-rlz-18
26 | hazard_map | hazard-map(0.1)-PGA-rlz-13
27 | hazard_map | hazard-map(0.1)-PGA-rlz-14
28 | hazard_map | hazard-map(0.1)-PGA-rlz-15
29 | hazard_map | hazard-map(0.1)-PGA-rlz-16
30 | hazard_map | hazard-map(0.1)-PGA-quantile(0.5)
```

4.3. Output from Event Based PSHA

The Event Based PSHA calculator computes and stores stochastic event sets and the corresponding ground motion fields.

A ground motion field is defined in a GMF element, which consists of a sequence of GMFNode elements, each containing a geographical location and the associated ground motion value.

```

user@ubuntu:~$ openquake --lho <calc_id>
id | output_type | name
31 | ses | ses-coll-rlz-19
32 | gmf | gmf-rlz-19
33 | ses | ses-coll-rlz-20
34 | gmf | gmf-rlz-20
35 | complete_lt_ses | complete logic tree SES
36 | complete_lt_gmf | complete logic tree GMF
37 | hazard_curve | hazard-curve-rlz-19-SA(0.1)
38 | hazard_curve | hazard-curve-rlz-20-SA(0.1)
39 | hazard_curve | hazard-curve-rlz-19-PGA
40 | hazard_curve | hazard-curve-rlz-20-PGA
41 | hazard_curve | mean curve for SA(0.1)
42 | hazard_curve | quantile curve (poe >= 0.15) for imt SA(0.1)
43 | hazard_curve | quantile curve (poe >= 0.5) for imt SA(0.1)
44 | hazard_curve | quantile curve (poe >= 0.85) for imt SA(0.1)
45 | hazard_curve | mean curve for PGA
46 | hazard_curve | quantile curve (poe >= 0.15) for imt PGA
47 | hazard_curve | quantile curve (poe >= 0.5) for imt PGA
48 | hazard_curve | quantile curve (poe >= 0.85) for imt PGA

```

4. Hazard calculation and results provided

4.4. Output from Disaggregation

```
user@ubuntu:~$ openquake --lho <calc_id>
id | output_type | name
19 | hazard_curve | hc-rlz-3
20 | hazard_curve | hc-rlz-3
21 | hazard_curve | hc-rlz-4
22 | hazard_curve | hc-rlz-4
23 | disagg_matrix | disagg(0.02)-rlz-3-SA(0.025)-POINT(10.1 40.1)
24 | disagg_matrix | disagg(0.1)-rlz-3-SA(0.025)-POINT(10.1 40.1)
25 | disagg_matrix | disagg(0.02)-rlz-3-PGA-POINT(10.1 40.1)
26 | disagg_matrix | disagg(0.1)-rlz-3-PGA-POINT(10.1 40.1)
27 | disagg_matrix | disagg(0.02)-rlz-4-SA(0.025)-POINT(10.1 40.1)
28 | disagg_matrix | disagg(0.1)-rlz-4-SA(0.025)-POINT(10.1 40.1)
29 | disagg_matrix | disagg(0.02)-rlz-4-PGA-POINT(10.1 40.1)
30 | disagg_matrix | disagg(0.1)-rlz-4-PGA-POINT(10.1 40.1)
```


Demonstrative examples

5.1. Demo 01 - Classical PSHA

5.2. Demo 02 - Classical PSHA: simple logic tree

This demo contains simple logic tree structures accounting for epistemic uncertainties in the seismic source and ground motion intensity models.

The seismic source model incorporates epistemic uncertainty about the value of the maximum magnitude of the magnitude-frequency distribution used. The ground motion intensity model includes uncertainty about the ground motion prediction equations to be used in the calculation of hazard.

Given that the overall structure of the logic tree is not particularly complex and assuming that uncertainties are fully correlated we decide to compute all the possible realisations of the logic tree by fixing the `number_of_logic_tree_samples` parameter in the configuration file to zero.

```
[logic_tree]
number_of_logic_tree_samples = 0
```

Let's now run the OpenQuake:

```
user@ubuntu:~/demos/classical_psha_simple_lt$ openquake \
--rh job_1strike.ini
```

This is the list of results that we get at the end of this calculation:

