Development of an open-source platform for calculating losses from earthquakes

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Abstract

Risk analysis has a critical role in the reduction of casualties and damages due to earthquakes. Recognition of this relation has led to a rapid rise in demand for accurate, reliable and flexible risk assessment numerical tools and software. As a response to this need, the Global Earthquake Model (GEM) started the development of an open source platform called OpenQuake, for calculating seismic hazard and risk at different scales. Along with this framework, also several other tools to support users creating their own models and visualizing their results are currently being developed, and will be made available as a Modelers Tool Kit (MTK). In this paper, a description of the architecture of OpenQuake is provided, highlighting the current data model, workflow of the calculators and the main challenges raised when running this type of calculations in a global scale. In addition, a case study is presented using the Marmara Region (Turkey) for the calculations, in which the losses for a single event are estimated, as well as probabilistic risk for a 50 years time span.

1. INTRODUCTION

The OpenQuake project was initiated as part of the Global Earthquake Model (GEM [1]), a global collaborative effort that brings together state-of-the-art science and national/regional/international organizations and individuals with the aim of establishing uniform and open standards for calculating and communicating earthquake risk worldwide. In January 2009, GEM launched a pilot project, GEM1, in which a number of existing hazard and risk software applications were evaluated allowing the first scientific requirements of OpenQuake to be defined (Danciu *et al.* 2010; Crowley *et al.* 2010). Currently, OpenQuake is in its second year of development and it is comprised by three main calculators: a deterministic event-based risk calculator capable of computing losses and loss statistics due to a single event (deterministic earthquake) for a collection of assets (e.g.: buildings, population); a probabilistic event-based risk calculator that estimates the probability of exceedance certain levels of loss in a given time span based on stochastic event sets, and finally, a classical PSHA-based risk calculator that allows the computation of probability of losses and loss statistics for single assets, based on the probabilistic hazard. Such functionalities are fundamental in order to support activities as emergency management planning, raising societal awareness of risk, identification of areas with a high seismic risk or estimation of the expected economic or human losses for the upcoming years.

The case study that is presented herein is applied to the Marmara Region (Turkey). In this exercise, distribution of losses were computed for an event of magnitude 7.1 M_w with a location under the Sea of Marmara, as well as a probabilistic assessment for a 50 years time span, considering the reinforced concrete building stock of the Metropolitan Area of Istanbul.

2. OPENQUAKE: SEISMIC HAZARD AND RISK SOFTWARE

2.1 Foreword

OpenQuake is an open-source software written in Python and Java for calculating seismic hazard and risk at any scale. Its code is under a Lesser General Public License (LGPL) and therefore it is FOSS. It makes use of a number of other, independent, open-source projects such as OpenSHA (Field *et al.*, 2003), used as a foundation for the seismic hazard component of the engine, as well as Celery [2] and RabbitMQ [3]. Some of the main features of OpenQuake are as follows:

- It combines deterministic and probabilistic hazard and risk calculations within a single software;
- The development is "open-source", and takes place on a public repository that encourages collaboration on a single code base (through a distributed revision control system);
- All input and output follow an evolving data interchange format called NRML (Natural hazards Risk Markup Language), which is further described in this paper;
- It is engineered in such a way that it can be used on a single processor laptop as well as on a cloud of computers.

The current version of OpenQuake (v0.4) is a 'developer' release to be executed through a command line interface, though a graphics user interface is currently being developed. The OpenQuake input consists of an ASCII configuration file and a number of NRML files that contain the hazard and risk input models.

The main results currently produced by OpenQuake are the following:

- *Hazard curves*: curves providing probabilities of exceedance in a given time span for given values of a ground motion parameter.
- *Hazard maps*: maps describing the geographic distribution of values of a ground motion parameter with a fixed probability of exceedance in a given time span.
- *Stochastic event sets*: sets of earthquake ruptures - occurring in a given time span - obtained through random sampling of an earthquake rupture forecast.
- *Ground-motion fields*: each ground-motion field describes the geographic distribution of a scalar ground-motion parameter obtained considering an earthquake rupture and a GMPE; the spatial correlation of the intra-event residuals can be considered in the generation of the field.
- *Loss exceedance curves*: curves describing losses versus probability of exceedance in a given time span; losses can refer to single assets or can be aggregated where there are multiple assets.
- *Loss maps*: maps describing the geographical distribution of values of loss with a fixed probability of exceedance in a given time span.
- *Mean loss maps: maps* describing the geographic distribution of mean loss within a given time span.
- *Loss statistics* per event or across all events (mean loss, standard deviation of loss, etc.).

2.2 Development of OpenQuake

OpenQuake is being developed as an open-source project. Open source development has a number of requirements which go beyond the simple release of source code, and have the advantage of improving community engagement, providing free labor, and ultimately leading to better software. The following requirements have been followed:

- Release of source code with an open source license;
- Use of a public code repository where code changes can be viewed by "outsiders", that can track the code development, provide bug patches, etc.;
- An open process of discussion (e.g. through open mailing lists and/or an IRC channel);

- A policy for open, consensus-based, decision-making.

