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MODELING SEISMIC HAZARD BY INTEGRATING HISTORICAL EARTHQUAKE, FAULT, AND STRAIN RATE DATA

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Abstract

The OpenQuake-engine software developed by the Global Earthquake Model (GEM) is an open-source tool for the calculation of seismic hazard and risk. It provides the capability to execute complex seismic hazard calculations on a range of scales, from detailed site-specific analysis to regional or global-scale models. However, users need to construct earthquake source models (ESMs), which characterize both the magnitude-frequency distribution of the earthquakes and their potential finite rupture geometries, and feed the ESMs to OpenQuake for hazard calculations.

In this study, we propose a method to construct ESMs by integrating historical earthquake, geological fault, and strain rate data. The method requires division of the study area into large seismic zones, based on a set of defined seismotectonic criteria. For each zone, the seismicity rates are defined by a tapered Gutenberg-Richter (TGR) model. The TGR *a*- and *b*-values are calculated using observed earthquake data, while the corner magnitude is constrained independently using the seismic moment rate inferred from a geodetically-based strain rate model. Then, we model the spatial distribution of the seismic activity based on characteristics of active faults, and location and magnitude patterns of historical earthquakes. The rates of large earthquakes accommodated on active faults are estimated based on the dimension, slip rate, and paleoseismic data of the faults. Remaining seismicity is distributed to the background using a smoothed seismicity model. Consistency between observed seismic activity rates and those predicted by the model should be verified in terms of both spatial and magnitude distributions. To achieve this, the OpenQuake-engine's event-based seismic hazard tools are used to generate synthetic catalogs of tens or hundreds of thousands of years duration.

We are developing a toolkit to implement this method. The toolkit is built upon the functionalities of GEM's Hazard Modeller's Toolkit. We use southwest China as an example to illustrate the method, workflow, and toolkit. We build the toolkit in a flexible manner so that users can make different modeling decisions at each step. This approach will help make the seismic hazard modeling process more transparent, and prompt the development of new methodologies for seismic hazard assessment.

Keywords: GEM, Probabilistic Seismic Hazard Analysis, Earthquake Source Model

1. Introduction

The construction of earthquake source models (ESMs) for probabilistic seismic hazard analysis (PSHA) is a complex procedure involving various types of information that must be reconciled into a comprehensive interpretation of the earthquake occurrence process. In recent hazard models, epistemic uncertainties connected with the various steps of this process are organized into a logic tree structure, which contains the alternative interpretations for each uncertainty potentially able to control part of the overall results' variability.

Common methods for the construction of ESMs are well established. They typically comprise the construction of a harmonized earthquake catalog, the pre-processing of the catalog, the definition and the characterization of distributed seismicity sources using past seismicity, tectonics and geodesy, the description and characterization of shallow faults using geologic information, and the definition and characterization of subduction sources using past seismicity and tectonics. Today, the evolution of methods for building ESMs is relatively slow. The introduction of new procedures is intermittent, and usually of limited impact, albeit with notable exceptions such as the Uniform California Earthquake Rupture Forecast Version 3 model [1]. The creation of new PSHA methodologies is limited on the one hand by the rate at which new information is obtained and on the other hand by a general lack of transparency and standardization of the model building process – standardization that currently would be possible for the most common and uncomplicated cases. The lack of standardization and transparency on basic methodologies is preventing the implementation of an efficient community-based trial-and-error process, which would help progress towards new innovative and widely recognized methodologies.

The overall goal of this paper is to present a simple but practical method for constructing an onshore ESM by leveraging the suite of methods incorporated into the GEM OpenQuake Hazard Modeller's Toolkit (oq-hmtk) [2], and to discuss the relative advantages and limitations of alternative approaches for each step. In the next section, we briefly review the overall structure and the main features available in the oq-hmtk. In Section 3, we demonstrate the method for constructing an ESM and its workflow using southwest China as an example. In Section 4, we introduce the OpenQuake Earthquake Model Building Toolkit concept before summarizing the main results and possible directions for future work in Section 5.