```
Calculation 8 results:
id | output_type | name
```

5. Demonstrative examples

5	hazard_curve	hc-rlz-10
6	hazard_curve	hc-rlz-7
7	hazard_curve	hc-rlz-8
8	hazard_curve	hc-rlz-9
9	hazard_curve	hc-rlz-11
10	hazard_curve	hc-rlz-12
11	hazard_map	hazard-map(0.1)-PGA-rlz-10
12	hazard_map	hazard-map(0.1)-PGA-rlz-7
13	hazard_map	hazard-map(0.1)-PGA-rlz-8
14	hazard_map	hazard-map(0.1)-PGA-rlz-9
15	hazard_map	hazard-map(0.1)-PGA-rlz-11
16	hazard_map	hazard-map(0.1)-PGA-rlz-12

OpenQuake produced six hazard curves and six hazard maps i.e. one result for each leaf of the logic tree.

PART III

Risk

Introduction to the risk module

6.1. Introduction

The seismic risk results are being calculated using the OpenQuake risk library (oq-risklib), 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, that can be executed through a command line interface. The code of the library can be found on a public repository at GitHub at the following address <http://gitub.com/gem/oq-risklib>.

This section provides a brief description of the calculators currently implemented in oq-risklib, and an initial presentation of the input and output files is provided. In the following sections, the contents and structure of these files are discussed in detail. For further information regarding the methodologies behind each calculator, users are referred to the OpenQuake Engine Book (Risk).

6.2. Calculation workflows

The oq-engine is currently comprised of five risk calculation workflows: two that calculate losses and damage distributions due to a single earthquake, another two that calculate seismic risk using probabilistic seismic hazard, and a fifth one that uses loss exceedance curves to assess whether retrofitting measures would be economically viable or not.

6.2.1. Scenario Risk Calculator

This calculator computes loss maps and loss statistics due to a single seismic event, for a collection of assets. The hazard input can be a single ground motion

6. Introduction to the risk module

field (e.g. the median distribution of ground motion in the region of interest) or a set of ground motion fields allowing the characterisation of the inter- and intra-event variability from the GMPE. It is noted that the hazard input can either be calculated using the hazard component of OpenQuake engine (oq-hazardlib), or provided to the risk component in an external file following the respective Natural hazards' Risk Markup Language (NRML) schema (see [oq-nrmlib](#)). A vulnerability model is combined with the distribution of the ground motions at each asset location to calculate the loss distribution for each asset, as well as the statistics of the total loss throughout the region of interest. The required input files and resulting output files are depicted in Figure 6.1.

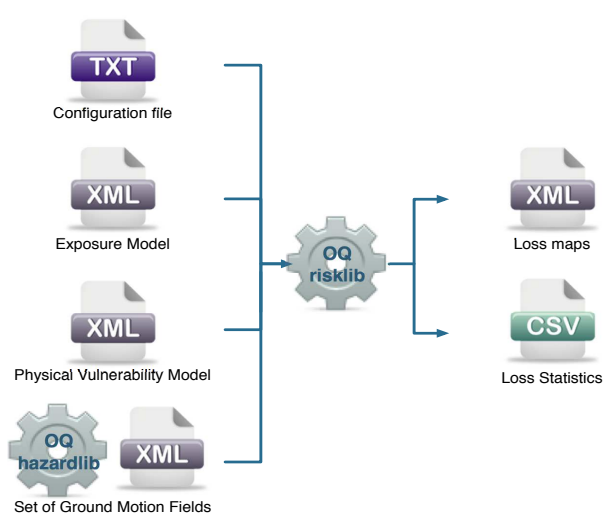


Figure 6.1. – *Scenario Risk Calculator input/output structure.*

6.2.2. Scenario Damage Calculator

This calculator is capable of assessing the damage distribution due to a single scenario earthquake, for a collection of assets. Similarly to the previous calculator, in order to perform the necessary risk calculations one or a set of ground motion fields are required, which can be derived using the oq-hazardlib, or introduced in the OpenQuake engine using the appropriate NRML schema. In this calculator, a fragility model is combined with the distribution of ground motion at the location of each asset, to estimate the number or area of buildings in each damage state. The damage distribution can be extracted per asset, per building typology (taxonomy) or considering all of the assets simultaneously (total damage distribution). In addition, this calculator also provides collapse

maps, which contain the spatial distribution of the number or area of collapsed buildings throughout the region of interest. The input/output structure for this calculator is presented in Figure 6.2.

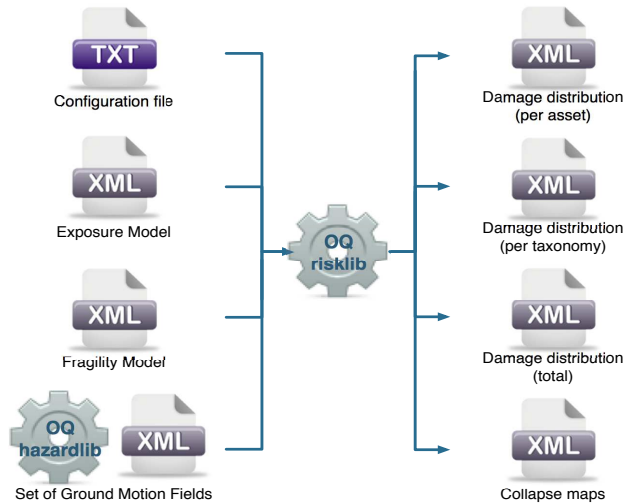


Figure 6.2. – Scenario Damage Calculator input/output structure.

6.2.3. Probabilistic Event-based Risk Calculator

In this calculator, loss exceedance curves and loss maps for various return periods can be calculated, based on probabilistic seismic hazard, with an event-based approach. A large number of stochastic event sets are generated, and the associated ground motion fields for each event are used together with a vulnerability model to compute the individual (per asset) and total (sum of all the losses per event) losses. Then, this distribution of losses is employed to derive a loss exceedance curve per asset, as well as a total loss exceedance curve representative of the complete building portfolio. Furthermore, oq-risklib can also compute loss maps for various return periods by interpolating each individual loss curve with the respective probability of exceedance. In Figure 6.3, the input/output scheme of this calculator is illustrated.

6.2.4. Classical PSHA-based Risk Calculator

In this calculator, probabilistic seismic hazard is employed to calculate a loss exceedance curve for each asset, through the usage of seismic hazard curves. A

6. Introduction to the risk module

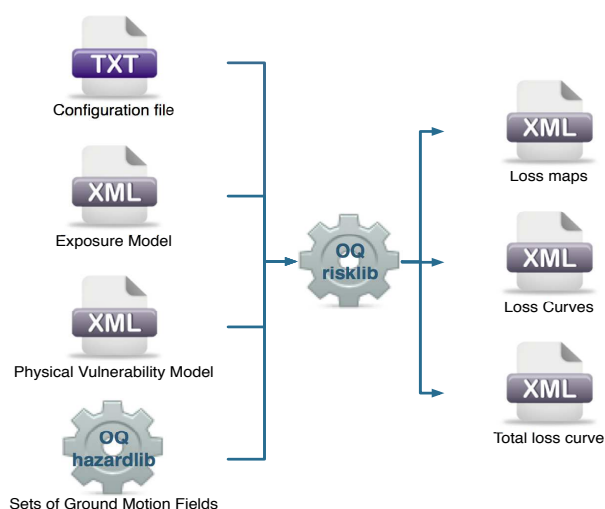


Figure 6.3. – *Probabilistic Event-based Risk Calculator input/output structure.*

convolution between the vulnerability function and the hazard curve at location of the asset is performed, leading to the probability of exceeding a set of loss ratios. Each loss ratio is multiplied by the asset value to obtain the final loss exceedance curve. Furthermore, probabilistic loss maps can be extracted by interpolating the loss curves at each location by various probabilities of exceedance. 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 input and output files involved in this calculator are presented in Figure 6.4.

6.2.5. Retrofitting Benefit/Cost Ratio Calculator

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 can be computed using either the previously described Probabilistic Event-based Risk or the Classical PSHA-based Risk calculators. 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 Figure 6.5, the input/output structure for this calculator is depicted.

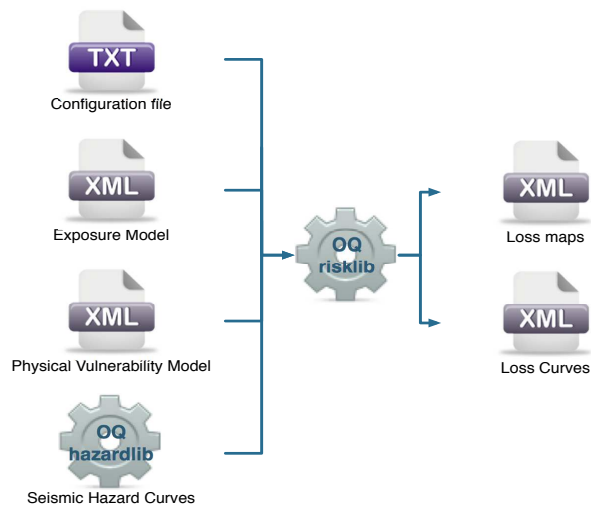


Figure 6.4. – *Classical PSHA-based Risk Calculator input/output structure.*

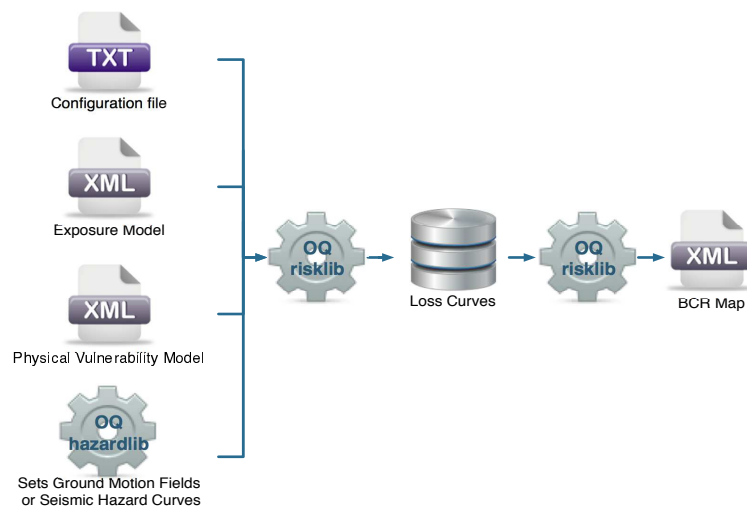


Figure 6.5. – *Retrofitting Benefit/Cost Ratio Calculator input/output structure.*

Using the risk module

7.1. Input data definition

7.1.1. Exposure model definition

All risk calculators in the OpenQuake engine require an **exposure model** that needs to be stored in NRML. The following metadata, that is common to all of the **assets** stored in a given **exposure model**, needs to be provided, as described below:

- **id**: a unique key used to identify the **exposure model**;
- **assetCategory**: a string used to define the type of **assets** being stored (e.g: buildings, population, contents);
- **areaType**: flag defining the way the area is being provided, as explained later in this section;
- **areaUnits**: attribute defining the units used to measure the area;
- **stcoType**: flag defining the way the structural replacement cost is being provided, as explained later in this section;
- **stcoUnits**: attribute defining the units used to measure the structural replacement cost;
- **recoType**: flag defining the way the retrofitting cost is being provided, as explained later in this section;
- **recoUnits**: attribute defining the units used to measure the retrofitting cost;

7. Using the risk module

- description: brief string with further information about the **exposure model**;
- taxonomySource: attribute used to define the **taxonomy** being used to classify the **assets**;

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 value of each building typology will be directly derived, and will be used for the estimation of economic losses. Thus, the following set of attributes were included in the latest version of the schema for the exposure model:

- number: number of units of a given **asset** at a given location;
- area: area of the **asset**, at a given location;
- stco: structural replacement cost of the **asset** at a given location;
- reco: retrofitting cost of the **asset** at a given location.

While the attribute number might be a rather simple parameter, the other two (area and cost) can be ambiguous, as different ways to define them might be used. With regards to the attribute area, one can either choose to provide the aggregated built up area of the **assets** per location or the average built up area for a single building unit (noting that an **asset** might be made up of a number of individual buildings). Similarly, the stco can also be defined as the aggregated structural replacement cost, the cost of replacing a single unit or even the structural replacement cost per unit of area. For the purposes of performing a retrofitting benefit/cost analysis, it is also necessary to define the retrofitting cost (reco). This parameter is being handled in the same manner as the structural replacement cost. Thus, it can be defined as the aggregated retrofitting cost, the average cost per unit of area, or as the average cost for a single building unit.

To establish the way these three attributes are being defined within the **exposure model**, three flags have been introduced in the schema model: areaType, stcoType and recoType.

Note that since the attribute number always represents the same quantity (number of units of a given **asset** in a given location), no flag providing further information about this attribute was introduced. Further information regarding the parameters that are currently being used to define the exposure elements can be found in the OpenQuake Engine Book (Risk). In order to clarify this methodology, several examples are presented later in this section.

Finally, a pair of coordinates (longitude and latitude) needs to be provided to define the location of each asset. The way this information is being stored is constantly being modified, as further feedback from users and experts is received. Hence, it is important to understand which version of NRML the engine is using, in order to avoid incompatibility issues. NRML is currently v0.4 and documentation about each release can be found on GitHub (see [oq-nrmlib](#)). Several examples of **exposure models** containing different types of information are presented below. Users will notice that some of the attributes are marked with a "gml" tag, which means that these parameters must follow the Geography Markup Language grammar, developed by the Open Geospatial Consortium.

Example 1

This example is comprised of an **exposure model** in which the aggregated economic value of the buildings of each building typology for a set of locations is directly provided.

```
<?xml version="1.0" encoding="UTF-8"?>
<nrml xmlns:gml="http://www.opengis.net/gml"
      xmlns="http://openquake.org/xmlns/nrml/0.4">
  <exposureModel gml:id="ep">
    <exposureList gml:id="Nepal_13_1" assetCategory="buildings"
      stcoUnit="EUR" stcoType="aggregated" recoUnit="EUR"
      recoType="aggregated">
      <gml:description>Buildings in Nepal</gml:description>
      <taxonomySource>Nepal taxonomy</taxonomySource>
      <assetDefinition gml:id="asset1">
        <site>
          <gml:Point srsName="epsg:4326">
            <gml:pos>15.22 38.80</gml:pos>
          </gml:Point>
        </site>
        <taxonomy>URM</taxonomy>
        <stco> 500.0 </stco>
      </assetDefinition>
    </exposureList>
  </exposureModel>
</nrml>
```

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```
        <reco> 50.0 </reco>
    </assetDefinition>
    ...
    <assetDefinition gml:id="asset999">
        <site>
            <gml:Point srsName="epsg:4326">
                <gml:pos>15.23 38.95</gml:pos>
            </gml:Point>
        </site>
        <taxonomy>RC</taxonomy>
        <stco> 700.0 </stco>
        <reco> 70.0 </reco>
    </assetDefinition>
</exposureList>
</exposureModel>
</nrml>
```

Each **asset** is uniquely identified by its `id`, which is used by the OpenQuake engine to relate each asset with the associated results (e.g. loss exceedance curves). Then, a pair of coordinates (latitude and longitude) for a site is defined. This position (`pos`) and the associated geographical projection (`srsName`) need to be provided in the `Point` attribute. 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 structural replacement value of the asset is stored in the `stco` attribute. In this case, the aggregated economic value for all units of 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.