OpenQuake is being developed following all of these practices. Furthermore, OpenQuake is being developed with the Agile development philosophy, where requirements and solutions continually evolve through collaboration between the researchers (the "customers") and the developers.

OpenQuake is currently hosted on GitHub [4], a web-based hosting service for software development projects that use the Git revision control system, which is distributed rather than centralized. The benefit of having a distributed revision control system is that any interested developer can work on a private or shared branch (offline or online), and can submit a "merge proposal" in order to have his/her code (or "patch") integrated into the Master code (following a review by the core developers). Such a framework means that the development can scale to thousands of developers and it thus further supports community engagement.

An important characteristic of the code that is being developed in OpenQuake is related to the use of Test-Driven Development (TDD) [5] and Continuous Integration [6]. TDD requires all developers to first write the code that will test their patches. All code is reviewed by at least one of the core developers of the OpenQuake team before being merged to the Master, which then leads to a full run of end-to-end tests (known as "smoketests"); this is the process of Continuous Integration. Example smoketests that are being implemented are the PEER tests, that have been set up by Thomas *et al.* (2010) to test hazard calculations. All such testing ensures that the code is fully checked for correctness, completeness and quality.

OpenQuake relies on a data model to represent the objects used in hazard and risk calculations, that is being developed in parallel with a transparent and standard markup language utilized to transfer different types of information within and out of the software. The NRML is language – called the Natural hazards Risk Markup Language (NRML) - is XML-based and it leverages from previous GEM experiences (Pagani *et al.*, 2010a) and existing standards, such as the Geography Markup Language (GML) and QuakeML [7], a markup language for seismic catalogues. NRML is being hosted in the OpenQuake repository at GitHub [4]. A and a document called the OpenQuake User Manual with all the information regarding how to create and edit these files has been compiled and is available at the OpenQuake website [8]. Although the present scope of NRML is seismic risk, it is planned to extend this markup language to cover other natural hazards such as hurricanes, floods or tsunamis.

2.3 OpenQuake Risk Calculation Workflows

OpenQuake currently comprises three risk calculation workflows: one computing losses due to a single event, and the other two computing seismic risk due to most or all of the possible events that might occur in a given region within a certain time span. The calculation workflows are comprised of a number of separate calculators. In order to run any of the calculation workflows, it is necessary to define the geographic coordinates of the region of interest, the type of calculations, the path to the input files, the type of results that are to be produced and several parameters necessary for the hazard calculations. Currently, a configuration file to be provided to OpenQuake incorporates this information.

With regards to the seismic hazard input, the first risk calculation workflow requires the definition of a finite earthquake rupture whilst for the other two calculation workflows, a PSHA input model is required. This latter input is comprised of two files: one describing the seismic source system (i.e. the combination of one or several initial seismic source models and a logic tree structure) and the other specifying the GMPE logic tree.

A comprehensive description of the methodologies included in OpenQuake can be found in a document - called the OpenQuake Book - available at the OpenQuake website [8]. In the following sections, a summary description of the properties characterizing each risk calculation methodology is provided.

Deterministic Event-Based Risk Calculation Workflow

This calculation sequence is capable of computing losses and loss statistics due to a single, deterministic earthquake, for a collection of assets. Such analyses are of importance, for example, for emergency management planning and for raising societal awareness of risk.

The hazard input consists of a finite rupture and a single GMPE. By repeating the same rupture, and sampling the inter- and intra-variability from the GMPE each time, many ground motion fields can be computed to account for the aleatory variability in the ground motion. During the generation of each ground motion field, the spatial correlation of the intra-event variability can be considered, so that assets located close to each other are likely to have similar ground motion levels (see e.g. Crowley *et al.*, 2008 for a summary of ground motion variability treatment in loss models). The set of ground motion fields is then provided to the Deterministic Event-Based Risk calculator, together with the vulnerability and exposure models, to compute the losses for each asset in the exposure model, per ground motion field. The mean or median value of losses across all ground motions fields can be found for a given asset, and the spatial variation of this value for a given asset typology can be plotted in a loss map. The losses to all assets across the region of interest can also be aggregated per ground motion field, to obtain a list of aggregated losses, which can then be used to compute the mean and standard deviation of the aggregated losses. The workflow in Figure 1 describes this procedure.

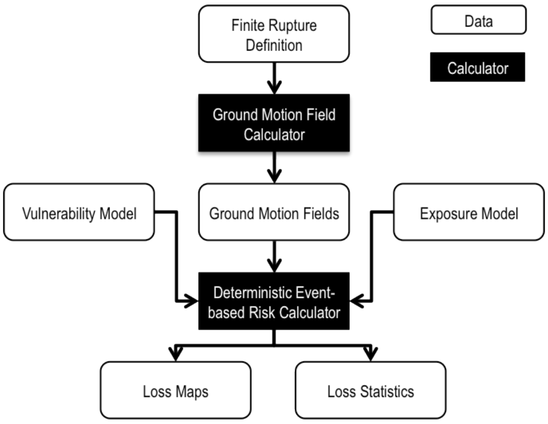

Figure 1 - Workflow of the Deterministic Event-Based Risk calculator.