2. The OpenQuake Hazard Modeller's Toolkit

The oq-hmtk [2] is a software suite for the preparation of various components of an ESM organized around three main modules. The first module contains the methods necessary to process a catalog and build sources for PSHA. These include methods for: declustering a catalog, analyzing the completeness of a catalog through time, computing the parameters characterizing earthquake occurrence, and assessing the maximum magnitude on a statistical basis. The second module contains methods for the construction of earthquake sources starting from information provided by geologic observations. The third module currently comprises one single calculation workflow based on the work of Bird and Liu [3]; this workflow uses the strain rate model obtained by the processing of GPS velocities for the calculation of seismic occurrence. The oq-hmtk source code can be downloaded from a github repository (https://github.com/GEMScienceTools/hmtk; license GPL Affero v. 3.0).

3. Workflow of constructing an ESM

The workflow we illustrate here can be used for the construction of ESMs in Active Shallow Crust tectonic environments by integrating a historical earthquake catalog, active faults, and geodetic strain rates. The required input data include a homogeneous historical and instrumental catalog, geological information of active faults (fault plane geometries and slip rates), and a strain rate model describing the long-term deformation process within the study region.

Active faults are primary sources of earthquake generation, however, not all faults are mapped. As a result, the fault database is not likely to include every fault that could generate earthquakes relevant to the seismic hazard analysis. Moreover, historical earthquake catalogs may not be long enough to include all the large earthquakes that happened in the past. These drawbacks are addressed in the modeling process by including another set of useful information based on geodetic (strain) measurements. For example, tectonic moment rate can be calculated from a strain rate model based on the reasonable assumption that the long-term average rate of elastic strain is negligible in comparison to the rate of permanent strains accumulated by frictional faulting (and other mechanisms such as cold-work plasticity, solution transfer, and dislocation creep [3]). Under these assumptions, the tectonic moment provides an upper limit for the seismic moment budget.

In the following subsections, we briefly outline the main steps comprising this workflow, from the initial processing of the catalog to the final combination of faults and distributed seismicity sources. We describe each step to emphasize the most crucial and controversial aspects and to promote open discussion.

3.1 Catalog pre-processing

For this step, we assume that a homogenized earthquake catalog with magnitudes defined in terms of moment magnitude (M_w) is available. GEM provides tools for constructing homogenized catalogs from a heterogeneous set of catalogs. However, the description of those tools and procedures is beyond the scope of this paper (see [4]).

Two fundamental steps are completed in this phase. The first is the catalog declustering in which dependent earthquakes are removed. While the declustering is often uniformly applied to the entire study area, it is certainly possible to use different declustering parameters in different tectonic regions. In the example of southwest China, we use a single declustering procedure based on the widely known algorithm of Gardner and Knopoff [5]. The second step is the definition of the magnitude-time windows in which the catalog can be considered complete, i.e., where we can confidently assume that for each temporal window considered, the catalog contains all the earthquakes with a magnitude equal to or larger than a threshold magnitude.

The blue dots in Fig. 1 show the epicenters of earthquakes included in the catalog by Weatherill et al. [4] and classified as independent mainshocks by the Gardner and Knopoff declustering algorithm [5] for a portion of the example study area; the red crosses show the dependent earthquakes identified as aftershocks or foreshocks. As expected, the largest concentration of aftershocks is from the 2008 M_w 7.9 Wenchuan earthquake located in the upper right corner of the map.

3.2 Seismic source zones definition

Many traditional PSHA models are based on small seismic source zones, and the seismicity rate is assumed to be uniform within each of the source zones. However, small source zones often do not have enough historical earthquakes to robustly characterize the earthquake magnitude-frequency distribution (MFD). We use large seismic source zones to mark large tectonic provinces with ‘similar’ geologic and seismotectonic characteristics; the use of large areas is motivated by the need to include an adequate number of past earthquakes in order to provide reliable estimates of the parameters characterizing a simple Gutenberg-Richter (GR) relationship. However, in our method, the seismicity does not need to be uniformly distributed within each of the large seismic source zones. Instead, we can assign the seismicity to the background using a smoothed seismicity approach, or onto the active faults, based on the location, size, and frequency of historical earthquakes and the characteristics of the faults. For each seismic source zone, we define a seismogenic depth based on seismicity and tectonics. Fig. 2 shows some example seismic source zones for southwest China; for the demonstration of this workflow, we will look at source zones 3 and 7.