Example 2

This example is comprised of an **exposure model** containing the number of units (buildings) at each location, and the associated structural replacement and retrofitting cost per unit of each building typology.

```
<?xml version="1.0" encoding="UTF-8"?>
<nrml xmlns:gml="http://www.opengis.net/gml"
      xmlns="http://openquake.org/xmlns/nrml/0.4">
```

```

<exposureModel gml:id="ep">
  <exposureList gml:id="Nepal_13_2" assetCategory="buildings"
    stcoUnit="EUR" stcoType="per_asset" recoUnit="EUR"
    recoType="per_asset">
    <gml:description>Buildings in Nepal</gml:description>
    <taxonomySource>Nepal taxonomy</taxonomySource>
    <assetDefinition gml:id="asset1">
      <site>
        <gml:Point srsName="epsg:4326">
          <gml:pos>15.22 38.80</gml:pos>
        </gml:Point>
      </site>
      <taxonomy>URM</taxonomy>
      <number> 10 </number>
      <stco> 50.0 </stco>
      <reco> 5.0 </reco>
    </assetDefinition>
    ...
    <assetDefinition gml:id="asset999">
      <site>
        <gml:Point srsName="epsg:4326">
          <gml:pos>15.23 38.95</gml:pos>
        </gml:Point>
      </site>
      <taxonomy>RC</taxonomy>
      <number> 5 </number>
      <stco> 140.0 </stco>
      <reco> 14.0 </reco>
    </assetDefinition>
  </exposureList>
</exposureModel>
</nrml>

```

In this example, the structural replacement and retrofitting value of each asset is not provided directly, as happened in the previous example. In order to carry out the risk calculations in which the structural and retrofitting value of each asset is required, the OpenQuake engine multiplies, for each asset, the number of units (buildings) by the "per unit" replacement cost. Note that in this case, there is no need to specify the attribute area.

7. Using the risk module

Example 3

This example is comprised of an **exposure model** containing the built up area of each building typology for a set of locations, and the associated structural replacement and retrofitting cost per area.

```
<?xml version="1.0" encoding="UTF-8"?>
<nrml xmlns:gml="http://www.opengis.net/gml"
      xmlns="http://openquake.org/xmlns/nrml/0.4">
  <exposureModel gml:id="ep">
    <exposureList gml:id="Nepal_13_3" assetCategory="buildings"
      stcoUnit="EUR/m2" stcoType="per_area" recoUnit="EUR/m2"
      recoType="per_area" areaUnit="m2" areaType="aggregated">
      <gml:description>Buildings in Nepal</gml:description>
      <taxonomySource>Nepal taxonomy</taxonomySource>
      <assetDefinition gml:id="asset1">
        <site>
          <gml:Point srsName="epsg:4326">
            <gml:pos>15.22 38.80</gml:pos>
          </gml:Point>
        </site>
        <taxonomy>URM</taxonomy>
        <area> 10000 </area>
        <stco> 400.0 </stco>
        <reco> 40.0 </reco>
      </assetDefinition>
      ...
      <assetDefinition gml:id="asset999">
        <site>
          <gml:Point srsName="epsg:4326">
            <gml:pos>15.23 38.95</gml:pos>
          </gml:Point>
        </site>
        <taxonomy>RC</taxonomy>
        <area> 20000 </area>
        <stco> 500.0 </stco>
        <reco> 50.0 </reco>
      </assetDefinition>
    </exposureList>
  </exposureModel>
</nrml>
```


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

Example 4

This example is comprised of an **exposure model** containing the number of buildings for each location, the average built up area per building unit and the associated structural replacement and retrofitting cost per area.

```
<?xml version="1.0" encoding="UTF-8"?>
<nrml xmlns:gml="http://www.opengis.net/gml"
      xmlns="http://openquake.org/xmlns/nrml/0.4">
  <exposureModel gml:id="ep">
    <exposureList gml:id="Nepal13_04" assetCategory="buildings"
      stcoUnit="EUR/m2" stcoType="per_area" recoUnit="EUR/m2"
      recoType="per_area" areaUnit="m2" areaType="per_asset">
      <gml:description>Buildings in Nepal</gml:description>
      <taxonomySource>Nepal taxonomy</taxonomySource>
      <assetDefinition gml:id="asset1">
        <site>
          <gml:Point srsName="epsg:4326">
            <gml:pos>15.22 38.80</gml:pos>
          </gml:Point>
        </site>
        <taxonomy>URM</taxonomy>
        <number> 10 </number>
        <area> 100.0 </area>
        <stco> 400.0 </stco>
        <reco> 40.0 </reco>
      </assetDefinition>
      ...
      <assetDefinition gml:id="asset999">
        <site>
          <gml:Point srsName="epsg:4326">
            <gml:pos>15.23 38.95</gml:pos>
          </gml:Point>
        </site>
        <taxonomy>RC</taxonomy>
```

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```
        <number> 5 </number>
        <area> 150.0 </area>
        <stco> 500.0 </stco>
        <reco> 50.0 </reco>
    </assetDefinition>
</exposureList>
</exposureModel>
</nrml>
```

In this example, the OpenQuake engine will make use of all the parameters to estimate the economic and retrofitting value for each asset, by multiplying the number of buildings by its average built up area, and then by the respective replacement or retrofitting cost per unit of area.

Example 5

This example is comprised of an **exposure model** containing population distribution.

```
<?xml version="1.0" encoding="UTF-8"?>
<nrml xmlns:gml="http://www.opengis.net/gml"
      xmlns="http://openquake.org/xmlns/nrml/0.4">
  <exposureModel gml:id="ep">
    <exposureList gml:id="Nepal13_5" assetCategory="population">
      <gml:description>Population in Nepal</gml:description>
      <taxonomySource>Nepal taxonomy</taxonomySource>
      <assetDefinition gml:id="asset1">
        <site>
          <gml:Point srsName="epsg:4326">
            <gml:pos>15.22 38.80</gml:pos>
          </gml:Point>
        </site>
        <taxonomy>VF1</taxonomy>
        <number> 200 </number>
      </assetDefinition>
      ...
      <assetDefinition gml:id="asset999">
        <site>
          <gml:Point srsName="epsg:4326">
            <gml:pos>15.23 38.95</gml:pos>
          </gml:Point>
        </site>
      </assetDefinition>
    </exposureList>
  </exposureModel>
</nrml>
```

```

        </site>
        <taxonomy>VF2</taxonomy>
        <number> 100 </number>
    </assetDefinition>
</exposureList>
</exposureModel>
</nrml>

```

In this final example, the OpenQuake engine will require population distribution instead of structural replacement cost, hence, only the attribute number needs to be provided. Notice that in order for the engine to recognize that human losses are going to be estimated rather than economic losses, the attribute `assetCategory` needs to be set to population.

Scripts capable of converting information about the assets stored in Excel or ASCII files into NRML have been developed by the scientists working at **Global Earthquake Model (GEM)** and can be found at the GEM Science tools repository at GitHub (<http://github.com/GEMScienceTools>).

7.1.2. Physical vulnerability model definition

In this section, the NRML schema for the **vulnerability model** is described in detail. In order to do so, a graphical representation of a **vulnerability model** (mean loss ratio for a set of intensity measure levels) is illustrated in Figure 7.1, and the equivalent NRML file is then presented. Note that although the uncertainty for each loss ratio is not represented in the aforementioned figure, it has been considered in the input NRML file, by means of a coefficient of variation per loss ratio and an associated lognormal distribution. This model is comprised of two discrete **vulnerability functions** and uses spectral acceleration for a given period of vibration as the intensity measure type.

Each component of the associated NRML file is presented herein:

```

<?xml version="1.0" encoding="UTF-8"?>
<nrml xmlns:gml="http://www.opengis.net/gml"
      xmlns="http://openquake.org/xmlns/nrml/0.4">
  <vulnerabilityModel>
    <discreteVulnerabilitySet vulnerabilitySetID="OpenQuake2013"
      assetCategory="buildings" lossCategory="economic loss">
      ...
    </discreteVulnerabilitySet>
  </vulnerabilityModel>
</nrml>

```

At the top of the NRML schema, the following metadata are being stored:

7. Using the risk module

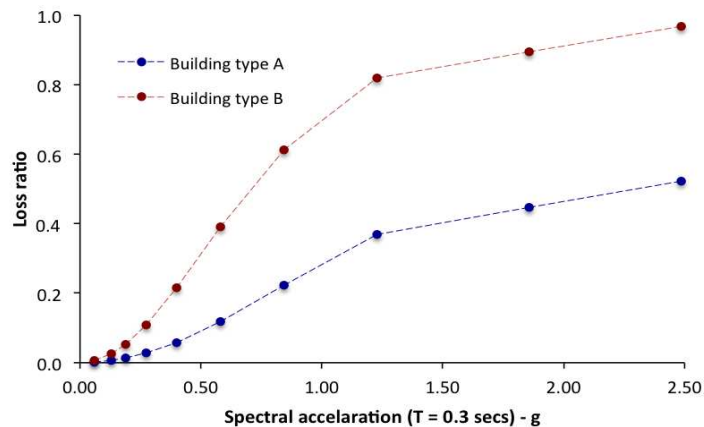


Figure 7.1. – Graphical representation of a vulnerability model.

- **vulnerabilitySetID**: A unique key used to identify the **vulnerability model** instance within the OpenQuake engine;
- **assetCategory**: An attribute that describes the asset typology (e.g.: population, buildings, contents);
- **lossCategory**: An attribute that describes the type of loss being modelled for the assetCategory (e.g.: fatalities, structural replacement cost, contents replacement cost).