Probabilistic Event-Based Risk Calculation Workflow

This calculation workflow computes the probability of losses and loss statistics for a collection of assets, based on the probabilistic hazard. The losses are calculated with an event-based approach, such that the simultaneous losses of a set of assets can be calculated.

This workflow requires a number of calculators in order to compute ground motion fields. Firstly, a Logic Tree Processor calculator uses information contained within the seismic source system together with a Monte Carlo approach to sample the logic tree structure and produce a seismic source model (SSM). Each seismic source model computed is used by the Earthquake Rupture Forecast (ERF) calculator to produce a list of all possible ruptures occurring on all the sources in the SSM; each rupture is associated with a probability of occurrence in the time span specified by the user in the configuration file. Then, the Stochastic Event Set calculator uses the ERF to create one or several groups of ruptures. Each group represents a possible realization of the seismicity generated in the specified time span by the entire set of seismic sources included in the seismic source model. Afterwards, the Logic Tree Processor is again used to process the GMPEs system and provide the ground motion relationship that shall be used by the Ground Motion Field calculator, together with each earthquake rupture, to compute the ground motion values at a set of sites. The spatial correlation of the intra-event residuals of the ground motion model can be considered if specified on the configuration file. As mentioned previously, in that case, sites that are closer are more likely to have similar levels of ground motion. This set of ground motion fields is combined with the exposure and vulnerability model in the Probabilistic Event-Based Risk calculator, to compute the losses for each asset per ground motion field. The list of losses per asset can be used to build a cumulative histogram which gives the number of losses in selected bins of loss over the time span, from which the loss exceedance curve is computed (loss versus probability of exceedance in a given time span). This approach can be used to compute a loss curve for each asset within the exposure model, or by aggregating all the losses throughout the region per ground motion field, an aggregated loss curve representative of the whole set of assets within the exposure file is obtained. The workflow in Figure 2 describes this procedure.

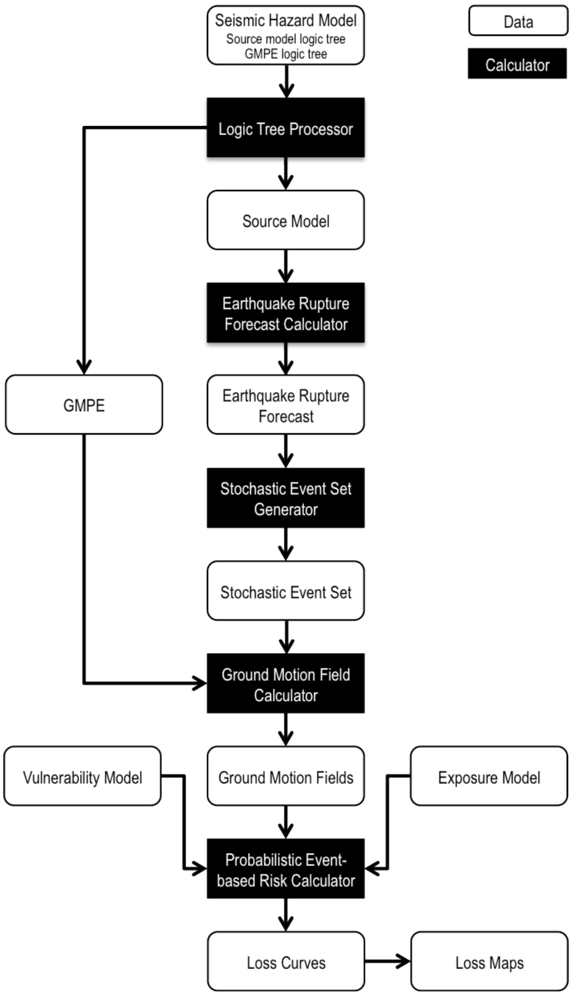

Figure 2 - Workflow of the Probabilistic Event-Based Risk calculator.

Classical PSHA-Based Risk Calculation Workflow

This calculation workflow leads to the computation of the probability of losses and loss statistics for single assets, based on the probabilistic hazard. The output of this calculator is useful for comparative risk assessment between assets at different locations.