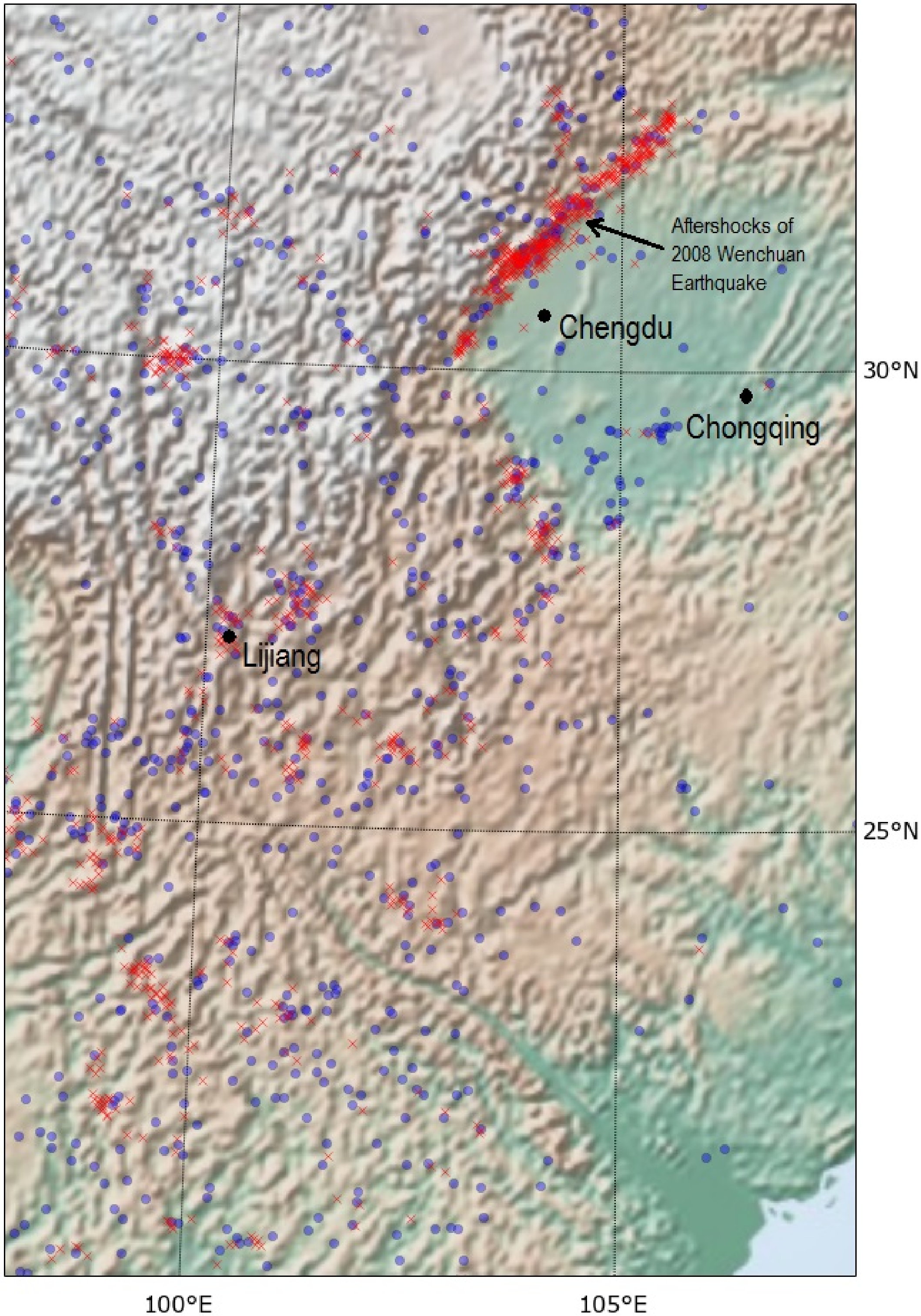


Fig. 1 – A map showing main shocks (blue dots) and aftershocks (red crosses) in southwest China from the catalog of Weatherill et al. [2]. Colors indicate elevation (green low, white high).