```
...  
<IML IMT = "SA(0.3)"> 0.061 0.129 0.188 0.273 0.398 0.579  
0.843 1.227 1.856 2.485 </IML>  
...
```

Within this component, an attribute specifying the intensity measure type (e.g.: Sa, PGA, MMI) is defined, followed by the list of intensity measure levels. This set of values is common to all of the **vulnerability functions** in the model.

```

...
<discreteVulnerability vulnerabilityFunctionID="typeA"
probabilisticDistribution="LN">
  <lossRatio> 0.002 0.007 0.014 0.028 0.058 0.118
  0.223 0.370 0.446 0.523 </lossRatio>
  <coefficientsVariation> 0.012 0.058 0.079 0.159 0.265
  0.244 0.211 0.152 0.088 0.082 </coefficientsVariation>
</discreteVulnerability>
<discreteVulnerability vulnerabilityFunctionID="typeB"
probabilisticDistribution="LN">
  <lossRatio> 0.006 0.025 0.052 0.108 0.215 0.391
  0.613 0.820 0.894 0.967 </lossRatio>
  <coefficientsVariation> 0.010 0.054 0.082 0.167 0.285
  0.278 0.261 0.132 0.084 0.021 </coefficientsVariation>
</discreteVulnerability>
</discreteVulnerabilitySet>
</vulnerabilityModel>
</nrml>

```

Finally, for each discrete **vulnerability function** the following parameters are required:

- **vulnerabilityFunctionID** : A unique key that is used to relate each **vulnerability function** with the **assets** in the **exposure model**;
- **probabilisticDistribution** : An attribute that establishes the type of probabilistic distribution used to model the uncertainty in loss ratio. At the moment, the OpenQuake engine only supports lognormal distributions, however, other types of distributions such as beta will be incorporated in future releases;
- **lossRatio** : A set of mean loss ratios (one for each intensity measure level defined previously). These values can represent different losses such as fatality rates (ratio between the number of fatalities and total population exposed) or so-called damage ratio (ratio between the repair cost and the replacement cost of a given structure).
- **coefficientsVariation** : A set of coefficients of variation (one per loss ratio) that describes the uncertainty in the loss ratio. If users do not want to consider the uncertainty, this set of parameters can be set to zero, and the OpenQuake engine assumes each loss ratio as a deterministic value.

7. Using the risk module

In the previously described **vulnerability model** all of the **vulnerability functions** were defined in terms of a single intensity measure type (Sa for 0.3 seconds). However, the current version of the engine also allows the employment of a **vulnerability model** that is comprised of **vulnerability functions** that each use distinct intensity measure types. In the following example, the schema of a **vulnerability model** in which three intensity measure types were used (PGA, PGV and Sa for 0.3 seconds) is presented.

```
<?xml version="1.0" encoding="UTF-8"?>
<nrml xmlns:gml="http://www.opengis.net/gml"
      xmlns="http://openquake.org/xmlns/nrml/0.4">
  <vulnerabilityModel>
    <discreteVulnerabilitySet vulnerabilitySetID="Nepal13_PGA"
      assetCategory="buildings" lossCategory="economic loss">
      <IML IMT = "PGA"> 0.1 0.2 0.4 0.7 1.0 1.3 </IML>
      <discreteVulnerability vulnerabilityFunctionID="RC1"
        probabilisticDistribution="LN">
        <lossRatio> 0.02 0.1 0.3 0.6 0.8 0.9 </lossRatio>
        <coefficientsVariation> 0.7 0.5 0.3 0.2 0.1 0.05
        </coefficientsVariation>
      </discreteVulnerability>
    </discreteVulnerabilitySet>
    <discreteVulnerabilitySet vulnerabilitySetID="Nepal13_PGV"
      assetCategory="buildings" lossCategory="economic loss">
      <IML IMT = "PGV"> 5 20 40 60 80 100 </IML>
      <discreteVulnerability vulnerabilityFunctionID="RC2"
        probabilisticDistribution="LN">
        <lossRatio> 0.05 0.2 0.3 0.4 0.5 0.6 </lossRatio>
        <coefficientsVariation> 0.6 0.3 0.2 0.1 0.05 0.05
        </coefficientsVariation>
      </discreteVulnerability>
    </discreteVulnerabilitySet>
    <discreteVulnerabilitySet vulnerabilitySetID="Nepal13_SA"
      assetCategory="buildings" lossCategory="economic loss">
      <IML IMT = "SA(0.3)"> 0.1 0.3 0.6 0.9 1.2 1.5 </IML>
      <discreteVulnerability vulnerabilityFunctionID="RC3"
        probabilisticDistribution="LN">
        <lossRatio> 0.01 0.06 0.12 0.17 0.24 0.33 </lossRatio>
        <coefficientsVariation> 1.5 1.1 1.0 0.9 0.8 0.5
        </coefficientsVariation>
      </discreteVulnerability>
    </discreteVulnerabilitySet>
  </vulnerabilityModel>
</nrml>
```

```

    </discreteVulnerabilitySet
  </vulnerabilityModel>
</nrml>

```

Several methodologies to derive vulnerability functions are currently being evaluated by GEM and will be a part of a set of modelling tools. Scripts to convert **vulnerability functions** stored in Excel or ASCII files into NRML have already being developed, and can be found at the GEM Science tools repository at GitHub (<http://github.com/GEMScienceTools>).

7.1.3. Fragility model definition

This section describes the schema currently used to store **fragility models**, which are required for the Scenario Damage Calculator. A **fragility model** can be comprised of several **fragility functions**, describing the probability of exceeding a set of limit, or damage, states. These **fragility functions** can be defined in two ways: discrete or continuous. In the former manner, sets of probabilities of exceedance (one set per limit state) are defined for a list of intensity measure levels, as illustrated in Figure 7.2.

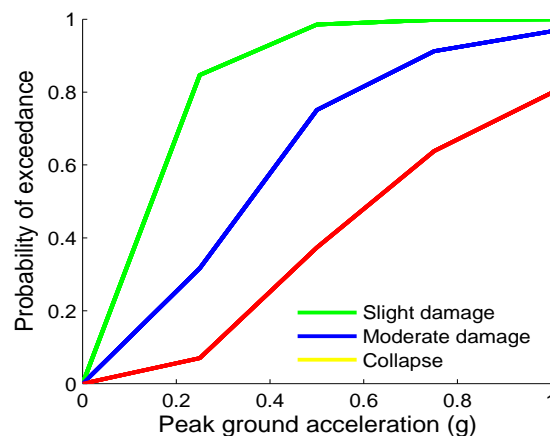


Figure 7.2. – Graphical representation of a discrete fragility model.

Similarly to what has been described for the **vulnerability models**, the NRML schema for this input also has some attributes that are common to all of the **fragility functions** comprising the model. This initial portion of the schema is depicted below:

7. Using the risk module

```
<?xml version="1.0" encoding="UTF-8"?>
<nrml xmlns:gml="http://www.opengis.net/gml"
      xmlns="http://openquake.org/xmlns/nrml/0.4">
  <<fragilityModel format="discrete">>
    <description "Fragility Model for RC" </description>
    <limitStates
      slight damage
      moderate damage
      collapse
    </limitStates>
    ...
```

- description: represents an attribute that can be used to include some information about the **fragility model**, for example, what building typologies are being covered or the source of the **fragility model**;
- limitStates: this field is used to define the number and nomenclature of each limit state. Despite the fact that three limit states are being employed in this example, it is possible to use any number of states, as long as a fragility curve is always defined for each limit state.

```
...
<ffs noDamageLimit= 0.05>
  <taxonomy RC </taxonomy>
  <IML IMT="PGA" imlUnit="g"> 0.0 0.25 0.50 0.75 1.00 </IML>

  <ffd ls="slight damage">
    <poes> 0.0 0.85 0.98 0.99 1.00 < /poes>
  </ffd>
  <ffd ls="moderate damage">
    <poes> 0.0 0.32 0.75 0.91 0.97 < /poes>
  </ffd>
  <ffd ls="collapse">
    <poes> 0.0 0.07 0.37 0.64 0.80 < /poes>
  </ffd>
</ffs>
</fragilityModel>
</nrml>
```


7.1. Input data definition

For each building typology, a set of limit state curves need to be stored within the field `ffs` (fragility function set). The following attributes are currently being employed to define this input:

- `noDamageLimit`: this attribute defines the intensity measure level below which the probability of exceedance for all curves is zero;
- `taxonomy`: a unique key that is used to relate each **fragility function** with the relevant **assets** in the **exposure model**;
- `IML`: this attribute serves the purposes of defining the list of intensity measure levels for which the limit state curves are defined. In addition, it is also necessary to define the intensity measure type (IMT) being used and the respective units (`imlUnit`);
- `ffd`: this field (fragility function discrete) is used to define the probabilities of exceedance (`poes`) of each limit state curve. It is also necessary to include which limit state is being defined in the attribute `ls`.

As previously mentioned, the user may choose to define the **fragility functions** in a continuous manner, through the use of cumulative lognormal functions. In Figure 7.3, a continuous fragility model is presented.

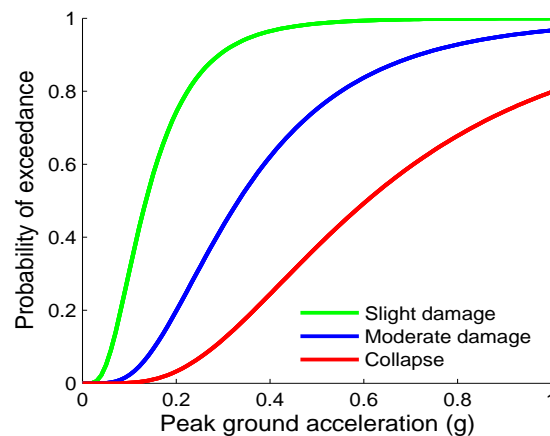


Figure 7.3. – Graphical representation of a continuous fragility model.

The NRML schema to store these functions has an initial structure similar to that described for the discrete **fragility models**. Then, the continuous limit state curves are stored as illustrated below:

7. Using the risk module

