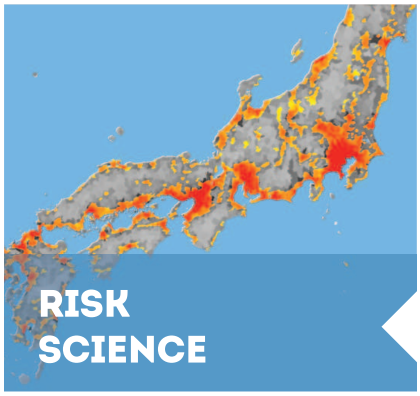

OPENQUAKE ENGINE

UNDERLYING RISK SCIENCE

Version 1.0.0 Beta

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.

GEM
GLOBAL EARTHQUAKE MODEL
working together to assess risk

"OpenQuake: Shaken not stirred"

OpenQuake Engine Book: Risk

May 2013

GEM Foundation, Pavia

Authors:
Helen Crowley[1], Vitor Silva[2]

[1] GEM Foundation
via Ferrata, 1
20133 Pavia
Italy

[2] GEM Model Facility
via Ferrata, 1
20133 Pavia
Italy

Email address (for all the authors):
<name.surname>@globalquakemodel.org

Credit
Crowley, H., V. Silva (2013). OpenQuake Engine Book: Risk. GEM Foundation, Pavia, Italy.

Acknowledgements

A number of internal and external collaborators contributed to the development of the OpenQuake engine and their input is herewith acknowledged. As of version 0.9 (April 2013), these were the current and former GEM Model Facility Team members (Zurich, Switzerland, and Pavia, Italy):

Lars Butler
Andrea Cerisara
Fabian Euchner
Anton Gritsay
Paul Henshaw
Muharem Hrnjadovic
Christopher MacGown
Joshua McKenty
Marco Milanesi
Matteo Nastasi
Luigi Panzeri
Michele Simionato
John Tarter
Giuseppe Vallarelli
Ben Wyss

Contents

CHAPTER 1

Motivation and Basics of the OpenQuake Engine

This book aims to provide 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. The book follows the traditional openness and transparency features of the Global Earthquake Model (GEM) as clearly indicated in the development principles of the OpenQuake engine.

The GEM initiative is a global collaborative effort with the aim to provide organisations and people with tools and resources for transparent assessment of earthquake risk anywhere in the world. The OpenQuake engine is a fully integrated, flexible and scalable hazard and physical risk calculation engine whose development is at the core of GEM's overall objectives.

1.1. Basics of the Engine

The implementation of the OpenQuake software officially started in Summer 2010 following the experience gained in GEM's kick-off project GEM1 [**?**], during which an extensive appraisal of existing hazard and physical risk codes was performed [**??**] and prototype hazard and risk software were selected, designed and implemented [**??**].

The current version of the OpenQuake engine is Python code developed following the most common requirements of Open Source software development, such as a public repository, IRC channel and open mailing lists. The source code, released under an open source software license, is freely and openly accessible on a web based repository (see github.com/gem) while the development process is managed so that the community can participate to the day by day development as well as in the mid- and long-term design process. The software development also leverages on a number of open source projects such as Celeryd and RabbitMQ, just to mention a few.

The hazard component of the engine largely relies on classes belonging to the OpenQuake Hazard library (see oq-hazardlib) a comprehensive library for performing state-of-the-art PSHA. This library has been designed and implemented following the successful collaboration and important lessons learnt working with the OpenSHA software and the developing teams at United States Geological Survey (USGS) and Southern California Earthquake Center (SCEC) in GEM1. The risk component of the engine was designed in GEM1, prototyped in Java and eventually coded in Python by the team operating at the GEM Model Facility. This scientific code was originally integrated with the engine, but in late 2012 it was extracted to form the OpenQuake Risk Library (see oq-risklib).

1.2. Structure of the Book

The OpenQuake Engine Book is organized into two volumes, one which describes the science behind the hazard component of the engine and another which illustrates the theory of the physical risk calculators incorporated into the software. Readers that are interested in learning how to run calculations using the OpenQuake engine are referred to the OpenQuake Engine User Manual.

The GEM Hazard Team is currently updating the volume on hazard. In the meantime, interested readers are referred to the OpenQuake Engine User Manual, or they can contact the coordinator, Dr Marco Pagani, for further information.

This volume on risk is organised as follows:

- Chapter 2 introduces the main physical risk concepts and workflows.
- Chapter 3 contains an explanation of the exposure, physical vulnerability and fragility concepts, which are input to the calculations.
- Chapter 4 describes the scenario risk methodology, for estimating loss distributions for single events.
- Chapter 5 describes the scenario damage methodology, for estimating damage ditributions for single events.
- Chapter 6 provides an overview of the probabilistic event-based risk calculation methodology, which produces loss exceedance curves for portfolios of buildings.
- Chapter 7 illustrates single-site risk calculations based on the hazard curves from classical PSHA.
- Chapter 8 outlines the benefit/cost ratio calculations based on loss curves for structures with and without retrofitting.

CHAPTER 2

Introduction to Physical Risk

This book aims to provide 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. The book follows the traditional openness and transparency features of the GEM as clearly indicated in the development principles of the OpenQuake engine.

The GEM initiative is a global collaborative effort with the aim to provide organisations and people with tools and resources for transparent assessment of earthquake risk anywhere in the world. The OpenQuake engine is a fully integrated, flexible and scalable hazard and physical risk calculation engine whose development is at the core of GEM's overall objectives.

2.1. Basics of the Engine

The implementation of the OpenQuake software officially started in Summer 2010 following the experience gained in GEM's kick-off project GEM1 [**?**], during which an extensive appraisal of existing hazard and physical risk codes was performed [**??**] and prototype hazard and risk software were selected, designed and implemented [**??**].

The current version of the OpenQuake engine is Python code developed following the most common requirements of Open Source software development, such as a public repository, IRC channel and open mailing lists. The source code, released under an open source software license, is freely and openly accessible on a web based repository (see github.com/gem) while the development process is managed so that the community can participate to the day by day development as well as in the mid- and long-term design process. The software development also leverages on a number of open source projects such as Celeryd and RabbitMQ, just to mention a few.

The hazard component of the engine largely relies on classes belonging to the OpenQuake Hazard library (see oq-hazardlib) a comprehensive library for performing state-of-the-art PSHA. This library has been designed and implemented following the successful collaboration and important lessons learnt working with the OpenSHA software and the developing teams at USGS and SCEC in GEM1. The risk component of the engine was designed in GEM1, prototyped in Java and eventually coded in Python by the team operating at the

GEM Model Facility. This scientific code was originally integrated with the engine, but in late 2012 it was extracted to form the OpenQuake Risk Library (see oq-risklib).

2.2. Structure of the Book

The OpenQuake Engine Book is organized into two volumes, one which describes the science behind the hazard component of the engine and another which illustrates the theory of the physical risk calculators incorporated into the software. Readers that are interested in learning how to run calculations using the OpenQuake engine are referred to the OpenQuake Engine User Manual.

The GEM Hazard Team is currently updating the volume on hazard. In the meantime, interested readers are referred to the OpenQuake Engine User Manual, or they can contact the coordinator, Dr Marco Pagani, for further information.

This volume on risk is organised as follows:

- Chapter 2 introduces the main physical risk concepts and workflows.
- Chapter 3 contains an explanation of the exposure, physical vulnerability and fragility concepts, which are input to the calculations.
- Chapter 4 describes the scenario risk methodology, for estimating loss distributions for single events.
- Chapter 5 describes the scenario damage methodology, for estimating damage ditributions for single events.
- Chapter 6 provides an overview of the probabilistic event-based risk calculation methodology, which produces loss exceedance curves for portfolios of buildings.
- Chapter 7 illustrates single-site risk calculations based on the hazard curves from classical PSHA.
- Chapter 8 outlines the benefit/cost ratio calculations based on loss curves for structures with and without retrofitting.