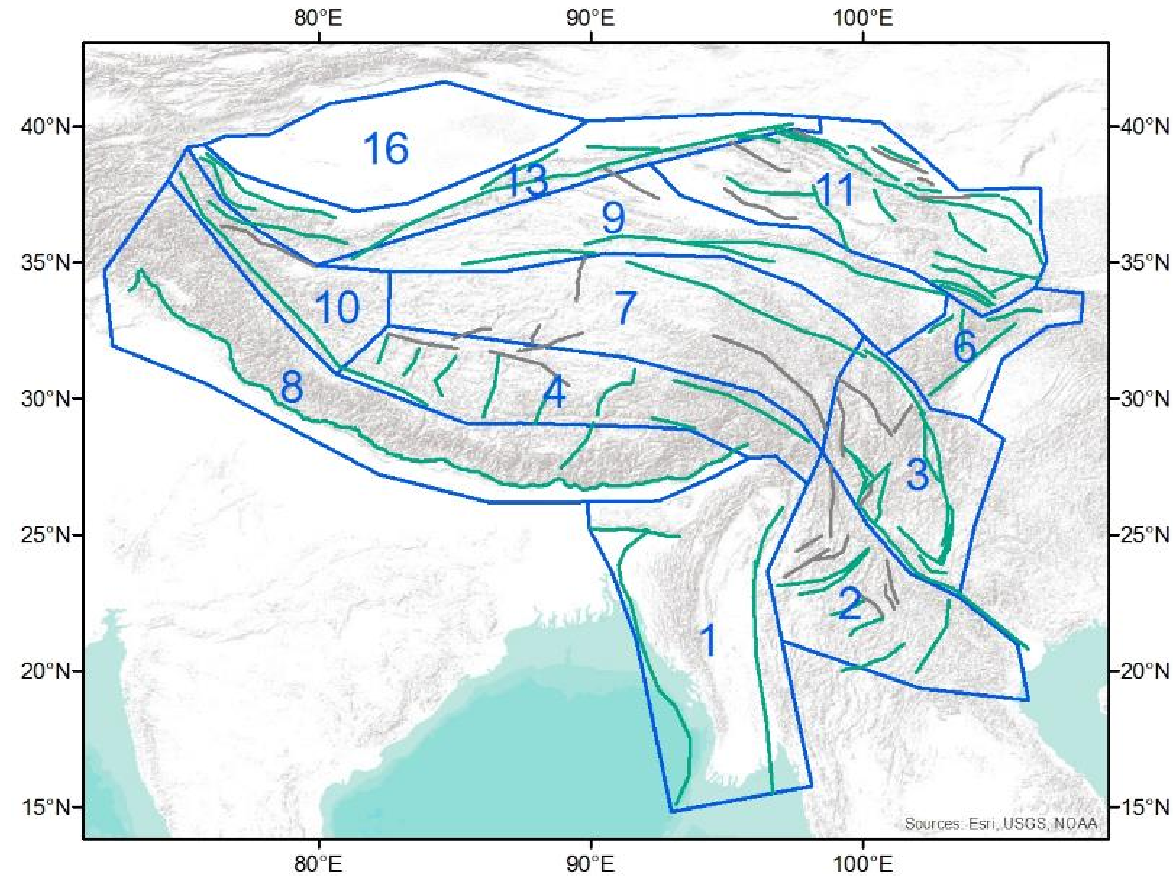


Fig. 2 – Exemplary seismic source zones (blue polygons labeled by numbers) and major active faults in southwest China. Green lines are faults with known slip rates, and gray lines are faults whose slip rates are unknown.

3.3 Modeling fault sources

Faults are primary sources of earthquake generation. For seismic hazard analysis, seismogenic fault sources need to be compiled from geologic fault databases. The workflow from fault traces to fault sources is demonstrated in [6].

In many seismic hazard analyses (e.g., [7, 8]), earthquake magnitude rates on faults are modeled using the characteristic earthquake model, which assumes that large characteristic earthquakes repeatedly rupture the same fault segments with a similar magnitude and slip distribution [9, 10]. Implementing the characteristic model into seismic hazard analysis is tempting because of its simplicity and clarity dictated by an almost regular rupturing process on the same fault by almost the same size earthquakes. However, the characteristic model has its limitations and its validity has been seriously challenged [11, 12, 13, 14, 15, 16]. Moreover, implementing a characteristic model requires the knowledge of fault segmentation, characteristic magnitude, and recurrence times, which are all very uncertain for most faults.