```
...
<ffs noDamageLimit= 0.05>
  <taxonomy RC </taxonomy>
  <IML IMT="PGA" minIML="0.0" maxIML="1.0" imlUnit="g" ></IML>
  <ffd ls="slight damage">
    <params mean="0.16" stddev="0.11" />
  </ffd>
  <ffd ls="moderate damage">
    <params mean="0.40" stddev="0.26" />
  </ffd>
  <ffd ls="collapse">
    <params mean="0.73" stddev="0.48" />
  </ffd>
</ffs>
</fragilityModel>
</nrml>
```

Again, the set of limit state curves for each building typology needs to be stored within the field `ffs` (fragility function set), through the definition of the following attributes:

- `noDamageLimit`: this attribute defines the intensity measure level below which the probability of exceedance for all curves is zero;
- `type`: this parameter defines the type of probabilistic distribution being used to define the limit state curves. Currently the engine only supports lognormal distributions, however, the capability of considering other types of distributions (e.g. normal, exponential) will be developed in the future;
- `taxonomy`: a unique key that is used to relate each **fragility function** with the relevant **assets** in the **exposure model**;
- `IML`: in this field, the intensity measure type (`IMT`) and associated units (`imlUnit`) for the limit state curves is defined, along with the minimum (`minIML`) and maximum (`maxIML`) intensity measure levels enclosing the range of applicability of the set of fragility functions;
- `ffc`: this field (fragility function continuous) is used to define the mean (`mean`) and standard deviation (`stddev`) of the cumulative lognormal function. In addition, the limit state for the curve being defined needs to be specified in the attribute `ls`.

7.1.4. Configuration file

The configuration file (or job.ini file) represents the location where the paths to the input files, the parameters controlling the risk calculations and the type of outputs are defined. Some initial parameters common to all the risk calculators are presented below. The remaining parameters that are specific to each risk calculator are discussed in subsequent sections. For additional information about how each parameter is being used within the methodologies implemented in the oq-engine, users advised to consult the OpenQuake Engine Book (Risk).

```
[general]
description = Scenario Risk Nepal
calculation_mode = scenario

exposure_file = exposure_model.xml
region_constraint = 78.0 31.5,89.5 31.5,89.5 25.5,78 25.5
maximum_distance = 10
...
```

- **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 sets the type of calculations. The key word for each risk calculator is described in the following sections;
- **exposure_file**: this parameter is used to specify the path to the **exposure model** file;
- **region_constraint**: this field is used to define the polygon enclosing the region of interest. Assets outside of this region will not be considered in the risk calculations. This region is defined using pairs of coordinates (longitude and latitude in decimal degrees) that indicate the vertexes of the polygon;
- **maximum_distance**: this parameter indicates the maximum allowable distance between an **asset** and the closest hazard input. If no hazard input is found within this distance, the **asset** is skipped and a message is provided mentioning the id of the asset that is affected by this issue.

Depending on the type of calculations, other parameters besides the aforementioned ones need to be provided, as will be described in the following sections.

7. Using the risk module

7.1.4.1. Scenario Risk Calculator

In order to run this calculator, the parameter `calculation_mode` needs to be set to `scenario`. The remaining parameters are illustrated bellow.

```
...  
vulnerability_file = vulnerability_model.xml  
asset_correlation = 0.7  
master_seed = 3
```

- `vulnerability_file`: this parameter is used to specify the path to the **vulnerability model** file;
- `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. Any value between zero and one will lead to increasing levels of correlation;
- `master_seed`: this parameter is used to control the random generator in the loss ratio sampling process. This way, if the same `master_seed` is defined at each calculation run, the same random loss ratios will be generated, thus allowing replicability of the results.

7.1.4.2. Scenario Damage Calculator

For this calculator, the parameter `calculation_mode` needs to be defined as `scenario_damage`. There is only one parameter specific to this calculator, which is the **fragility model** file path, as presented below.

```
...  
fragility_file = fragility_model.xml
```

- `fragility_file`: a parameter used to define the path to the **fragility model** file.

7.1.4.3. Probabilistic Event-based Risk Calculator

The parameter `calculation_mode` needs to be set to `event_based` in order to use this calculator. Similarly to that described for the Scenario Risk Calculator, a Monte Carlo sampling process is also employed within this module to take into account the loss ratio uncertainty. Hence, the parameters `asset_correlation` and `master_seed` need to be defined as previously described. The remaining parameters are presented below.

```
...
vulnerability_file = vulnerability_model.xml
asset_correlation = 0.7
master_seed = 3

loss_curve_resolution = 20
conditional_loss_poes = 0.01, 0.05, 0.1
```

- `loss_curve_resolution`: since this calculator uses an event-based approach, a large number of levels of loss (and associated probabilities of exceedance) is computed (one per event) for each asset. The `oq-risklib` will use this large set of results to extrapolate a loss curve, whose number of points are controlled by this parameter;
- `conditional_loss_poes`: this parameter is used to define the probabilities of exceedance at which loss maps are to be produced.

7.1.4.4. Classical PSHA-based Risk Calculator

In order to run this calculator, the parameter `calculation_mode` needs to be set to `classical`. With this calculator it is also possible to extract loss maps, so the parameter `conditional_loss_poes` needs to be defined as explained in the previous sub-section. The remaining parameter is illustrated below.

```
...
vulnerability_file = vulnerability_model.xml

lrem_steps_per_interval = 2
conditional_loss_poes = 0.01, 0.05, 0.1
```

- `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

7. Using the risk module

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. More details are provided in the OpenQuake Engine Book (Risk).

7.1.4.5. Retrofitting Benefit/Cost Ratio Calculator

As previously explained, this calculator uses loss exceedance curves which can be calculated using the Classical PSHA-based Risk or the Probabilistic Event-based Risk calculators. Therefore, depending on which calculator a user chooses to employ, the configuration file will be different. If the Classical PSHA-based Risk calculator is employed, then the `calculation_mode` should be set to `classical_bcr` and the calculator-specific part of the configuration file should be defined as presented below.

```
...
vulnerability_file = vulnerability_model.xml
vulnerability_retrofitted_file = vulnerability_model_retrof.xml

lrem_steps_per_interval = 2

interest_rate= 0.005
asset_life_expectancy = 50
```

- `vulnerability_retrofitted_file`: this parameter is used to specify the path to the **vulnerability model** file containing the **vulnerability functions** for the retrofitted assets;
- `interest_rate`: this parameter represents the interest rate and it serves the purposes of taking into account the variation of building value throughout time;
- `asset_life_expectancy`: this variable defines the life expectancy, or design life, of the assets.

Alternatively, if a user decides to employ the Probabilistic Event-based Risk calculator for the calculation of the loss curves, then the `calculation_mode` should be set to `event_based_bcr` and the remaining portion of the configuration file should be defined as follows.

7.1. Input data definition

```
...  
vulnerability_file = vulnerability_model.xml  
vulnerability_retrofitted_file = vulnerability_model_retrof.xml  
asset_correlation = 0.7  
master_seed = 3  
  
loss_curve_resolution = 20  
  
interest_rate= 0.005  
asset_life_expectancy = 50
```


Risk calculations and results

8.1. Running OpenQuake engine for risk calculations

Using the command line interface, risk calculations can be launched and the resulting outputs can be extracted. This section describes all the currently implemented commands and presents examples for each of the calculators. One of the first tasks that needs to be performed is the definition of the seismic hazard input. As mentioned in section 6.2, the risk calculations can use the results produced by the hazard component of the OpenQuake engine. Moreover, for the two scenario-based calculators, users also have the option of loading a set of ground motion fields that might have been produced using the OpenQuake engine, or other software. In order to load ground motion fields based on a single earthquake event, it is fundamental to ensure that the ground motion values have been stored according to the appropriate NRML schema, as presented in section (TO BE ADDED). Then, the following command can be used:

```
user@ubuntu:~$ openquake --loadgmf <gml_directory>
```

Whether a user chooses to load pre-computed ground motion fields, or calculate this input using the hazard component of the OpenQuake engine, a unique id is associated to the set of ground motion fields, as depicted below.

```
Calculation 3 results:
id | output_type | name
12 | gmf_scenario | gmf_scenario
```

This is the parameter that will be used when launching the risk calculations to indicate which hazard input should be employed. In the case of the scenario-based calculators, there is only a single hazard input (one or a set of ground

8. Risk calculations and results

motion fields). For the remaining calculators, where probabilistic seismic hazard is used, it is possible to have multiple hazard inputs due to the employment of logic trees, as described in section 3.1. In the following illustration, a set of hazard results produced using the Classical PSHA calculator is presented.

Calculation 4 results:

id	output_type	name
32	hazard_curve	hc-rlz-32-PGA
33	hazard_curve	hc-rlz-33-PGA
34	hazard_curve	hc-rlz-34-PGA
35	hazard_curve	hc-rlz-35-PGA
36	hazard_curve	mean curve for PGA
37	hazard_curve	quantile curve (poe>= 0.15) for imt PGA
38	hazard_curve	quantile curve (poe>= 0.85) for imt PGA

In this case, since the logic tree had four branches, four sets of hazard curves were produced, each one with its own id. In addition, mean and quantile hazard curves were also produced. A user may choose to run risk calculations using results from one of the branches or mean/quantile curves. To do so, the id of the respective hazard result should be employed when launching the risk calculations, as depicted below.