CHAPTER 3

Physical Risk Input Description

The main sources of input information required for a risk calculation with the OpenQuake engine are an exposure model and a physical vulnerability model or fragility model (in addition to the calculation type, such as those described in Chapter 2, and the region of interest). An exposure model for a given category of asset (e.g. population, buildings, contents) describes, at each location of interest within a given region, the value of each asset of a given taxonomy. The physical vulnerability model described the loss ratio distribution for a set of intensity measure levels, while the fragility model provides the probability of exceeding a set of damage states, given a set of intensity measure levels.

3.1. Exposure

The OpenQuake engine requires an exposure model that needs to be stored according to the respective Natural hazards' Risk Markup Language (NRML) schema (see oq-nrmllib). More information on the formats of this input model is provided in the OpenQuake Engine User Manual. This file format can include several typologies of asset such as population or buildings. The following parameters are currently being used to describe each asset in the exposure model:

- Asset reference: A unique key used to identify the asset instance;
- Location: Geographic coordinates of the asset expressed in decimal degrees;
- Taxonomy: Reference to the classification scheme hat describes the asset;
- Number: A numerical value describing the number of units at the given location (e.g. building count).
- Area: This parameter specifies the built-up area of the asset, and can be defined in the two following ways: the aggregated area (i.e. the total built-up area of all the units at a given location, with a certain taxonomy); area per unit (i.e. the average built-up area for a single building);

- Structural cost: This parameter represents the structural replacement cost of the asset. This value can be defined in three possible ways: the aggregated structural cost (i.e. the total economic value of all the units with a certain taxonomy at a given location); the cost per unit (i.e. the average value for a single building); the cost per unit of area. Further information about how the structural cost is handled within the OpenQuake engine can be found in the OpenQuake Engine User Manual.

- Non-structural cost: This parameter is used to define the cost of the non-structural components. This cost defined in the same way as the structural cost.

- Contents cost: This parameter is used to define the contents cost, and it can be defined in the same way as the structural cost.

- Retrofitting cost: This parameter is used to define the economic structural cost due to the implementation of a retrofitting/strengthening intervention. The retrofitting cost can be defined in the same way as the structural cost.

- Occupants: This parameter defines the number of people that might exist inside of a given structure. Different values of occupants can be stored according to the time of the day (e.g day, night, transit).

- Deductible: This parameter is used in the computation of the insured losses, and it establishes the economic value that needs to be deducted from the ground-up losses. A deductible needs to be defined for each cost type (structural, non-structural and contents). This threshold can be defined in two ways: 1) the direct (absolute) value that will be deducted; 2) the fraction (relative) of the total cost that will be deduted.

- Limit: This parameter establishes the maximum economic amount that can be insured, and it also needs to be defined for each cost type. As described in the previous parameters, the limit can also be define as an absolute or relative quantity.

3.2. Physical Vulnerability

Physical vulnerability is defined as the probabilistic distribution of loss, given an intensity measure level. These vulnerability functions can be derived directly, usually through empirical methods where the losses from past events at given locations are related to the levels of intensity of ground motion at those locations, or they can be derived by combining fragility functions and consequence functions. Fragility functions describe the probability of exceeding a set of limit states, given an intensity measure level; limit states describe the limits to performance levels, such as damage or injury levels. Fragility functions can be derived by expert-opinion, empirically (using observed data), or analytically, by explicitly modeling the behavior of a given asset typology when subjected to increasing levels of ground motion. Consequence functions describe the probability distribution of loss, given a performance level and are generally derived empirically.

Version 0.9 of the OpenQuake engine only supports physical vulnerability through the aforementioned vulnerability functions. As part of the plans for a risk modelling toolkit, calculators are envisaged that will combine fragility functions and consequence functions to produce vulnerability functions that can be input into the engine.

3.2.1. Vulnerability Functions

3.2.1.1. Discrete Vulnerability Functions

In the current version of the OpenQuake engine (v0.9) discrete vulnerability functions are used to directly estimate fatalities and economic losses due to physical damage. Discrete vulnerability functions are described by a list of intensity measure levels and corresponding mean loss ratios (the ratio of mean loss to exposed value), associated coefficients of variation and probability distributions. The uncertainty on the loss ratio can follow a lognormal or Beta distribution. Figure 3.1 illustrates a discrete vulnerability function.

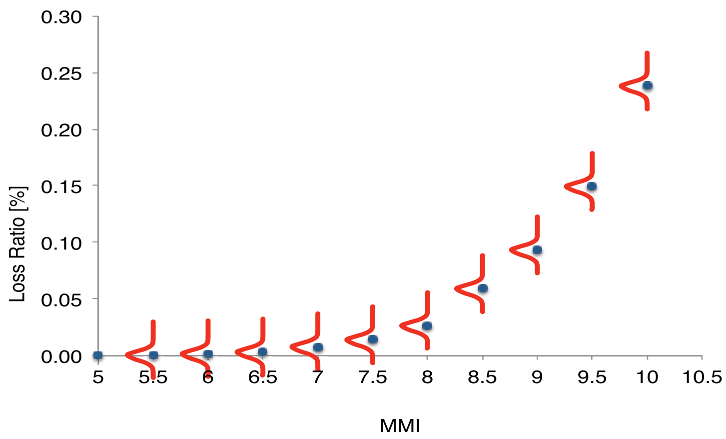

Figure 3.1 – *Discrete vulnerability function.*

3.2.1.2. Continuous Vulnerability Functions

Continuous vulnerability functions may be implemented in future versions of the OpenQuake engine. Continuous vulnerability functions will probably be described by continuous distributions of mean loss ratio and other fractiles of loss ratio, with ground motion intensity. Figure 3.2 illustrates this type of function, showing the distribution of mean loss and the 10 percent and 90 percent fractiles.

Continuous vulnerability functions are not currently supported

3.2.2. Fragility Functions

Fragility functions describe the probability of exceeding a set of limit states, given an intensity measure level. When the asset category concerns structures (e.g. buildings), the

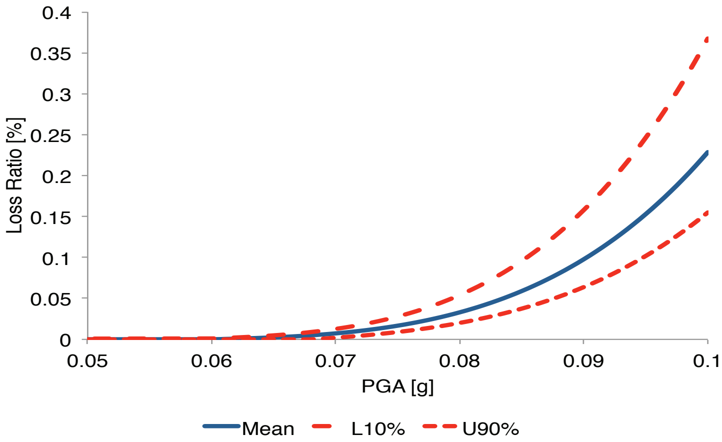

Figure 3.2 – *Continuous vulnerability function.*

intensity measure can either be structure-independent or structure-dependent. The former can be calculated directly from recorded measurements of ground shaking (e.g. peak ground acceleration, peak ground velocity, spectral acceleration at a given period of vibration, or even macroseismic intensity). The latter requires information on the characteristics of the structures in order to be calculated, for example spectral acceleration at the fundamental period of vibration, or spectral displacement at the limit state period of vibration. The calculation of these structural characteristics might be through a simple formulae (e.g. a yield period-height equation, see e.g. **?**) or through so-called non-linear static methods, which are needed when the intensity measure is a non-linear response quantity such as spectral displacement at the limit state period of vibration (see e.g. **?**). The oq-risklib currently does not support non-linear static methods.

3.2.2.1. Discrete Fragility Functions

Fragility functions can be defined in a discrete way by providing, for each limit state, a list of intensity measure levels and respective probabilities of exceedance. Figure 3.3 presents a set of discrete fragility functions using a macroseismic intensity measure.

3.2.2.2. Continuous Fragility Functions

Continuous fragility functions are defined by the parameters of a cumulative distribution function. In Figure 3.4 an example of a set of continuous fragility functions with a structure-dependent intensity measure is presented.

3.2.2.3. Uncertainty in Fragility Functions

uncertainty in fragility functions is not currently supported

The uncertainty in continuous glsplfragility function will be accounted for in future versions of the engine. Figure 3.5 shows a lognormal distribution that has been fit to the data (i.e.