This workflow has an initial architecture similar to the previous one, in which a Logic Tree Processor uses the structure defined in the Seismic Source System to provide the required parameters to the Earthquake Rupture Forecast (ERF) calculator, which produces a list of all the possible ruptures occurring on all the sources included in the seismic hazard model. Then, using the GMPEs system, the Logic Tree processor states which GMPEs the Classical Hazard Curves calculator will use. This calculator uses the classical PSHA approach (Cornell, 1968, McGuire, 2004) following the methodology presented by Field *et al*. (2003) to compute a hazard curve at each site. This set of hazard curves is then provided, together with the vulnerability and exposure model to the Classical PSHA-based Risk calculator. Here, the first step is to convert each discrete vulnerability function into a loss ratio exceedance matrix (e.g. a matrix which describe the probability of exceedance of each loss ratio for a discrete set of intensity measure levels). Once these matrices are built, the values of each column are multiplied by the probability of occurrence of the associated intensity measure level. This probability is extracted from the previously computed hazard curves. Finally, the list of probabilities of exceedance of the loss ratio curve is obtained by summing all the values per loss ratio. This loss ratio curve is then converted into a loss curve by multiplying each loss ratio by the associated asset value. The workflow in Figure 3 describes the architecture of this calculator.

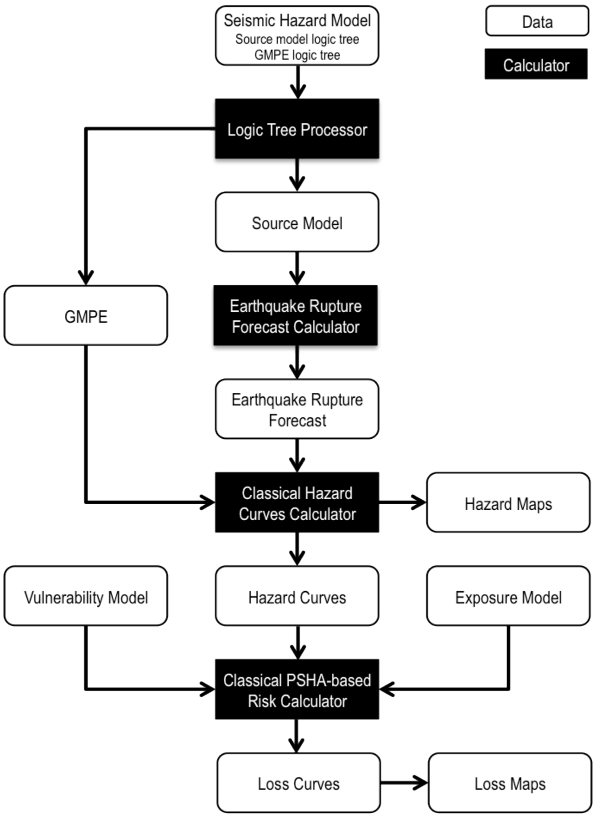

Figure 3 - Workflow of the Classical PSHA-Based Risk calculator.

The loss exceedance curves produced using the Probabilistic Event-Based and the Classical PSHA-Based calculators can also be used to create loss maps representing the distribution of the expected loss per location for a certain probability of exceedance within a given time span. Furthermore, mean losses within the given time span (e.g. average annual loss) can also be extracted by integrating the loss exceedance curves.

3. CASE STUDY APPLICATIONS

3.1 Introduction

Turkey is located in one of the most seismically active regions in the world with a large amount of population exposed to a significant risk of major earthquakes (Bommer *et al.*, 2002). Proof of this is given by the numbers from the last two catastrophic earthquakes that occurred in the region: Kocaeli (August, 1999) and Duzce (November, 1999), in which over 18 thousand people lost their life and more than 50 thousand were injured. Furthermore, it is believed that a similar earthquake will hit the southern region of Istanbul with a probability of 62% in the next 30 years (Bakıra and Boduroglu, 2002). Within this section, the OpenQuake capabilities are demonstrated for case study applications in Turkey, describing the input data and presenting some exemplificative hazard and risk results.

3.2 PSHA model

The seismic hazard input data utilized to exercise the OpenQuake calculators comes from a preliminary seismic hazard model developed for Turkey (Demicioglu *et al.*, 2008). The PSHA model consists of a seismic source model based on two source typologies: area and faults. Faults are utilized to model large magnitude events ($M_w \geq 6.7$), while area sources describe distributed seismicity for $M_w \geq 5.0$. Faults are assumed to be vertical (dip angle equal to 90 degrees) with a strike-slip mechanism (rake angle equal to 0 degrees according to the Aki and Richards convention). Fault surfaces extend from 0 to 15 km depth. Area sources are associated to an average hypocentral depth of 3 km. Both faults and area sources occurrence rates follow a truncated Gutenberg-Richter magnitude frequency distribution. The ground motion model contains a logic tree consisting of three GMPEs: Boore and Atkinson (2008), Campbell and Bozorgnia (2008), and Chiou and Youngs (2008). All three GMPEs received an equal weight. Figure 4 illustrates the fault sources whereas Figure 5 presents the area sources..