```
user@ubuntu:~$ openquake --run-risk job.ini --hazard-output-id  
<hazard_output_id>
```

or simply:

```
user@ubuntu:~$ openquake --rr job.ini --ho <hazard_output_id>
```

On the other hand, a user might also want to run the risk calculations considering all the hazard results from a certain calculation run. In this case, rather than providing the hazard-output-id, users need to provide the id of the hazard calculation as follows.

```
user@ubuntu:~$ openquake --run-risk job.ini --hazard-calculation-id  
<hazard_calculation_id>
```

or simply:

```
user@ubuntu:~$ openquake --rr job.ini --co <hazard_calculation_id>
```

8.1. Running OpenQuake engine for risk calculations

For further information about consulting the id of hazard results or calculations, users are referred to section 6.2. To obtain a list of all the risk calculations, the following command can be employed.

```
user@ubuntu:~$ openquake --list-risk-calculations
```

or simply:

```
user@ubuntu:~$ openquake --lrc
```

Which will display a list of risk calculations as presented below.

calc_id	num_jobs	latest_job_status	last_update	description
1	1	successful	2013-04-02 08:50:30	Scenario Damage
2	1	failed	2013-04-03 09:56:17	Scenario Risk
3	1	successful	2013-04-04 10:45:32	Scenario Risk
4	4	successful	2013-04-04 10:48:33	Classical PSHA Risk

Then, in order to display a list of the risk outputs from a given job, the following command can be used

```
user@ubuntu:~$ openquake --list-risk-outputs <risk_calculation_id>
```

or simply:

```
user@ubuntu:~$ openquake --lro <risk_calculation_id>
```

Which will display a list of risk calculations as presented below.

Calculation 4 results:		
id	output_type	name
29	loss_curve	Loss Curve set for hazard 32
30	loss_map	Loss Map Set with poe 0.1 for hazard 32

Then, in order to export the risk calculation outputs in the appropriate xml format, the following command can be used.

```
user@ubuntu:~$ openquake --export-risk <risk_output_id>  
<output_directory>
```

or simply:

```
user@ubuntu:~$ openquake --er <risk_output_id> <output_directory>
```

8.2. Description of the outputs

This section describes how the different risk outputs are being stored using the Natural Hazards risk Markup Language (NRML). For each output, the various attributes are discussed, and example schema is provided.

8.2.1. Loss statistics

This output is produced by the Scenario Risk calculator and is comprised by a mean total loss and associated standard deviation. These results are stored in a comma separate value (csv) file as follows:

Mean,Standard Deviation 8717775315.66,2047771108.36

8.2.2. Loss maps

A loss map contains the spatial distribution of the losses throughout the region of interest. This result can be produced by the Scenario Risk calculator (representing the losses from a single event), or from the Probabilistic Event-based Risk or Classical PSHA-based Risk calculators (representing the expected losses from probabilistic seismic hazard). In the former case, the loss map is comprised of a mean loss and respective standard deviation for each **asset**, whilst for the latter, a single value is provided, representing the expected loss for a given return period (or probability of exceedance for a certain time span, or investigation interval). In the following example, a loss map due to a single earthquake is presented.

```
<?xml version="1.0" encoding="UTF-8"?>
<nrml xmlns:gml="http://www.opengis.net/gml"
      xmlns="http://openquake.org/xmlns/nrml/0.4">
  <lossMap lossCategory="buildings" unit="EUR">
    <node>
      <gml:Point>
        <gml:pos>83.31 29.46</gml:pos>
      </gml:Point>
      loss assetRef="a1" mean="53.3" stdDev="109.25"/>
      loss assetRef="a2" mean="386.0" stdDev="695.7"/>
      loss assetRef="a3" mean="303.1" stdDev="447.4"/>
    </node>
  </lossMap>
</nrml>
```

8.2. Description of the outputs

```
        loss assetRef="a4" mean="298.9" stdDev="453.7"/>
    </node>
    ...
    <node>
        <gml:Point>
            <gml:pos>83.33 28.71</gml:pos>
        </gml:Point>
        loss assetRef="a997" mean="277.3" stdDev="100.8"/>
        loss assetRef="a998" mean="219.6" stdDev="123.5"/>
        loss assetRef="a999" mean="576.3" stdDev="210.9"/>
    </node>
</lossMap>
</nrml>
```

- **lossCategory**: the type of losses that are being stored. This parameter is taken from the **vulnerability model** that was used in the loss calculations (e.g. fatalities, economic loss);
- **unit**: this attribute is used to define the units in which the losses are being measured (e.g. EUR);
- **node**: each loss map is comprised by various nodes, each node possibly containing a number of **assets**. The location of the node is defined by a latitude and longitude in decimal degrees within the field `gml:Point`. The mean loss (mean) and associated standard deviation (stdDev) for each **asset** (identified by the parameter `assetRef`) is stored in the `loss` field.

For the probabilistic loss maps (expected losses for a given return period), a set of additional parameters need to be considered as depicted in the following example.

```
<?xml version="1.0" encoding="UTF-8"?>
<nrml xmlns:gml="http://www.opengis.net/gml"
      xmlns="http://openquake.org/xmlns/nrml/0.4">
  <lossMap investigationTime="50" poE="0.1" sourceModelTreePath="b1"
    gsimTreePath="b1" lossCategory="buildings" unit="EUR">
    <node>
      <gml:Point>
        <gml:pos>83.31 29.46</gml:pos>
      </gml:Point>
      loss assetRef="a1" value="696.1"/>
    </node>
  </lossMap>
</nrml>
```

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```
        loss assetRef="a2" value="4201.4"/>
        loss assetRef="a3" value="2666.0"/>
        loss assetRef="a4" value="1291.8"/>
    </node>
    ...
    <node>
        <gml:Point>
            <gml:pos>83.33 28.71</gml:pos>
        </gml:Point>
        loss assetRef="a997" value="4077.3"/>
        loss assetRef="a998" value="2466.4"/>
        loss assetRef="a999" value="4434.5"/>
    </node>
</lossMap>
</nrml>
```

- investigationTime: time span used to compute the probability of exceedance;
- poE: parameter specifying the probability of exceedance (e.g. 0.1);
- sourceModelTreePath: this is a parameter indicating the path used to create the seismic source model;
- gsimTreePath: this parameter designates the ground motion model;
- node: this attribute follows an identical structure as seen in the previous example, but only a single loss (value) is provided per **asset**.

8.2.3. Damage distribution

The damage distribution is part of the outputs from the Scenario Damage calculator, and can be provided in three ways: per **asset**, per taxonomy or the total damage distribution. In the following illustration, an example of the NRML schema for the damage distribution per **asset** is presented:

```
<?xml version="1.0" encoding="UTF-8"?>
<nrml xmlns:gml="http://www.opengis.net/gml"
      xmlns="http://openquake.org/xmlns/nrml/0.4">
  <dmgDistPerAsset>
    <damageStates>
```

8.2. Description of the outputs

```
no_damage
slight
moderate
complete
</damageStates>
<DDNode>
  <gml:Point>
    <gml:pos>83.31 29.46</gml:pos>
  </gml:Point>
  <asset assetRef="a1">
    <damage ds="no_damage" mean="486.6" stddev="130.1"/>
    <damage ds="slight" mean="118.8" stddev="9.9"/>
    <damage ds="moderate" mean="130.3" stddev="20.3"/>
    <damage ds="complete" mean="186.5" stddev="90.8"/>
  </asset>
  <asset assetRef="2">
    <damage ds="no_damage" mean="877.08" stddev="257.9"/>
    <damage ds="slight" mean="171.3" stddev="13.2"/>
    <damage ds="moderate" mean="161.5" stddev="014.5"/>
    <damage ds="complete" mean="563.8" stddev="223.6"/>
  </asset>
</DDNode>
...
<DDNode>
  <gml:Point>
    <gml:pos>83.91 28.19</gml:pos>
  </gml:Point>
  <asset assetRef="999">
    <damage ds="no_damage" mean="21.5" stddev="16.6"/>
    <damage ds="slight" mean="15.5" stddev="8.7"/>
    <damage ds="moderate" mean="39.1" stddev="17.3"/>
    <damage ds="complete" mean="493.5" stddev="53.1"/>
  </asset>
</DDNode>
</dmgDistPerAsset>
</nrml>
```

- damageStates: this field serves the purposes of storing the set of damage states, as defined in the **fragility model** employed in the calculations;

8. Risk calculations and results

- **DDNode**: this attribute is used to store the damage distribution of a number of **assets**, at a given location (defined within the attribute `gml:Point`). For each **asset**, the mean number of buildings (mean) and associated standard deviation (stddev) in each damage state is defined.