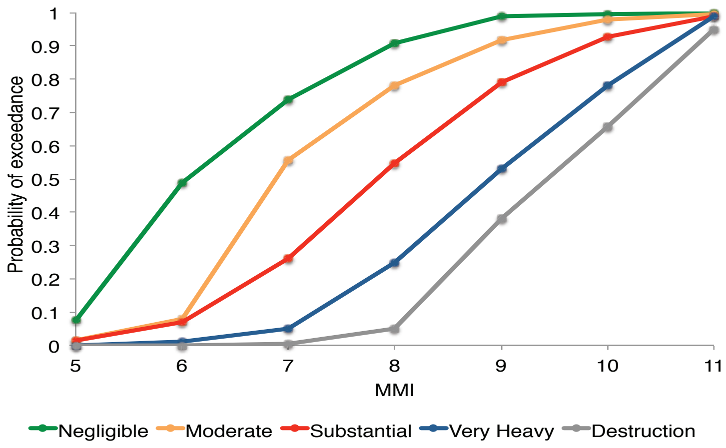

Figure 3.3 – *Set of discrete fragility functions.*

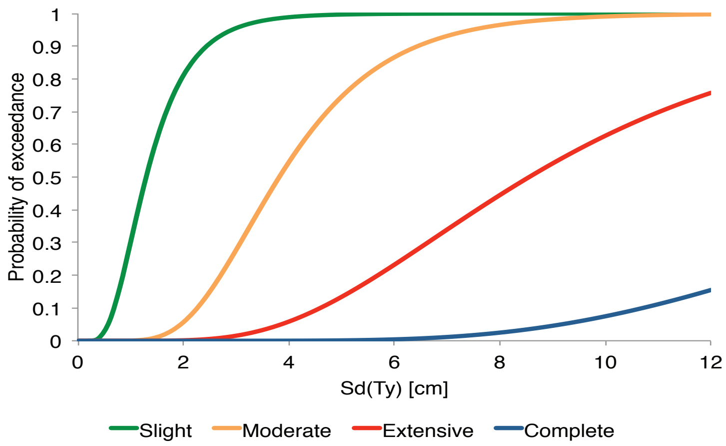

Figure 3.4 – *Set of continuous fragility functions.*

the fragility function), and the probabilistic distribution (i.e. mean and standard deviation) to describe the uncertainty in both the logarithmic mean and logarithmic standard deviation of the fragility function. When a set of glsplfragility function for different limit states are used, it is also necessary to provide information on the correlation between the logarithmic means and logarithmic standard deviations of each limit state.

3.2.3. Consequence Functions

Consequence functions describe the probability distribution of loss, given a performance level. For example, if the asset category is buildings and the performance level is significant damage, the consequence function will describe the mean loss ratio, coefficient of variation and probability distribution for that level of damage. Figure 3.6 presents the mean damage ratios for a set of performance levels proposed by two different sources. Although these

Consequence functions are not currently supported

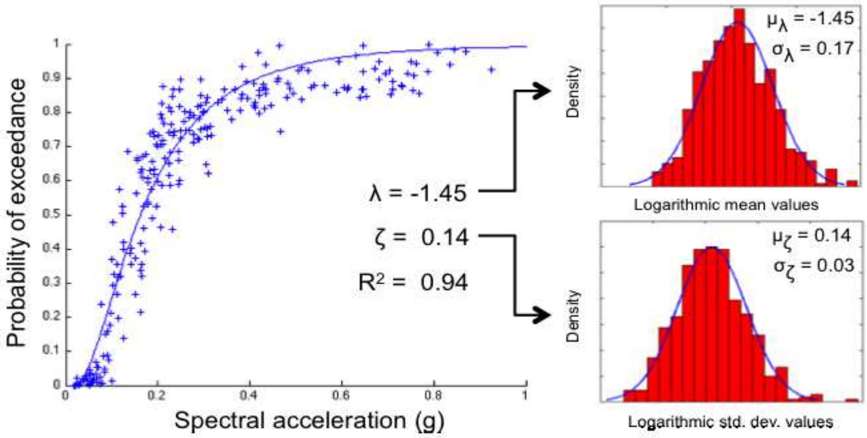

Figure 3.5 – *Uncertainty of continuous fragility functions.*

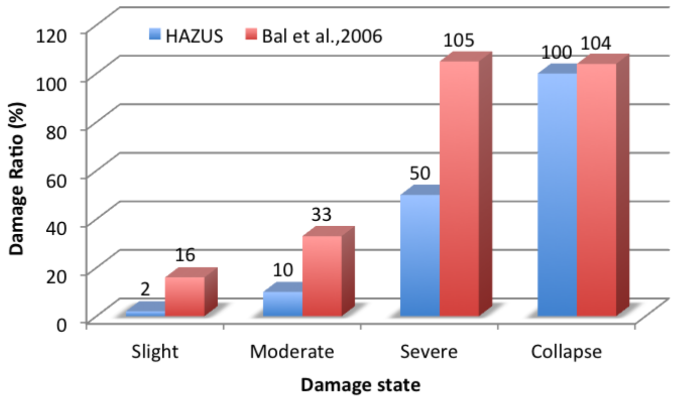

Figure 3.6 – *Consequence functions adapted from* **?**

functions are not directly supported, users can combine consequence functions with fragility functions to produce vulnerability functions to be input into the engine.

CHAPTER 4

Scenario Risk Calculator

4.1. Introduction

The scenario risk calculator is capable of computing losses and loss statistics from a single event for a collection of assets, given a set of ground-motion fields. The use of a set of ground-motion fields is recommended so that the aleatory variability (both inter- and intra-event) in the ground-motion prediction equation is modelled. The input ground-motion fields can be calculated with oq-hazardlib or by an external software; in either case they need to be stored in the OpenQuake engine database. With the use of the oq-hazardlib, these ground-motion fields can be calculated either with or without the spatial correlation of the ground motion residuals.

For each ground-motion field, the intensity measure level at a given site is combined with a vulnerability function, from which a loss ratio is randomly sampled, for each asset contained in the exposure model. The loss ratios that are sampled for assets of a given taxonomy classification at different locations can be considered to be either independent, fully correlated, or correlated with a specific correlation coefficient. Using these results, the mean and standard deviation of the loss ratios across all ground-motion fields can be calculated. Loss ratios are converted into ground-up losses by multiplying by the cost (which can be the structural, non-structural or contents) of the asset given in the exposure model. It is furthermore possible to sum the losses throughout the region and to compute the mean and standard deviation of the total . This process is common to any of the costs type (structural, non-structural or contents) or occupants. Besides the ground-up losses, it is also possible to calculate insured losses (i.e. economic value that can be covered by the insurance industry according to a certain policy). To do so, a deductible and a limit for each type of cost (structural, non-structural or contents) need to be defined. The methodologies employed to calculate the ground-up losses and insured losses are described below.

4.2. Calculation Steps

To compute the mean ground-up losses:

1. For each ground-motion field, the intensity measure level at the location of the asset is used to derive the mean loss ratio and associated coefficient of variation from the vulnerability function. Since currently the vulnerability functions are being defined in a discrete manner, it is quite probable that the intensity measure level provided by the ground-motion field is not contained in the vulnerability function. In these cases, linear interpolation methods are being employed to derive the mean loss ratio at the intensity measure level of interest.

2. The engine takes the vulnerability function assigned to each asset and checks if the coefficient of variation is zero. If so, the loss ratios are derived based on the mean loss ratio for each intensity measure level. Otherwise, if the uncertainty is defined, it is randomly sampled following the probabilistic distribution of the respective vulnerability function, as described below:

   $$\log LR_n = \mu + \epsilon\sigma \tag{4.1}$$

   Where μ and σ stand for the mean and standard deviation of the logarithm of the loss ratios respectively and ϵ is a term that has a standard normal distribution with a zero mean and a standard deviation of one.