Therefore, we prefer to characterize seismicity on the faults using fault dimensions and slip rates, using methods similar to the ones proposed by [17, 18]. In these methods, we assume that the occurrence of earthquakes on a fault follows a truncated GR or a Tapered GR (TGR) distribution and the total seismic moment rate from the magnitude distribution equals the geological moment rate derived from the fault dimension and slip rate. We assume the TGR *b*-value of earthquakes on the fault is the same as the *b*-value of the seismic source zone containing the fault. For a truncated GR distribution, we assign lower- and upper-bound magnitudes for each of the faults. The upper-bound magnitude should not be larger than that inferred from fault length or area scaling relationships. For TGR, we assign a corner magnitude for each of the faults. The corner magnitude of the seismic source zone may be used. When we simulate earthquakes on a fault, we use appropriate earthquake magnitude-area scaling relationships, and allow earthquakes to float along the fault plane [19].

3.4 Characterizing earthquake occurrence for a seismic source zone

We use a TGR distribution to define earthquake MFD for each source zone. The TGR distribution has an exponential taper applied to the number of events of large seismic moment, which ensures a finite moment flux for a region. It is most conveniently expressed in terms of seismic moment, M, instead of magnitude (M_w) [20]:

$$F(M) = \alpha_t \left(\frac{M_t}{M}\right)^{\beta} exp\left(\frac{M_t - M}{M_c}\right) \;\; for\ M_t \leq M < \infty \tag{1}$$

where M is in N·m, and $M = 10^{1.5M_w+9.05}$ [21]. Here, $F(M)$ is the rate of earthquakes with moment larger than M, and β equals 2/3 of the GR b-value. M_c is called corner moment (the corresponding magnitude is called corner magnitude, m_c), which controls the distribution in the upper ranges of M. M_t is a threshold moment (the corresponding magnitude is threshold magnitude, m_t) above which the catalog is assumed to be complete, and α_t is the seismicity rate for earthquakes with moment M_t and greater. To construct a TGR MFD, three parameters need to be determined: α_t, β, and M_c (or m_c).

We estimate the TGR b-value and a-value (and therefore β and α_t) using the Weichert method [22]; catalog completeness is obtained using an automated version of the Stepp methodology [23] implemented in the oq-hmtk. For a large region, the b-value is usually close to 1.0 [24, 25]. After α_t and β have been determined, M_c can be estimated using the seismic moment conservation principle [26]:

$$M_c \backsimeq \left[\frac{\chi \dot{M}_{T0}(1-\beta)}{\alpha_t {M_t}^{\beta} \Gamma(2-\beta)}\right]^{1/(1-\beta)} \tag{2}$$

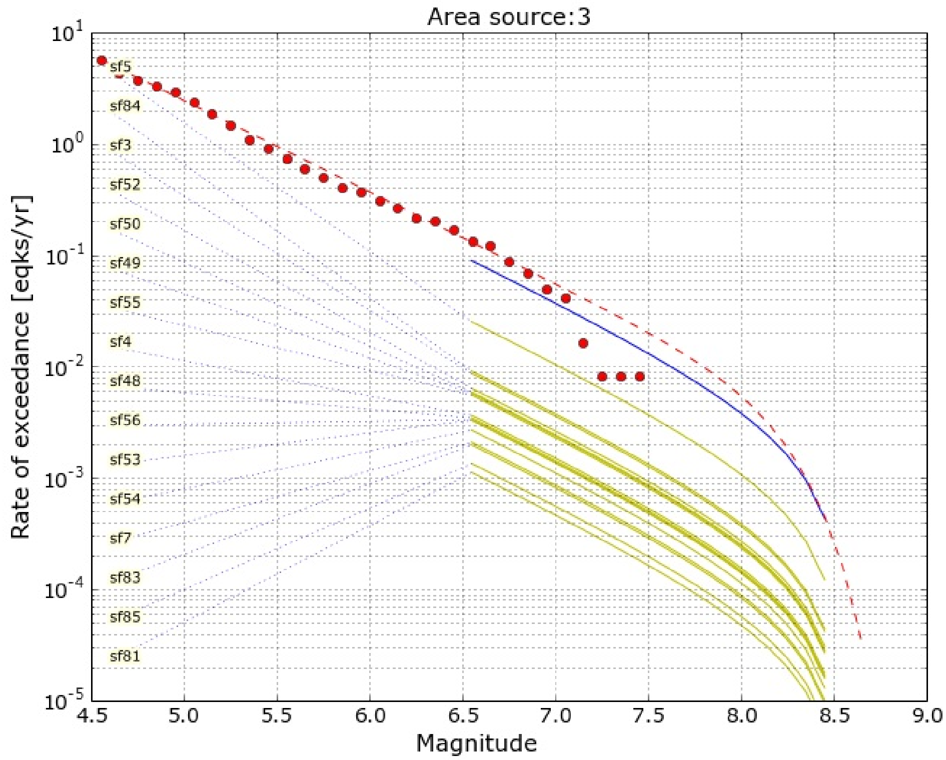
where $\dot{M_{T0}}$ is the total tectonic moment rate determined from geodetic or geologic measurements (without considering the seismic coupling, χ), and Γ is the gamma function. We estimate $\dot{M_{T0}}$ from the geodetic strain rate model using the method described in [3, 12, 27].