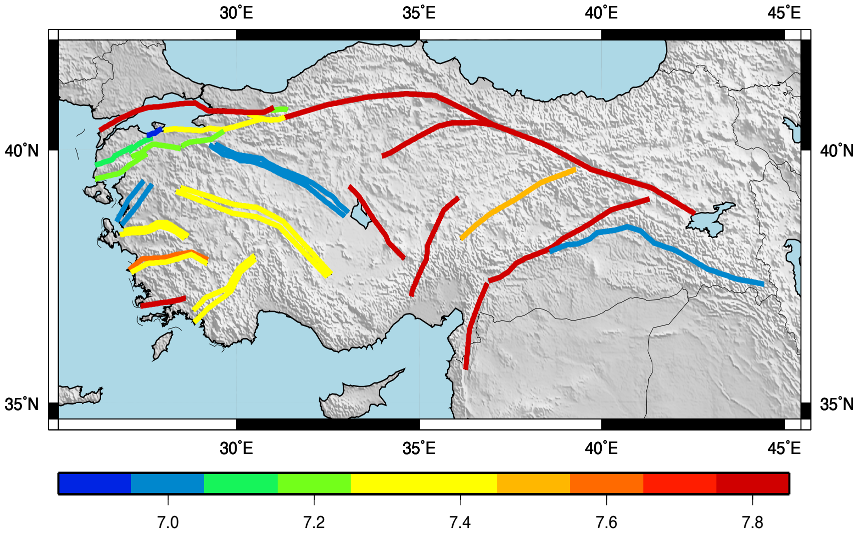

Figure 4 - Fault source model for Turkey. Faults are assumed to be vertical, so only fault traces are shown. Colours represent maximum magnitude (M_w).

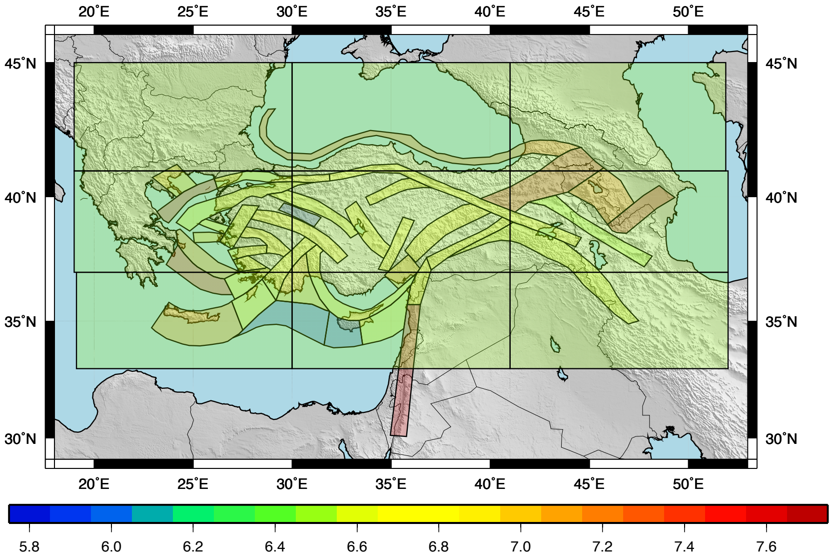

Figure 5 - Area source model for Turkey. Large-scale rectangular background sources cover the entire country, whilst most of the small-scale area sources follow fault source geometries. Colours represent maximum magnitude (M_w) in each source.

3.3 Deterministic Scenario Model

The deterministic scenario model for the city of Istanbul considers a single rupture equivalent to a magnitude of 7.5 M_W. The rupture extends for 120 km along the North Anatolian fault, on a section close to the Bosphorus strait, as shown in Figure 6.

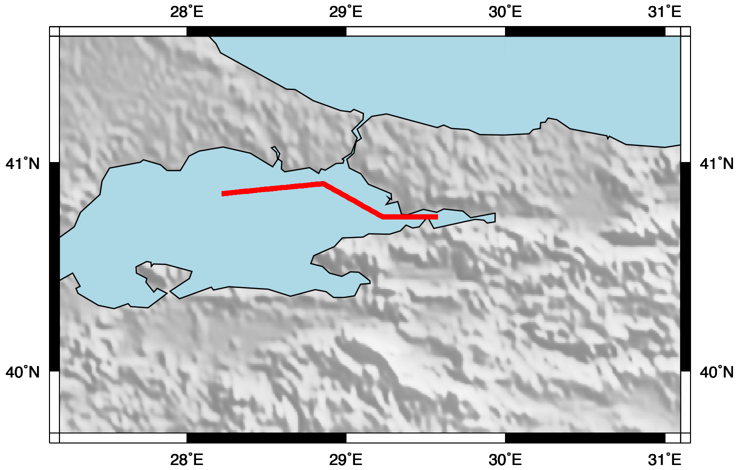

Figure 6 - Rupture trace (in red) used for the deterministic risk analysis. The rupture extends for 120 km and has M_w = 7.5.