The Scenario Damage calculator can also estimate the total number of buildings with a certain **taxonomy**, in each damage state. This distribution of damage per building **taxonomy** is depicted in the following example.

```
<?xml version="1.0" encoding="UTF-8"?>
<nrml xmlns:gml="http://www.opengis.net/gml"
      xmlns="http://openquake.org/xmlns/nrml/0.4">
<dmgDistPerAsset>
  <damageStates>
    no_damage
    slight
    moderate
    complete
  </damageStates>
  <DDNode>
    <taxonomy>W</taxonomy>
    <damage ds="no_damage" mean="456450.2" stddev="26376.62"/>
    <damage ds="slight" mean="88102.3" stddev="3283.9"/>
    <damage ds="moderate" mean="103564.6" stddev="3487.1"/>
    <damage ds="complete" mean="275891.1" stddev="26676.8"/>
  </DDNode>
  ...
  <DDNode>
    <taxonomy>RC</taxonomy>
    <damage ds="no_damage" mean="4484.2" stddev="460.9"/>
    <damage ds="slight" mean="932.4" stddev="106.7"/>
    <damage ds="moderate" mean="1691.7" stddev="177.9"/>
    <damage ds="complete" mean="7659.5" stddev="799.3"/>
  </DDNode>
</dmgDistPerAsset>
</nrml>
```

In the damage distribution per **taxonomy**, each **DDNode** contains the statistics of the number of buildings in each damage state, belonging to a given building class as specified in the `taxonomy` attribute. Finally, a total damage distribution

can also be calculated, which contains the mean and standard deviation of the total number of buildings in each damage state, as illustrated bellow.

```
<?xml version="1.0" encoding="UTF-8"?>
<nrml xmlns:gml="http://www.opengis.net/gml"
      xmlns="http://openquake.org/xmlns/nrml/0.4">
  <totalDmgDist>
    <damageStates>
      no_damage
      slight
      moderate
      complete
    </damageStates>
    <damage ds="no_damage" mean="456450.2" stddev="26376.62"/>
    <damage ds="slight" mean="88102.3" stddev="3283.9"/>
    <damage ds="moderate" mean="103564.6" stddev="3487.1"/>
    <damage ds="complete" mean="275891.1" stddev="26676.8"/>
  </totalDmgDist>
</nrml>
```

8.2.4. Collapse maps

Collapse maps are part of the Scenario Damage calculator outputs. These results provide the spatial distribution of the number of the collapsed buildings throughout the area of interest. An example of the schema is presented below.

```
<?xml version="1.0" encoding="UTF-8"?>
<nrml xmlns:gml="http://www.opengis.net/gml"
      xmlns="http://openquake.org/xmlns/nrml/0.4">
  <collapseMap>
    <CMNode>
      <gml:Point>
        <gml:pos>83.31 29.46</gml:pos>
      </gml:Point>
      <cf assetRef="a1" mean="227.1" stdDev="95.8"/>
      <cf assetRef="a2" mean="703.2" stdDev="240.2"/>
      <cf assetRef="a3" mean="199.5" stdDev="63.3"/>
      <cf assetRef="a4" mean="357.8" stdDev="136.1"/>
    </CMNode>
    ...
  </collapseMap>
</nrml>
```

8. Risk calculations and results

```
<CMNode>
  <gml:Point>
    <gml:pos>83.33 28.71</gml:pos>
  </gml:Point>
  <cf assetRef="a997" mean="239.4" stdDev="102.0"/>
  <cf assetRef="a998" mean="733.0" stdDev="253.2"/>
  <cf assetRef="a999" mean="207.4" stdDev="66.5"/>
</CMNode>
</collapseMap>
</nrml>
```

This schema follows the same structure of the loss maps presented previously. Thus, the results for a number of **assets** at a given location are stored within the field **+CMNode+**). This field is associated with a location defined within the **gml:Point** attribute) and it contains the mean number of collapses (**mean**) and respective standard deviation (**stdDev**) for each **asset** (identified by the parameter **assetRef**).

8.2.5. Loss exceedance curves

Loss exceedance curves can be calculated using the Classical PSHA-based Risk or Probabilistic Event-based Risk calculators, and they provide the probability of exceeding a set of levels of loss, within a given time span (or investigation interval). Similarly to what has been described for the probabilistic loss maps, also here it is necessary to define the parameters **investigationTime**, **sourceModelTreePath**, **gsimTreePath** and **unit**. Then, the set of loss exceedance curves are stored as presented in the following example.

```
<?xml version="1.0" encoding="UTF-8"?>
<nrml xmlns:gml="http://www.opengis.net/gml"
<lossCurves investigationTime="50" sourceModelTreePath="b1"
  gsimTreePath="b1" unit="EUR">
  <lossCurve assetRef="a1">
    <gml:Point>
      <gml:pos>83.31 29.46</gml:pos>
    </gml:Point>
    <poE> 0.970 0.297 0.137 0.019 0.005 0.001</poE>
    <losses> 235 477 989 4102 7444 15631</losses>
    <lossRatios> 0.02 0.03 0.06 0.26 0.48 1.0</lossRatios>
  </lossCurve>
```

```

...
<lossCurve assetRef="a999">
  <gml:Point>
    <gml:pos>83.33 28.71</gml:pos>
  </gml:Point>
  <poE> 0.99 0.714 0.112 0.020 0.004 0.001</poE>
  <losses>58 402 819 3664 8001 13540</losses>
  <lossRatios> 0.02 0.04 0.07 0.32 0.59 1.0</lossRatios>
</lossCurve>
</lossCurves>
</nrml>

```

Each lossCurve is associated with a location (defined within the gml:Point attribute) and a reference to the **asset** (assetRef) whose loss is being represented. Then, three lists of values are stored: the probabilities of exceedance (poE), levels of absolute loss (losses) and percentages of loss (lossRatios).

8.2.6. 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 PSHA-based Risk or Probabilistic Event-based Risk calculators. For this reason, the parameters sourceModelTreePath and gsimTreePath are also included in this NRML schema, so the whole calculation process can be tracked back. The results for each **asset** are being stored as depicted below.

```

<?xml version="1.0" encoding="UTF-8"?>
<nrml xmlns:gml="http://www.opengis.net/gml"
  xmlns="http://openquake.org/xmlns/nrml/0.4">
<bcrMap interestRate="0.05" assetLifeExpectancy="50.0"
  sourceModelTreePath="b1" gsimTreePath="b1" unit="EUR">
  <node>
    <gml:Point>
      <gml:pos>83.31 29.46</gml:pos>
    </gml:Point>
    <bcr assetRef="a1" ratio="1.96" aalOrig="1466.9"
      aalRetr="253.0"/>
    <bcr assetRef="a2" ratio="2.33" aalOrig="937.9"
      aalRetr="215.7"/>
    <bcr assetRef="a3" ratio="1.32" aalOrig="492.0"

```

8. Risk calculations and results

```
        aalRetr="83.7"/>
    <bcr assetRef="a4" ratio="0.76" aalOrig="294.1"
        aalRetr="57.9"/>
</node>
...
<node>
    <gml:Point>
        <gml:pos>83.33 28.71</gml:pos>
    </gml:Point>
    <bcr assetRef="a997" ratio="0.84" aalOrig="18323.1"
        aalRetr="7340.7"/>
    <bcr assetRef="a998" ratio="1.36" aalOrig="152027.6"
        aalRetr="29123.5"/>
    <bcr assetRef="a999" ratio="0.83" aalOrig="60727.3"
        aalRetr="12676.1"/>
</node>
</bcrMap>
</nrml>
```

- **interestRate**: this parameter represents the inflation rate of the economic value of the **assets**;
- **assetLifeExpectancy**: a parameter specifying 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.

Demonstrative examples

This section describes the set of demos that have been compiled to exercise the OpenQuake engine. These demos can be found in a public repository in GitHub at the following link <http://github.com/gem/oq-engine/tree/master/demos>. Furthermore, a folder containing all of these demonstrative examples is provided when an OATS (OpenQuake Alpha Testing Service) account is requested, and it is also part of the OpenQuake engine virtual image package. These examples are purely demonstrative and do not intend to represent accurately the seismicity, vulnerability or exposure characteristics of the region of interest, but simply to provide example input files that can be used as a benchmark 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.

The five demos use Nepal as the region of interest. An example **exposure model** has been developed for this region, comprising 9144 assets distributed amongst 2221 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 Figure 9.1.

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, **vulnerability functions** and **fragility functions** were collected from the literature. 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/>).

9. Demonstrative examples

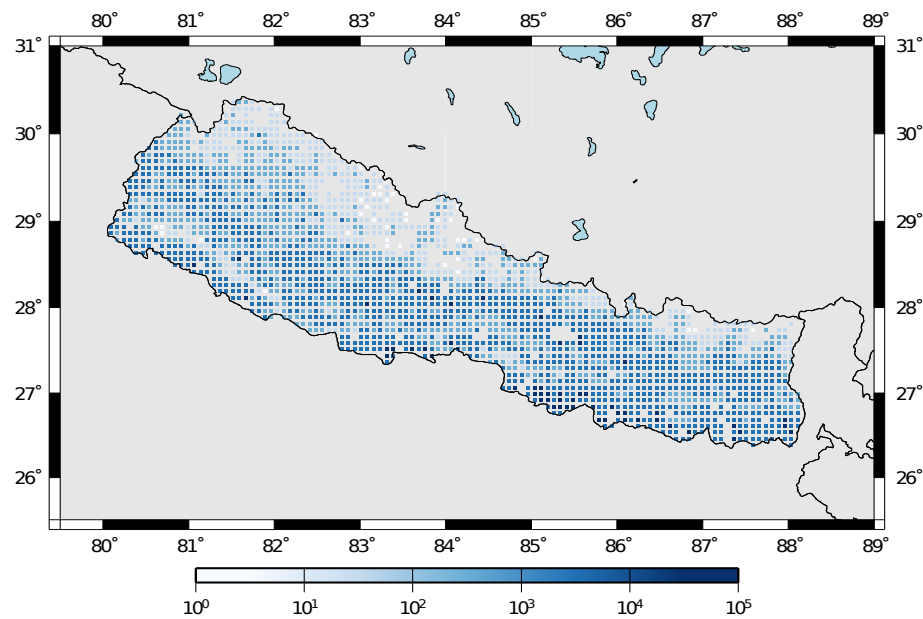


Figure 9.1. – *Distribution of number of buildings in Nepal.*

This section includes instructions not only on how to run the risk calculations, but also on how to produce the necessary hazard input. Thus, each demo comprises the configuration file, exposure model and fragility/vulnerability models fundamental for the risk calculations, but also a configuration file and associated input models to produce the hazard input.