   The method used to sample epsilon depends on whether the correlation between the vulnerability uncertainty of assets of a given taxonomy is to be considered or not:

   - Perfectly correlated: the term ϵ is randomly sampled once for the first asset and this result is used to derive the loss ratio for all the assets of the same taxonomy.
   - Correlated: the term ϵ is randomly sampled for each asset considering the specified correlation coefficient between assets.
   - Uncorrelated: the term ϵ is always randomly sampled for each asset and therefore the correlation between the vulnerability of the assets is ignored.

3. The mean loss ratio for each asset across all possible simulations of the scenario event can be calculated through the formula:

   $$LR = \frac{\sum_{n=1}^{m} LR_n | IML}{m} \tag{4.2}$$

   Where m stands for the number of ground motion fields simulated.

4. The mean loss can then be derived by multiplying the mean loss ratio by the value of the asset contained in the exposure model file.

To compute the standard deviation of the ground-up losses:

1. In order to compute the uncertainty, the engine takes the set of loss ratios for each asset, and computes the associated standard deviation using the classical formula:

$$SD[LR] = \sqrt{\frac{1}{m}\sum_{n=1}^{m}(LR_n - E[LR])^2} \tag{4.3}$$

   Where $E[LR]$ stands for the mean loss ratio computed previously.

2. The standard deviation of the absolute loss can finally be computed by multiplying the standard deviation of the loss ratio by the value of the respective asset.

To compute the insured losses: The calculation of the insured losses is valid for the structural, non-structural and contents costs. When the computation of the insured losses is triggered, the ground-up losses from each asset, at each ground-motion field are modified in the following manner:

1. If the limit has been defined in a relative way, this fraction is first multiplied by the respective total cost, in order to obtain the absolute value. If the ground-up loss is above the absolute limit, the resulting loss is reduced to this threshold.

2. Then, the absolute deductible is taken directly from the exposure model, or calculated by multiplying the associated fraction by the respective total cost. Once the absolute deductible is obtained, the ground-up loss is reduced by this amount. If the deductible is above the ground-up loss, then the insured loss is null.

   This process is clarified in Figure 4.1.

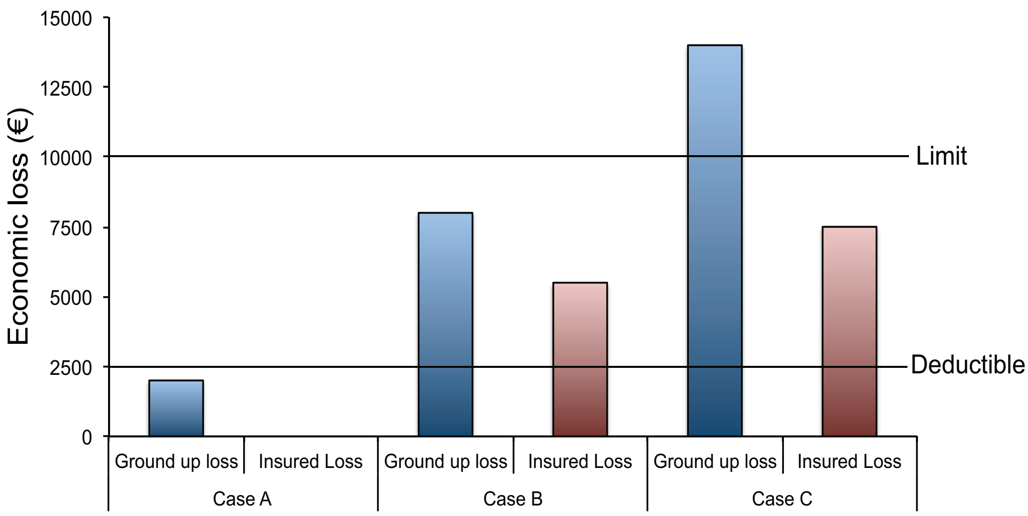

Figure 4.1 – *Representation of the process to estimate the insured losses.*

In Case A, the ground-up loss does not exceed the deductible, which leads to an insured loss equal to zero.In Case B, The ground-up loss is above the deductible, but does not reach the limit. Hence, the resulting insured loss if equal to the ground-up loss subtracted by the deductible. Finally, in Case C the ground up loss is greater than the limit. Thus, this loss is firstly reduced to the value of the limit, and then subtracted by the deductible. In other words, the portion of the ground-up losses that are insured, is the fraction located between the deductible and the limit thresholds.

3. The calculation of the mean and standard deviation of the insured losses follows the same approach described previously for the ground-up losses.

4.3. Calculator Output

The output of the Scenario Risk Calculator currently comprises ground-up and insured loss statistics (mean total loss and standard deviation of total loss) and ground-up and insured loss maps. Loss maps are comprised by a set of loss nodes, which are associated with a pair of coordinates. For each node, one or more loss values might exist, due to the fact that several different assets can be located at the same location. Figure 4.2 presents an example of a loss map containing the expected economic losses for residental buildings located in Nepal, considering a rupture of magnitude 7.0Mw in the central part of the country.

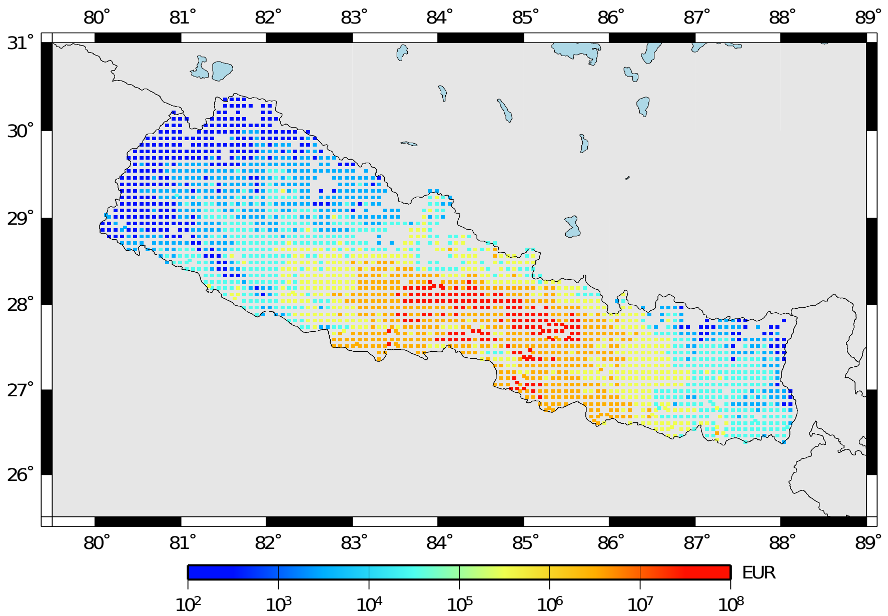

Figure 4.2 – *Loss map with the distribution of mean economic losses for residential buildings in Nepal.*

CHAPTER 5

Scenario Damage Calculator

5.1. Introduction

The scenario damage calculator can be employed to estimate the distribution of damage due to a single earthquake, for a spatially distribute building portfolio. Similarly to what has been described for the scenario risk calculator, a finite earthquake rupture should be used to derive sets of ground-motion fields.

In this calculator, each ground-motion field is combined with a fragility model (discrete or continuous), in order to compute the fractions of buildings in each damage state. These fractions are calculated based on the difference in probabilities of exceedance between consecutive limit state curves at a given intensity measure level. This process is repeated for each ground-motion field, leading to a list of fractions for each asset. These results can then be multiplied by the respective number or area of buildings in order to obtain the absolute building damage distribution.

5.2. Calculation Steps

1. For each ground-motion field, the intensity measure level at the location of the asset is used to derive the fraction of buildings in each damage state. In order to do so, the distance between each pair of consecutive limit states is calculated. This process is illustrated in Figure 5.1, using a continuous fragility function.

   When a continuous fragility function is used for the calculations, the fractions of building in each damage state are calculated using the analytical expression of the lognormal cumulative distribution functions. On the other hand, if a discrete fragility function was chosen, these fractions are computed using linear interpolation between the pair of points either side of the intensity measure level.