3.4 Building Exposure Model

The building inventory for the metropolitan area of Istanbul was created based on a combination of data from aerial photos taken in 1995 and 1998 and census data from 2000 conducted by the Turkish State Statistics Institute. In this dataset, buildings are organized according to construction type (RC frames, RC shear walls, Masonry and Pre-cast buildings), height (low-, mid- and high-rise) and code level (pre-1979 or post-1980) (BU-ARC, 2002). For the purposes of the current application, only the RC frame buildings have been considered. The dataset uses an evenly spaced grid with a 0.005×0.005 decimal degree spatial resolution and for each grid cell, the number of buildings for each typology is provided. This exposure model has been used in several past studies such as the NERIES project (Strasser *et al.*, 2008), in which 5 different earthquake loss estimation methodologies were used to compute the distribution of building damage for the same earthquake rupture. For the purposes of this case study, the number of RC frame buildings per grid cell was converted to an economic value (in USD), by multiplying each building count by the associated replacement cost. The total economic value of the RC frame building stock was estimated as 71.7 billion USD. In order to understand the distribution of building value throughout the metropolitan area of Istanbul, the economic value of the buildings was aggregated per grid cell and the results are illustrated in Figure 7.

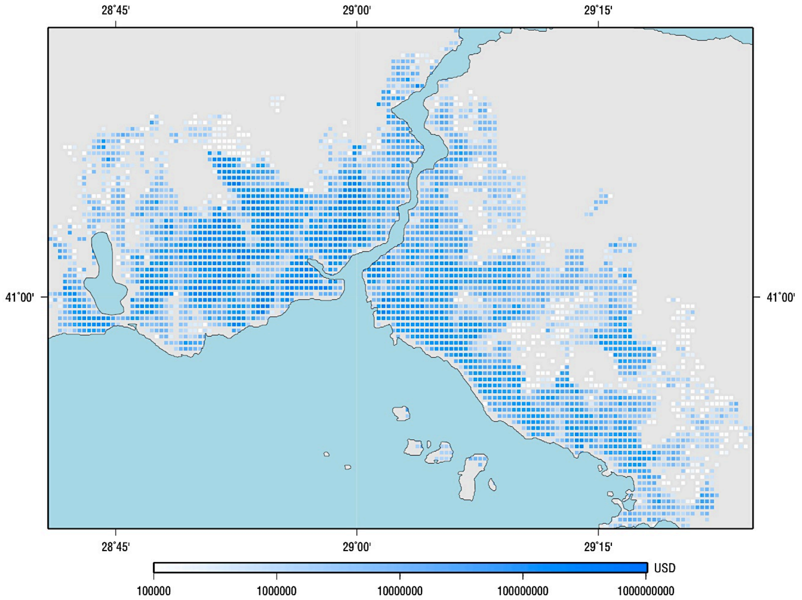

Figure 7 - Distribution of the value of RC frame buildings in the metropolitan area of Istanbul.

3.5 Vulnerability Model

Only reinforced concrete frame buildings have been considered in the case study application as they constitute 75% of the building stock in Istanbul and this percentage is even higher when one considers the building value rather than count (BU-ARC, 2002). Several studies have been carried out in the past to calculate fragility functions of typical Turkish buildings (Akkar *et al.*, 2005, Hancilar *et al.*, 2006, Kirçil and Polat, 2006, Erberik, 2008, Ozmen *et al.*, 2010). The vulnerability model used in this exercise was developed by Silva *et al.* (2012) and it is composed by 6 vulnerability functions (one per asset typology) and it gives the probability of loss for a set of intensity measure levels.

3.6 Output

Seismic Hazard Map for Turkey

By using the Classical PSHA-Based Risk Calculator, OpenQuake is able to produce hazard curves, from which a hazard map (corresponding to a certain probability of exceedance in a given time span) can be derived. Hazard curves for all the three GMPEs defined in the ground motion model logic tree (Section 3.2) were computed, and a mean hazard map was obtained (as shown in Figure 8). Hazard curves have been computed from 35.0 to 43.0 degree north, and from 25.0 to 47.0 degree east, every 0.05 degrees. A total of 71001 hazard curves have been derived for each GMPE. As can be seen, the hazard is mostly driven by fault sources, especially the North Anatolian fault, with levels of PGA of about 1.3g along the fault trace. Area sources surrounding fault sources also play an important role. Their effect is to widen the region of significant hazard around fault sources. Large-scale background area sources produce instead a rather stable value of PGA of about 0.2g in all locations that are far from small-scale area sources or fault sources.