The obtained TGR relationship defines the total MFD for a large seismic source zone. We will split the total MFD in two parts: one part is attributed to the earthquakes on active faults, and the rest to the background seismicity. Figure 3 demonstrates the cumulative MFDs for source zones 3 and 7. For demonstration purposes, we assume that the earthquakes on the active faults span a magnitude range of 6.5 to 8.5. In practical applications, the magnitude range of earthquakes on each fault should be determined based on characteristics of the fault, regional tectonics, and earthquake history.

In the case of area source 7, it is worth noting that the MFD shows a tapering only at very large magnitudes. This means that the seismic moment rate derived from strain rate is very high compared to the moment rate from earthquake history. This is a trend that we observe in some of the zones so far considered; clearly this is an aspect that will require further investigation.

3.5 Characterizing background seismicity

After we characterize earthquake occurrence for a source zone and for faults within that source zone, we attribute the difference between earthquake occurrences in a source zone and on faults to background seismicity. We use a smoothed seismicity method to distribute the background seismicity, that is, the distribution of background seismicity is based on the MFD and spatial distribution of historical earthquakes. Distributed seismicity is modeled on a regular grid of point sources covering the extent of the source zone. The total MFD for each zone is scaled proportionally to the rate of occurrence computed on each node using a smoothed seismicity process. In order to avoid double counting contributions, the MFD of point sources within a buffer around each fault source is truncated at the magnitude value which corresponds to the minimum magnitude of the MFD of the corresponding fault.



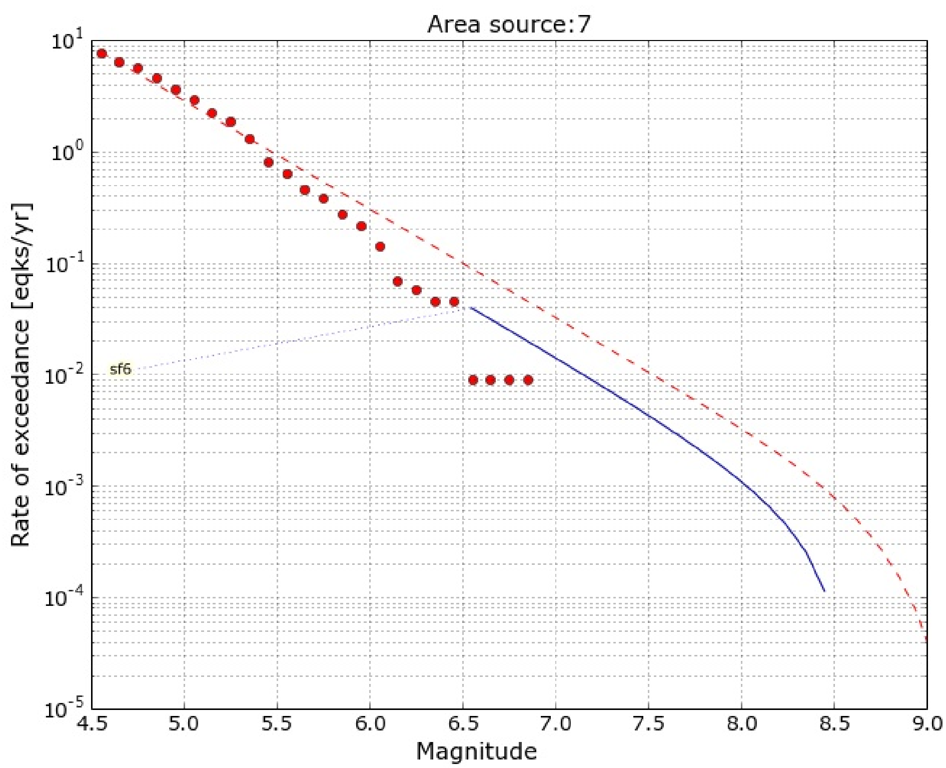


Fig. 3 – Cumulative magnitude-frequency distributions of source zones 3 (upper panel) and 7 (lower panel) considered in this demonstrative example. The red dashed lines show the TGR distribution obtained using the information contained in the historical seismicity catalog (for the calculation of α_t, and β), and the GEM strain rate model version 2.1 [28] (for the calculation of the corner magnitude). The red dots show the MFD obtained using historical seismicity. Yellow lines are the MFDs obtained for the individual faults (fault IDs are labeled in the plots) inside each zone; the blue curve shows the MFD obtained by summing the individual fault MFDs.