2. Step 1 is repeated for each ground-motion field, leading to a list of fractions (one per damage state), for each asset. From this list of values, the mean ($E[FR]$) and standard deviation ($SD[FR]$) for each fraction can be estimated using the following

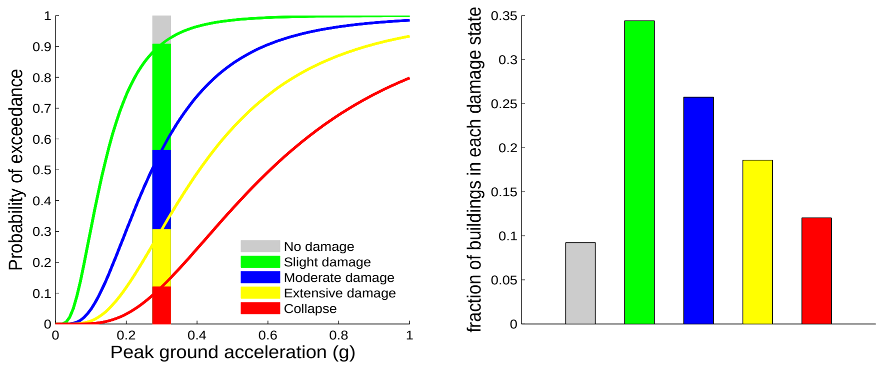

Figure 5.1 – *Representation of the fractions of building in each damage states, for a given intensity measure level (0.3 g).*

formulae:

$$E[FR] = \frac{\sum_{n=1}^{m} FR_n|IML}{m} \tag{5.1}$$

$$SD[FR] = \sqrt{\frac{1}{m}\sum_{n=1}^{m}(FR_n - E[FR])^2} \tag{5.2}$$

Where m stands for the number of ground-motion fields simulated.

3. These fractions of buildings in each damage state can be multiplied by the quantity of the respective asset, leading to the mean and standard deviation of the number or area of buildings in each damage state (see Figure 5.2).

4. This calculator is also capable of estimating the aggregated number or area of buildings from the same taxonomy in each damage state (see Figure 5.3). In order to do so, for each ground-motion field, the absolute quantity of buildings in each damage state is calculated, and aggregated according to their taxonomy. After processing all the ground-motion fields, the associated statistics for each building taxonomy are calculated according to the formulae described in Step 2.

5. The total damage distribution is also calculated, by summing the quantity of buildings in each damage state, across all the assets existing in the building portfolio. This calculation will lead to a single damage distribution, represented by a mean and standard deviation for each damage state (see Figure 5.4).

5.3. Calculator Output

The output of the Scenario Damage Calculator currently comprises damage distributions at three levels: per asset, per building taxonomy and total. In addition, with this calculator, is it also possible to extract collapse maps, which contain the spatial distribution of the number or area of collapsed buildings throughout the region of interest (see Figure 5.5). In the figures shown herein, examples of the outputs are depicted for a scenario event of magnitude 7.0Mw in the central region of Nepal.

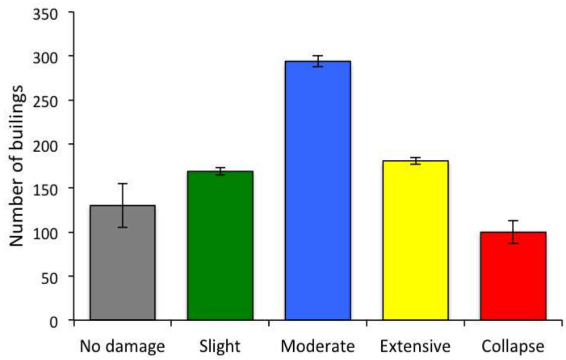

Figure 5.2 – *Damage distribution for a single asset.*

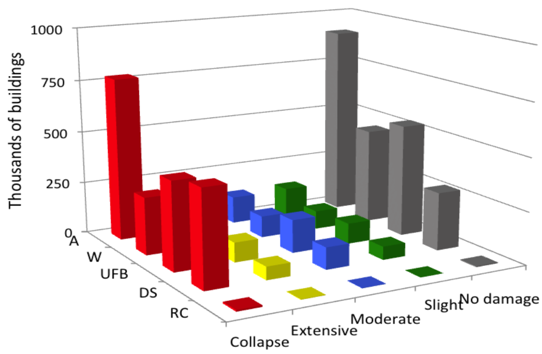

Figure 5.3 – *Damage distribution according to the building taxonomy.*

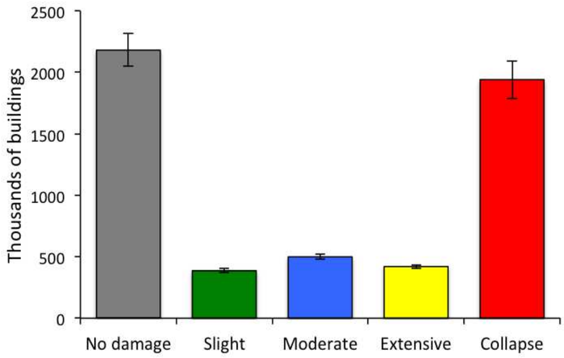

Figure 5.4 – *Damage distribution of the whole building portfolio.*

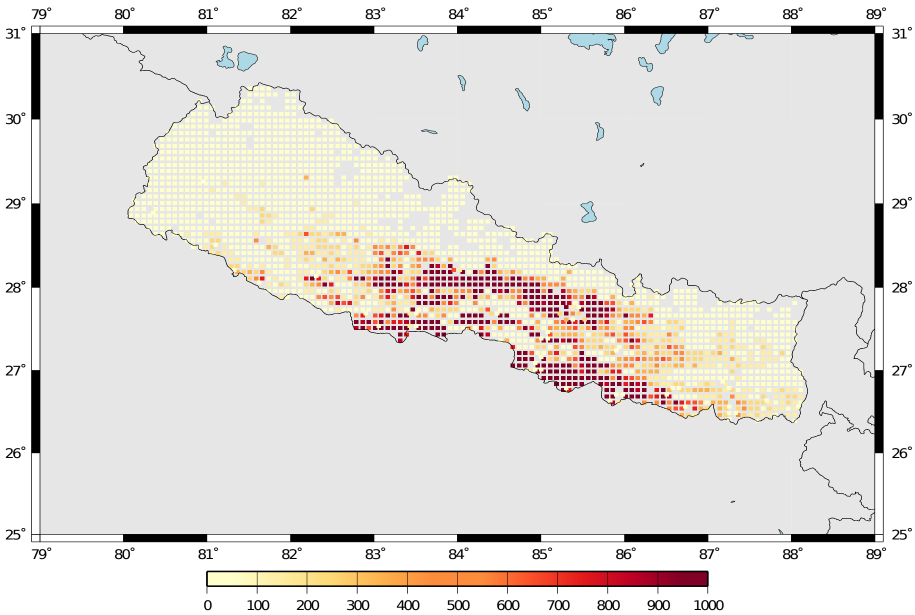

Figure 5.5 – *Collapse map considering the whole building portfolio.*

CHAPTER 6

Probabilistic Event-Based Risk Calculator

6.1. Introduction

The probabilistic event-based risk calculator uses stochastic event sets and associated ground–motion fields to compute loss exceedance curves for each asset contained in an exposure model. This calculator thus requires ground-motion fields from a number of stochastic events as an input, which the engine can calculate using the oq-hazardlib.

For each ground-motion fields, the intensity measure level at a given site is combined with a vulnerability function, from which a loss ratio is randomly sampled, for each asset contained in the exposure model. The loss ratios that are sampled for assets of a given taxonomy classification at different locations are considered to be either independent or correlated. The losses for a given asset are calculated using all of the ground-motion fields, leading to list of events and associated loss ratios. This list is then sorted from the highest loss ratio to the lowest. The rate of exceedance of each loss ratio is calculated by dividing the number of exceedances of that loss ratio by the number of stochastic event sets multiplied by the length of each event set. By assuming a Poissionian distribution of the occurrence model, the probability of exceedance of each loss ratio is calculated. If a total loss curve for a portfolio of assets is required, a secondary module is used in order to sum the losses from all the assets in the exposure file, per event, before calculating the exceedance distribution of loss. This distribution of the total losses per event can also be extracted, and it is termed here as an event loss table.

Similarly to what has been described for the Scenario Risk Calculator (see section 4), this module can compute insured losses following the same approach (i.e. modifying the based on the deductible and limit for each cost type).