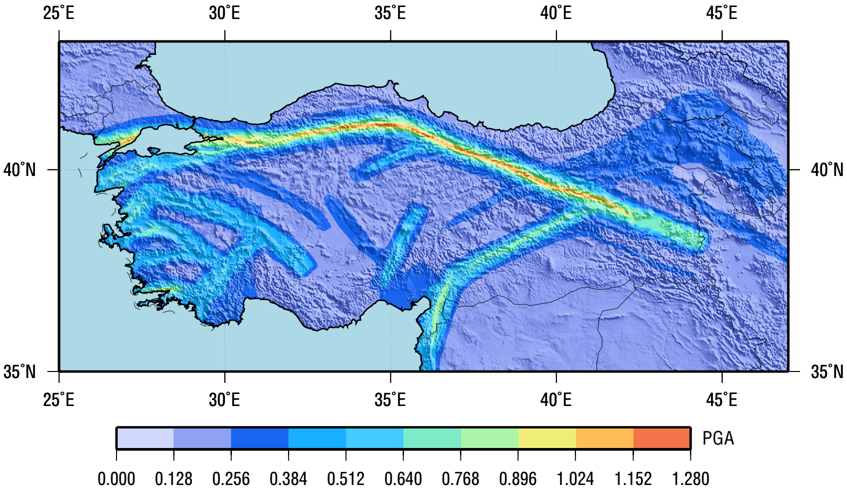

Figure 8 - Mean hazard map for Turkey (corresponding to a probability of exceedance of 10% in 50 years), as obtained from the PSHA model described in Section 3.2.

Deterministic Scenario for Istanbul

Using the previously described input data, losses for a deterministic scenario in the metropolitan area of Istanbul were computed using the Deterministic Event-Based Risk calculator. In this process, about 500 ground motion fields were produced for the same rupture using a single GMPE (Boore and Atkinson, 2008). For each ground motion field, the intra-event variability was sampled taking into account the spatial correlation using the model proposed by Jayaram and Baker (2009). Figure 9 presents a loss map with the distribution of mean economic losses (across all ground motion fields) for the reinforced concrete buildings. When many building typologies existed simultaneously in a given grid cell, the loss values for each typology were aggregated per event.

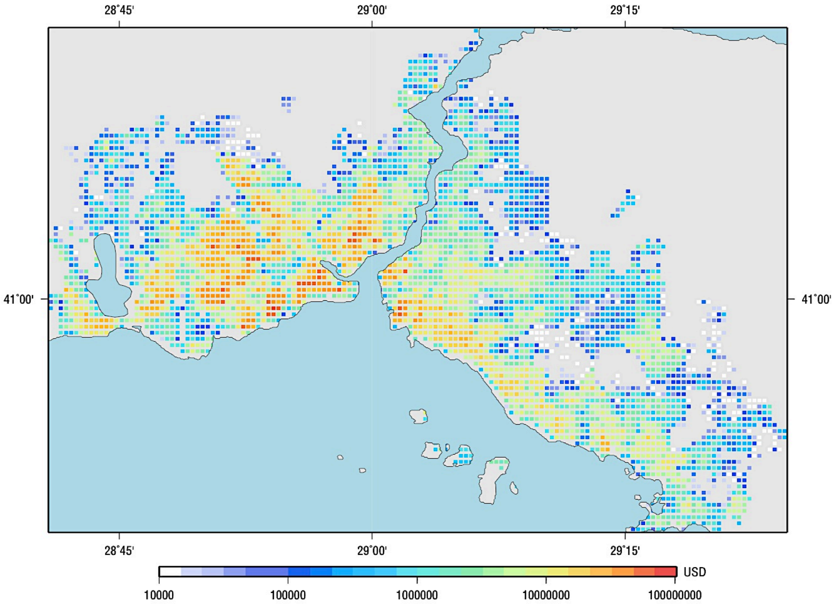

Figure 9 - Loss map with the distribution of mean economic losses for reinforced concrete buildings.

For this seismic event, it was estimated that a total mean economic loss equal to 20.39 billion USD (with a standard deviation of 7.60 billion USD) would occur, representing about 26% of economic value of the reinforced concrete building stock.

Probabilistic risk assessment for Istanbul

Using the Probabilistic Event-Based Risk Calculator described in Section 2.3, about 200 realizations of the seismicity, with a 50 years time span in each case, were used for this probabilistic risk assessment, leading to more than 10,000 ground motion fields. Although area and background sources are also presented in the PSHA model section, only fault sources were considered in this demonstration in order to reduce the computation time for these illustrative results and because, as mentioned previously, the hazard is mostly driven by the fault sources. In total, due to the different building typologies present within the exposure model, about 28,488 loss curves were computed for 4,107 different locations. Again, the spatial correlation of the intra-event variability was considered, allowing the possibility of aggregating the losses throughout the region and the calculation of an aggregate loss exceedance curve representative of the whole RC building stock, as shown in Figure 10.

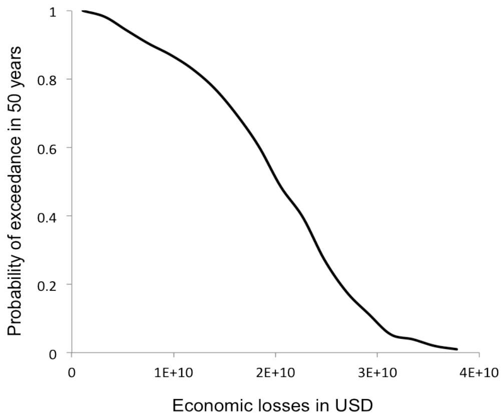

Figure 10 - Aggregate loss exceedance curve for RC buildings in Istanbul.