9.1. Scenario Risk demo

A rupture of magnitude 7 Mw in the central part of Nepal was considered within this demo. The characteristics of this rupture (geometry, dip, rake, hypocentre, upper and lower seismogenic depth) have been defined in the `rupture.xml` file, whilst the hazard calculation settings have been established on the `job_haz_ini` file. In order to calculate the set of ground motion fields due to this rupture, users should navigate to the folder where the demo files are located, and use the following command:

```
user@ubuntu:~$ openquake --rh job_gmfq.ini
```

which will produce the following hazard result:

```
Calculation 10 results:
id | output_type | name
20 | gmf_scenario | gmf_scenario
```

Then, this hazard input can be used for the risk calculations using the following command:

```
user@ubuntu:~$ openquake --rr job_risk.ini --hazard-output-id 20
```

leading to the following results:

```
Calculation 11 results:
id | output_type | name
21 | aggregate_loss | Aggregate Loss
22 | loss_map | Loss Map
```

9.2. Scenario Damage demo

The same rupture described in the Scenario Risk demo was used for this demo. The workflow to produce the set of ground motion fields described in the previous section is also valid herein. Then, to run the Scenario Damage demo, users should move to the folder where the required files have been placed and employ following command:

```
user@ubuntu:~$ openquake --rr job_damage.ini --hazard-output-id 20
```

and the following outputs will be produced:

```
Calculation 12 results:
id | output_type | name
23 | collapse_map | Collapse Map per Asset
24 | dmg_dist_per_asset | Damage Distribution per Asset
25 | dmg_dist_per_taxonomy | Damage Distribution per Taxonomy
26 | dmg_dist_total | Damage Distribution Total
```

9. Demonstrative examples

9.3. Classical PSHA-based Risk demo

The seismic source model developed within the Global Seismic Hazard Assessment Program (GSHAP) was used with the [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 seismic hazard curves will be produced. To do so, the following command needs to be employed:

```
user@ubuntu:~$ openquake --rh job_hazard.ini
```

which will produce the following hazard output:

```
Calculation 13 results:
id | output_type | name
27 | hazard_curve | hc-rlz-70
```

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:~$ openquake --rr job_risk.ini --hazard-output-id 27
```

and the following outputs are expected:

```
Calculation 14 results:
id | output_type | name
28 | loss_curve | Loss Curve set for hazard 27
29 | loss_map | Loss Map Set with poe 0.1 for hazard 27
30 | loss_map | Loss Map Set with poe 0.01 for hazard 27
```

9.4. Probabilistic Event-based demo

This demo uses the same probabilistic seismic hazard assessment (PSHA) model described in the previous example. However, instead of hazard curves, sets of ground motion fields are required. To trigger the hazard calculations the following command needs to be used:

9.5. Retrofitting Benefit/cost ratio demo

```
user@ubuntu:~$ openquake --rh job_hazard.ini
```

and the following results are expected:

```
Calculation 15 results:
id | output_type | name
31 | gmf | gmf-rlz-72
32 | ses | ses-coll-rlz-72
```

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, which can be launched through the following command:

```
user@ubuntu:~$ openquake --rr job_risk.ini --hazard-output-id 31
```

leading to the following outputs:

```
Calculation 16 results:
id | output_type | name
33 | loss_curve | Loss Curve set for hazard 31
34 | loss_map | Loss Map Set with poe 0.1 for hazard 31
35 | loss_map | Loss Map Set with poe 0.01 for hazard 31
36 | agg_loss_curve | Aggregated loss curve for hazard 31
```

9.5. Retrofitting Benefit/cost ratio demo

The loss exceedance curves used within this demo are produced using the Classical PSHA-based Risk calculator. Thus, the process to produce the seismic hazard curves described in the respective section (9.3) can be employed here. Then, the risk calculations can be initiated using the following command:

```
user@ubuntu:~$ openquake --rr job_bcr.ini --hazard-output-id 27
```

which should produce the following output:

```
Calculation 17 results:
id | output_type | name
37 | bcr_distribution | BCR Distribution for hazard 27
```


PART IV

Appendixes

Supported ground motion prediction equations

- **Abrahamson and Silva [2008]** - A ground motion prediction equation for shallow earthquakes in active tectonic regions developed in the context of the NGA West project (<http://peer.berkeley.edu/ngawest/>)
- **Akkar and Bommer [2010]** - A ground motion prediction equation for shallow earthquakes in active tectonic regions developed in using mostly data from Europe and the Middle East. The dataset used to derive these equations contains events with moment magnitude between 5 and 7.6 and distances up to 100 km.
- **Akkar and Çağnan [2010]** - A ground motion prediction equation for shallow earthquakes in active tectonic regions developed using data from the Turkish strong-motion database. Equations are valid for a distance range of 0–200 km and are derived for moment magnitudes between 5 and 7.6.
- **Atkinson and Boore [2003]** - A ground motion prediction equation for subduction interface and in-slab events obtained using a global dataset of subduction earthquakes with moment magnitude between 5.0 and 8.3.
- **Atkinson and Boore [2006]** - A ground motion prediction equation for Stable Continental regions.
- **Boore and Atkinson [2008]** - A ground motion prediction equation for shallow earthquakes in active tectonic regions developed in the context of the NGA West project (<http://peer.berkeley.edu/ngawest/>)
- **Campbell and Bozorgnia [2003]**

A. Supported ground motion prediction equations

- [Cauzzi and Faccioli \[2008\]](#) - A ground motion prediction equation for shallow earthquakes in active tectonic regions mostly based on japanese data.
- [Chiou and Youngs \[2008\]](#) - A ground motion prediction equation for shallow earthquakes in active tectonic regions developed in the context of the NGA West (<http://peer.berkeley.edu/ngawest/>)
- [Faccioli et al. \[2010\]](#)
- [Lin and Lee \[2008\]](#)
- [Sadigh et al. \[1997\]](#)
- [Toro \[2002\]](#)
- [Youngs et al. \[1997\]](#)
- [Zhao et al. \[2006\]](#)

APPENDIX B

Supported magnitude-area scaling relationships

- [Wells and Coppersmith \[1994\]](#) - Probably the most well known magnitude-scaling relationship.

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Glossary

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.

asset

An asset is something of value, which can include buildings and population. For example, an asset can include an individual building at a given location, or a number of buildings that are grouped and co-located at a single location and are classified with the same **taxonomy**.

characteristic fault source

A fault source typology where ruptures always cover the entire fault surface .

complex fault source

A source typology usually adopted to model subduction interface faults, where ruptures can be floated over the fault surface.

dip

The dip is the steepest angle of descent of the fault plane relative to a horizontal plane; it is measured in degrees $[0,90]$.

exposure model

A set of **assets** grouped according to their geographical location, **taxonomy** and value.

fault trace

A curve representing the intersection between the surface representing the fault and the topographic surface .

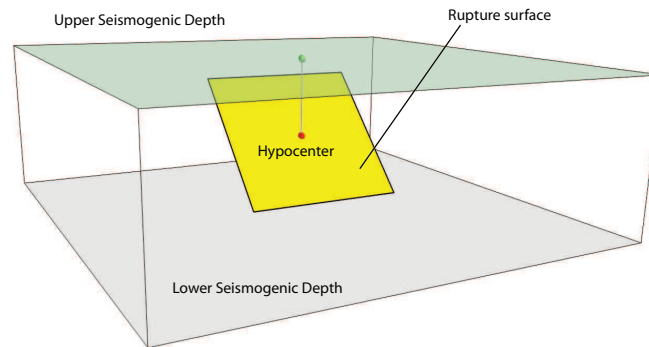


Figure B.1. – *Trace example*

fragility function

the probability of exceeding a set of limit states, given an intensity measure level. These functions can be discrete or continuous.

fragility model

A set of **fragility functions** used to model the fragility of all the **assets** in the **exposure model**..

GEM

Global Earthquake Model.

GMPE

Ground Motion Prediction Equation.

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**.

initial seismic source input model

An initial seismic source input model is a **seismic source input model** included in the first branching level of a seismic source logic tree.

magnitude-frequency distribution

See **magnitude-frequency distribution** .

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 .

MFD

Magnitude-Frequency Distribution.

oq-hazardlib

OpenQuake hazard library.

OQe

OpenQuake-engine.

point source

The elemental source typology used in OpenQuake-engine to model distributed seismicity.

probabilistic seismic hazard analysis

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.

PSHA

Probabilistic Seismic Hazard Analysis.

PSHA input model

An object containing the information necessary to describe the seismic source and the ground motion models - plus the related epistemic uncertainties.

rake

The rake is the angle .

seismic source input model

A collection of seismic source input. In the OpenQuake-engine a seismic source model doesn't contain epistemic uncertainty.

simple fault source

A source typology usually adopted to model shallow structures with an uncomplicated geometry .

SSHA

Scenario Based Seismic Hazard Analysis.

SSIM

Seismic Source Input Model.

Glossary

strike

The strike .

taxonomy

Scheme used to classify the **assets**. For buildings, a classification scheme has been proposed by **GEM** 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 **assets** in the **exposure model** to the relevant **vulnerability function** or **fragility function**.

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.

vulnerability model

A set of **vulnerability functions** used to model the physical vulnerability of all the **assets** in the **exposure model**..