This calculator is also capable of performing loss disaggregation in terms of magnitude/distance or latitude/longitude. In order to do so, the losses at each location are disaggregated based on the aforementioned parameters, and a loss percentage for each possible combination is calculated.

6.2. Calculation Steps

To compute the loss exceedance curves:

1. The oq-engine starts by using the set of ground-motion fields to extract the intensity measure levels for the location of each asset.

2. Then the oq-engine takes the vulnerability function assigned to each asset and checks if the coefficient of variation is zero. If so, the loss ratios are derived based on the mean loss ratio for each intensity measure level. Otherwise, if the uncertainty is defined, it is randomly sampled following the probabilistic distribution, mean loss ratio and associated coefficient of variation of the respective function, as described below:

$$\log LR_n = \mu + \epsilon\sigma \tag{6.1}$$

   Where μ and σ stand for the mean and standard deviation of the logarithm of the loss ratios respectively and ϵ is a term that has a standard normal distribution with a zero mean and a standard deviation of one.

   The method used to sample epsilon can follow tree approaches depending on whether the correlation between the vulnerability of assets of a given taxonomy is to be considered or not:

   - Perfectly correlated: the term ϵ is randomly sampled once for the first asset and this result is used to derive the loss ratio for all the assets of the same taxonomy.
   - Correlated: the term ϵ is randomly sampled for each asset considering the specified correlation coefficient between assets.
   - Uncorrelated: the term ϵ is always randomly sampled for each asset and therefore the correlation between the vulnerability of the assets is ignored.

3. Each loss ratio is multiplied by the associated asset value, leading to the absolute loss values. If these losses are related with the structural, non-structural or contents cost, the insured losses module can be used to modify the ground-up losses according to the associated deductible and limit thresholds, as described in section 4.

4. In this method the losses to each asset for each event are estimated and then sorted from highest to lowest. The rate of exceedance of each loss is calculated by dividing the number of exceedances of that loss by the number of stochastic event sets multiplied by the length of each event set. Hence, the top loss will have zero exceedances, the next loss ratio will have one exceedance, and so on.

   The following formula is employed to compute the rate of exceedance:

$$\lambda(L_n) = \frac{NE_L}{TSES} \tag{6.2}$$

Where λ stands for the rate of exceedance of the respective loss ratio, NE_L stands for the number of exceedances of the given loss, and $TSES$ stands for the time span of all stochastic event sets, i.e. the number of stochastic event sets multiplied by the time span of each.

5. Assuming a Poissonion distribution of the occurrence model, the probability of exceedance of the set of losses in a given time span can be derived using the following formula:

$$PE(L_n) = 1 - \exp -\lambda_n \times t \tag{6.3}$$

Where t stands for the time span used to produce the stochastic event set.

To perform the loss disaggregation:

1. For the disaggregation of the losses it is necessary to provide the coordinates of the locations where this procedure should be employed. Then, for the selected locations, the oq-engine calculates the sum of the losses (considering all the assets existing at each of the selected sites) for each seismic event. In addition, the rupture distance (Joyner-Boore) and coordinates of the point within the vertical projection of the rupture plane closest to each site are estimated. An example of this type of information is presented in Figure 6.1, for 20 stochastically produced seismic events.

2. The oq-engine calculates the range (maximum and minimum values) of the list of magnitudes, distances, latitudes and longitudes across all the events, and using the increment defined for each parameter, a set of linearly spaced bins is calculated. Then, the losses from every seismic event are aggregated depending on which combination of magnitude/distance or latitude/longitude they fall. The previously presented losses have been disaggregated according to these two combinations as presented in Figure 6.2:

3. The resulting losses for each pair of parameters (magnitude/distance and latitude/longitude) are divided by the total loss across all the events. This percentage of the overall loss for each combination is depicted in Figure 6.7 in the following section.

6.3. Calculator Output

The output of this calculator comprises loss exceedance curves and loss maps. Loss exceedance curves are represented by a list of losses and respective probabilities of exceedance. Furthermore, each curve is associated with a pair of coordinates, an end branch label (that allows the curve to be connected to the set of specifications used in the calculations) and an asset ID (that permits tracking of the asset that each loss curve was computed for). Loss maps for a given probability of exceedance in a given time span can be produced, as well as maps of mean loss within a given time span. Figure 6.4 and 6.3 present a loss map for

Rup ID	Mag	R_{JB}	Lon	Lat	Loss
1	6.3	71.3	80.6	29.4	157.4
2	7.3	72.6	80.8	28.6	178.2
3	6.3	60.1	80.8	29.5	162.2
4	5.1	27.7	81.0	29.2	161.3
5	6.5	27.5	81.1	29.0	221.4
6	5.7	70.8	81.2	28.5	161.6
7	6.1	21.5	81.2	28.9	189.4
8	5.3	16.2	81.2	29.2	173.3
9	6.1	54.9	81.3	29.6	166.1
10	5.7	87.7	81.4	29.9	158.7
11	5.7	43.8	81.5	29.4	234.4
12	5.5	53.1	81.6	29.5	185.6
13	5.3	32.0	81.6	29.2	159.3
14	5.7	49.4	81.7	28.8	159.9
15	5.1	52.6	81.8	29.4	160.7
16	5.9	52.8	81.8	28.9	172.1
17	6.1	50.7	81.8	29.2	171.6
18	5.7	83.8	82.2	29.1	157.2
19	6.7	92.7	82.2	28.8	160.7
20	6.5	102.0	82.3	29.5	200.7

Figure 6.1 – *Economic losses from a single asset for a set of seismic events.*

a probability of exceedance of 1% and 10% in 50 years for residential buildings located in Nepal, respectively.

For this calculator, total loss exceedance curves can be produced which combine the losses to all assets per event. It is noted that loss exceedance curves which present the probability of exceedance of the aggregate annual losses, or maximum annual losses, are not yet supported in the oq-risklib. In Figure 6.5, a total loss exceedance curve for the residential building portfolio in Nepal is presented.

For what concerns the event loss tables, the oq-engine can extract the total loss across all the assets for each seismic event. The results is a table with the rupture id, magnitude and total loss, as illustrated in Figure 6.6.

The output of the loss disaggregation is composed by the loss fraction associated to each combination of parameters (magnitude/distance or latitude/longitude), as presented in Figure 6.7 .

		Rupture distance				
		0	**25**	**50**	**75**	**100**
Magnitude	**5.0**	173.3	0.0	189.4	0.0	0.0
	5.5	320.6	394.3	0.0	221.4	0.0
	6.0	160.7	519.3	657.3	0.0	178.2
	6.5	0.0	315.9	0.0	160.7	0.0
	7.0	0.0	0.0	0.0	200.7	0.0

		Longitude				
		80.0	**80.5**	**81.0**	**81.5**	**82.0**
Latitude	**28.0**	0.0	0.0	161.6	0.0	0.0
	28.5	0.0	178.2	410.8	332.0	160.7
	29.0	0.0	319.6	334.6	726.0	357.9
	29.5	0.0	0.0	324.8	185.6	0.0

Figure 6.2 – *Disaggregation of the economic losses according to a set of magnitude/distance and latitude/longitude combinations.*