Linear interpolation of the loss curve can be used to estimate the economic loss for different probabilities of exceedance within a given time span. In Figure 11, a loss map for a probability of exceedance of 10% in 50 years is presented.

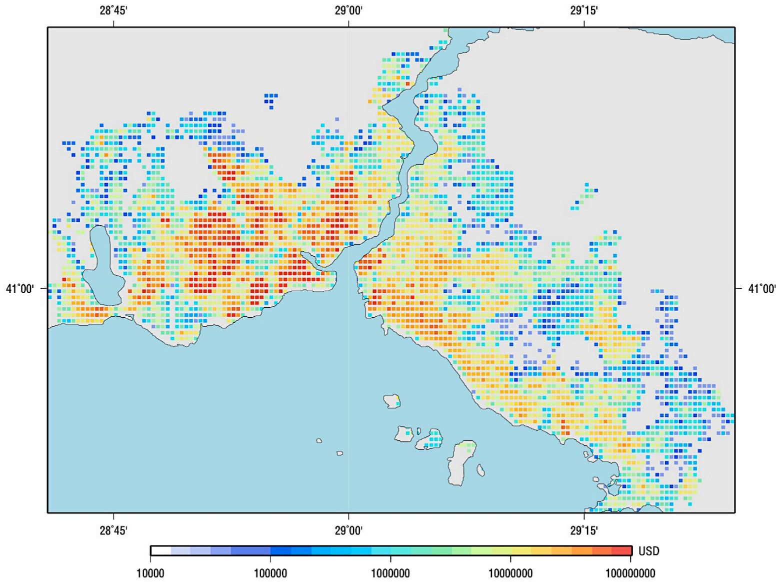

Figure 11 - Loss map for a probability of exceedance of 10% in 50 years.

Comparison of risk results with other models
It is recognized that comparisons of the computed results with real post-event data is fundamental for the testing of earthquake loss models. Despite the fact that Istanbul has been the target of many studies in the past, no data currently exists that could allow an intensive "validation" of the results (i.e. testing that the modeled results reflect reality). It is possible, however, to compare the results presented herein with those from previews studies.

Such an exercise needs to be performed carefully and taking into account the different assumptions from each study. For example, the size of the region, the magnitude of the rupture, or the consideration of site effects are aspects that are often not common to all of the studies carried out in a given region. One of the greatest obstacles to such an evaluation using the results presented herein could be the fact that only reinforced concrete buildings were considered in this study; nevertheless, according to the available exposure data, this building typology comprises 75% of the total building stock and represents 89% of its economic value.

Sozen (2006) has suggested that an event similar to the 7.5 magnitude scenario considered herein would cause the collapse of 10 % of the building stock, leading to a 7.2 billion USD economic loss in the RC building stock. Pyper Griffiths *et al.* (2007) propose that at least 40% of the building stock would collapse, representing an economic loss equal to 28.7 billion USD for the same building typology. The aforementioned study was discussed by Erdik (2007), who claimed that such a scenario would actually lead to losses 2.5 times smaller (11.5 billion USD). It is fundamental to note that the aforementioned loss values are exclusively due to collapsed buildings. However, in Turkey there is a law that requires that extensively damaged buildings should be demolished and rebuilt. Bal *et al.* (2010) performed a loss assessment utilizing the same exposure model and rupture magnitude considered in the study presented in this paper, and estimated that about 17.6% of the buildings would collapse or be damaged beyond repair (i.e. be extensively damaged), 27.5% would suffer moderate damage and 54.9% would experience none to slight damage. This damage distribution would lead to an expected economic loss of 24.3 billion USD for the reinforced concrete building stock based on the damage ratios considered herein. Although this comparison is not as robust as necessary (due to the inherent differences in the studies), it is fair to conclude that the scenario presented herein

(20.39 billion USD with a standard deviation of 7.6 billion USD) falls within the expected range.

It is recalled that the losses that have been presented in this section are purely exemplificative, and that they only refer to the RC building stock. Interested readers may refer to Erdik (2007) for a discussion on the expected losses in Istanbul.

4. CONCLUSIONS

In this paper, an open source software capable of computing seismic hazard and risk was presented, with focus given to the main risk calculation workflows that are currently supported to compute losses either due to a single event, or due to probabilistic hazard using both classical hazard-based and event-based methods. The description of these OpenQuake features serve also the purpose of providing an overview on the state-of-the-practice in seismic hazard and losses/risk assessment.

Due to its transparent, modular and test-driven development philosophy, OpenQuake aims to be a community effort in which anyone can contribute with their own methods and formulae. This differs from traditional practice, where a closed "enterprise" development tends to be followed, even if the source code is eventually openly released. Any interested researcher could include its own methodology to estimate seismic risk within the OpenQuake software.

Through the case study applications presented herein for Turkey, it has been demonstrated that OpenQuake – despite still being in a development phase – already offers several functionalities and a wide spectrum of tools for seismic risk assessment.

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