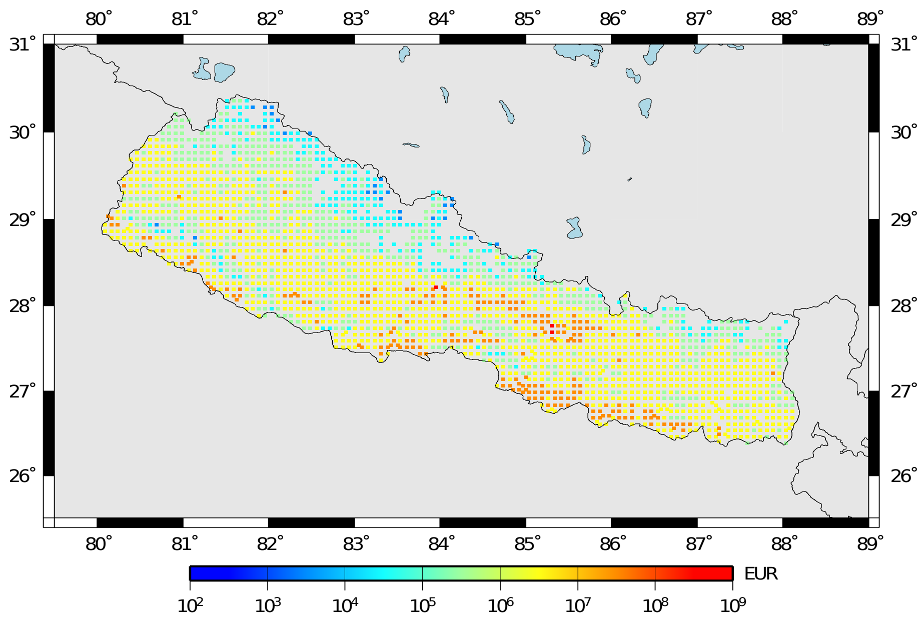

Figure 6.3 – *Loss map for a probability of exceedance of 10% in 50 years.*

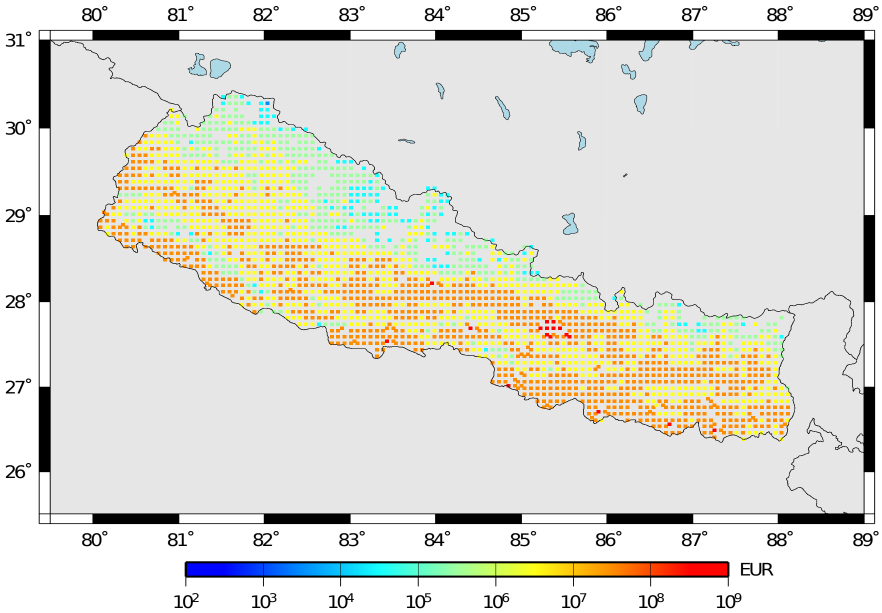

Figure 6.4 – *Loss map for a probability of exceedance of 1% in 50 years.*

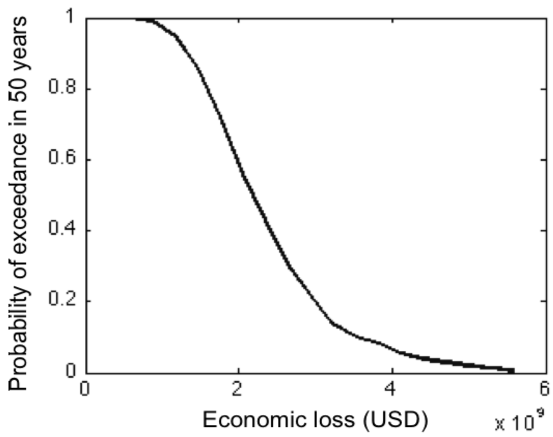

Figure 6.5 – *Total loss exceedance curve for RC buildings.*

Rupture	Magnitude	Aggregate Loss
1	8.25	79197
2	8.25	74478
3	7.75	46458
4	7.75	45153
5	7.75	42569
6	8.25	40649
7	7.75	38868
8	7.75	37707
9	7.50	37608
10	7.75	37141

Figure 6.6 – *Example of an event loss table.*

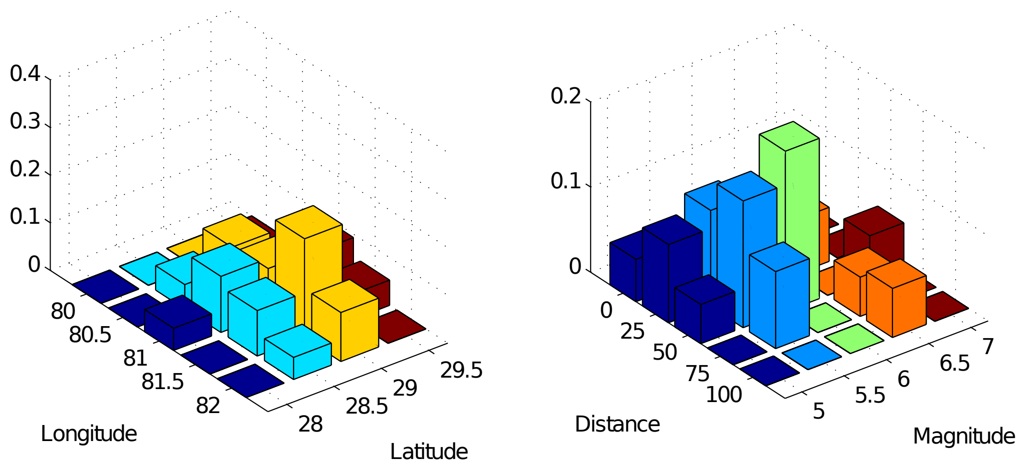

Figure 6.7 – *Example of a loss disaggregation according to a set of magnitude/distance and latitude/longitude combinations.*

CHAPTER 7

Classical PSHA-Based Risk Calculator

7.1. Introduction

The classical PSHA-based risk calculator can be used to calculate loss exceedance curves for single assets, calculated site by site, using hazard curves. This calculator thus requires hazard curves as an input, which the engine can calculate using the oq-hazardlib. Currently, this calculator is only capable of computing ground-up losses, thought insured losses will be covered in future releases.

7.2. Calculation Steps

1. By default, the oq-hazardlib computes hazard curves for a set of intensity measure levels that are pre-defined in the configuration file. If the user wishes to use oq-hazardlib to compute the hazard for the risk calculations, then a feature can be used which reads the vulnerability model and uses the intensity measure levels (IMLs) defined therein when producing the hazard curve. If instead externally produced hazard curves are used, the user needs to ensure that the IMLs in the hazard curves cover the full range required by the vulnerability functions.

2. To use this calculator, the hazard curves need first to be converted into probability mass functions (e.g. probability of occurrence of a discrete set of intensity measure levels). To do so, the engine starts by reading the intensity measure levels from the discrete vulnerability functions, and computes the central value between consecutive levels. Two consecutive values define the boundaries of the interval for each intensity measure level and by relating these limits with the hazard curve, the engine computes the corresponding probabilities of exceedance. Figure 7.1 contains a discrete vulnerability function (bottom figure) and a hazard curve (top figure) in which the definition of the interval for a given intensity measure level and associated estimation of the probabilities of exceedance of each limit are illustrated.

3. The probability of occurrence of the intensity measure levels that fall within each interval can be derived by subtracting the probabilities of exceedance of the lower and

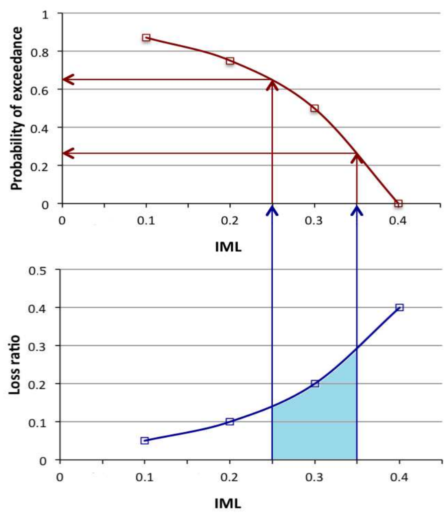

Figure 7.1 – *Workflow to estimate the probabilities of exceedance of the boundaries of each intensity measure level.*

upper limits, as described by the following formula:

$$PO = PE[lowerbound] - PE[upperbound] \tag{7.1}$$

4. The discrete vulnerability functions for each asset are converted into loss ratio exceedance matrices (e.g. matrices which describe the probability of exceedance of each loss ratio for a discrete set of intensity measure levels). These matrices have a number of columns equal to the number of intensity measure levels defined on the vulnerability function and a number of rows that can go from the number of loss ratios defined by the discrete function, up to any multiple of this number. In order to properly incorporate the probabilistic distribution of loss ratios per intensity measure level, the probabilities of exceedance should be computed not just for the loss ratios defined on the vulnerability function, but also for many intermediate values between consecutive loss ratios. Following a number of sensitivity analyses, it appears that 5 intermediate values between consecutive loss ratios is a reasonable value, however, this is a parameter that can be adjusted by the user. Figure 7.2 contains an example of a discrete vulnerability function and the respective loss ratio exceedance matrix (in light grey).

   Note that for this example only one intermediate value was considered between consecutive loss ratios and in order to consider the whole distribution of the loss ratios, the matrix was computed considering a minimum and maximum loss ratio of 0 and 1 respectively.

5. Finally, each column of the aforementioned matrix is multiplied by the probability of occurrence of the respective intensity measure level (extracted from the hazard curves) to produce a conditional loss ratio exceedance matrix. Then, for each loss ratio the

IML	LR	COV
0.1	0.05	0.5
0.2	0.08	0.3
0.4	0.20	0.2
0.6	0.40	0.1

	0.1	0.2	0.4	0.6
0.00	1.00	1.00	1.00	1.00
0.03	0.89	1.00	1.00	1.00
0.05	0.41	0.93	1.00	1.00
0.07	0.21	0.71	1.00	1.00
0.08	0.11	0.44	1.00	1.00
0.14	0.01	0.02	0.96	1.00
0.20	0.00	0.00	0.46	1.00
0.30	0.00	0.00	0.02	1.00
0.40	0.00	0.00	0.00	0.48
0.70	0.00	0.00	0.00	0.00
1.00	0.00	0.00	0.00	0.00

Figure 7.2 – *Example of a discrete vulnerability function and respective loss ratio exceedance matrix.*

probabilities of exceedance are summed, leading to a loss ratio exceedance curve, whose set of loss ratios can be multiplied by the value of the asset given by the exposure model to obtain an absolute loss exceedance curve.

7.3. Calculator Output

The output of this calculator comprises loss exceedance curves and loss maps. Loss exceedance curves are represented by a list of losses and respective probabilities of exceedance. Furthermore, each curve is associated with a pair of coordinates, an end branch label (that allows the curve to be connected to the set of specifications used in the calculations) and an asset ID (that permits tracking of the asset that each loss curve was computed for). Loss maps for a given probability of exceedance in a given time span can be produced, as well as maps of mean loss within a given time span, similarly to what has been described in the Probabilistic Event-based risk calculator.

CHAPTER 8

Retrofitting Benefit/Cost Ratio Calculator

8.1. Introduction

The retrofitting benefit/cost ratio calculator allows users to understand if from an economical point of view, a collection of buildings should be retrofitted. This calculator uses loss exceedance curves that can be calculated using either the probabilistic event-based risk or the classical PSHA-based risk calculators (see Figure **??**). These curves need to be calculated considering two vulnerability models: one with the original asset vulnerability, and a second one using the retrofitted vulnerability configuration. The average annual ground-up losses considering both vulnerability configurations are calculated, and employed to estimate the economic saving during the life expectancy (or design life) of the assets. This benefit is divided by the retrofitting cost, thus obtaining the benefit/cost ratio. This ratio is modified considering the inflation rate to take into account the fact that the losses will be observed in the future, whereas the cost is outlayed today. A ratio above one indicates that a retrofitting intervention would be advantageous from an economic point of view.

8.2. Calculation Steps

1. This calculator starts by calculating loss exceedance curves for a collection of assets, using either the classical PSHA-based risk calculator or the probabilistic event-based risk calculators. Two configurations of the vulnerability need to be considered: original and retrofitted. Thus, for each asset, two loss exccedance curves are determined, as depicted in Figure 8.1.

2. Then, an average annual loss (AAL) for each vulnerability configuration is calculated by numerically integrating the respective loss exceedance curve.

3. For the calculation of the economic benefit B, the following formula can be employed:

$$B = (AAL_{retrofitted} - AAL_{original}) \times \frac{1 - e^{rt}}{r} \tag{8.1}$$

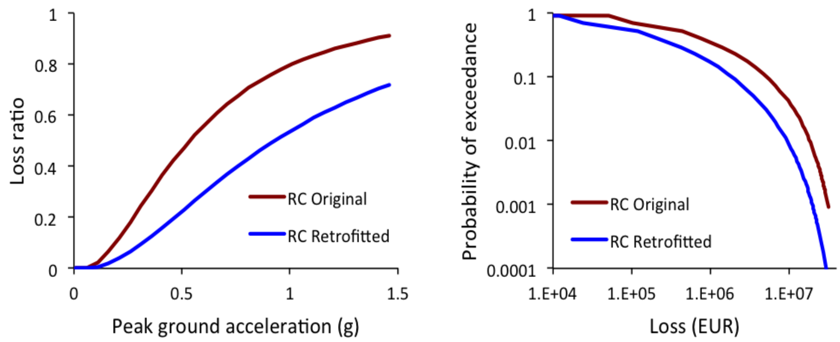

Figure 8.1 – *Vulnerability functions for the original and retrofitted configuration of a class of RC buildings (left) and respective loss exceedance curves (right).*

where r represents the inflation rate, which serves the purposes of considering the variation of the economic value of the assets during their life expectancy, or design life (t).

4. Finally, the previously defined benefit (B) is divided by the retrofitting cost (C), leading to the benefit/cost ratio (BCR). This process is repeated for all the assets comprised in the exposure model.

8.3. Calculator Output

The results of this calculator are stored in a benefit/cost ratio map, which includes the $AAL_{retrofitted}$, $AAL_{original}$ and the resulting BCR at each location. In Figure 8.2, a map of benefit/cost ratios for RC residential buildings in Nepal is presented.

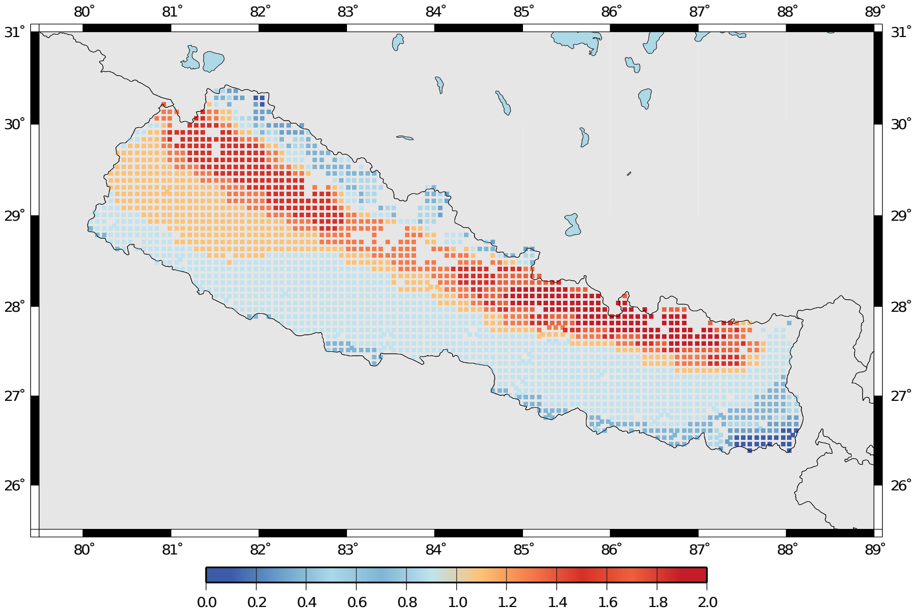

Figure 8.2 – *Retrofitting benefit/cost ratio map for residential buildings in Nepal.*