3.6 Consistency checks and handling exceptions

To ensure the workflow operates properly, the following consistency checks are performed for each of the source zones during the modeling process:

1) Comparing moment rates based on strain rate, fault sources, and seismicity (including historical earthquakes and TGR distribution of the zone);
2) Comparing the MFDs of fault sources with the TGR of the zone.

The first check ensures the consistency of different datasets. The scalar seismic moment rates from strain and scalar seismic moments from the MFDs (examples of MFDs used for determining scalar seismic moment are the red dashed lines in Fig. 3) should be consistent. However, the seismic moment rate directly calculated from historical earthquakes may not be consistent with moment rates from strain and from the MFDs. This is because the historical catalog-based moment rates are usually dominated by the few large earthquakes. If those large earthquakes happened within the catalog completeness times, the estimated seismic moment rates may be larger than those from MFDs; otherwise, the estimated moment rates may be smaller than those from MFDs.

The workflow described above assumes that the zone TGR distribution based on strain-rate and the historical earthquake catalog is higher than the total MFD from the faults, so that the leftover seismicity rates can go to the background seismicity. However, this assumption does not always hold, due mainly to the large uncertainties in the strain-rate model and fault parameters. For this case, scientific judgment on the fault coupling coefficients or on the use of the uncertainties in the strain-rate based seismic moment rate is needed.

3.7 Modeling finite ruptures

The final step of our modeling process is the construction of the input model for the OpenQuake-engine [19]. To calculate seismic hazard, earthquake ruptures must be specified. The OpenQuake-engine can take the sources in the ESM and generate ruptures using its standard hazard calculation module. It can also generate a synthetic catalog in which each synthetic event is modeled by a finite rupture. For the ruptures modeled on faults, their geometry is constrained by the characteristics of the corresponding faults. For the events belonging to background seismicity, we use the prevalent nodal planes determined from earthquake focal mechanisms and the strain rate model for each area source to define the geometry and style of their finite ruptures. The scaling relationships between magnitude and rupture area (or length) are used to define the extent of the finite ruptures.

Figure 4 shows an example of seismic hazard map computed using a classical PSHA methodology for the area around source zone 3. The ESMs are constructed using the methodology discussed in this paper. The ground motion prediction equations by Boore and Atkinson [29] are used in the calculation. The OpenQuake-engine is used for hazard calculation. The figure displays the seismic hazard (peak ground acceleration, PGA, with 10% probability of exceedance in 50 years) obtained by considering both faults and background seismicity sources.

4. Exploring the feasibility of an OpenQuake Earthquake Model Building Toolkit

It is desirable to create a repository where workflows similar to the one proposed here can be collected and shared for a wider application in various tectonic regions and seismotectonic contexts around the world. Thus, GEM plans to create a repository with the provisional name OpenQuake Earthquake Model Toolkit (oq-emtk). The oq-emtk will be created to formalize the various approaches for the construction of components of an ESM, and to collect methods assisting hazard modelers to build ESMs. For the construction of this repository, GEM will follow the approach used for the compilation of the OpenQuake-engine [19] [30] and the hazard toolkits of the OpenQuake suite [2].

The toolkit architecture will be flexible to accommodate various approaches and to prevent the need to strictly follow one specific workflow or particular modeling choices (such as the ones described above). For example, other types of magnitude-frequency distributions (such as the truncated GR or characteristic earthquake model) might be used. For the regions that do not have a strain rate model, a TGR corner magnitude or a truncated GR maximum magnitude can be determined by other methods, and input as a parameter. For the fault sources, users can choose to use slip rate or recurrence times of characteristic earthquake magnitude to model earthquake rates. The scaling relationships of earthquake magnitude and rupture length or area can also be specified by users, offering a configurable environment for earthquake source model development.

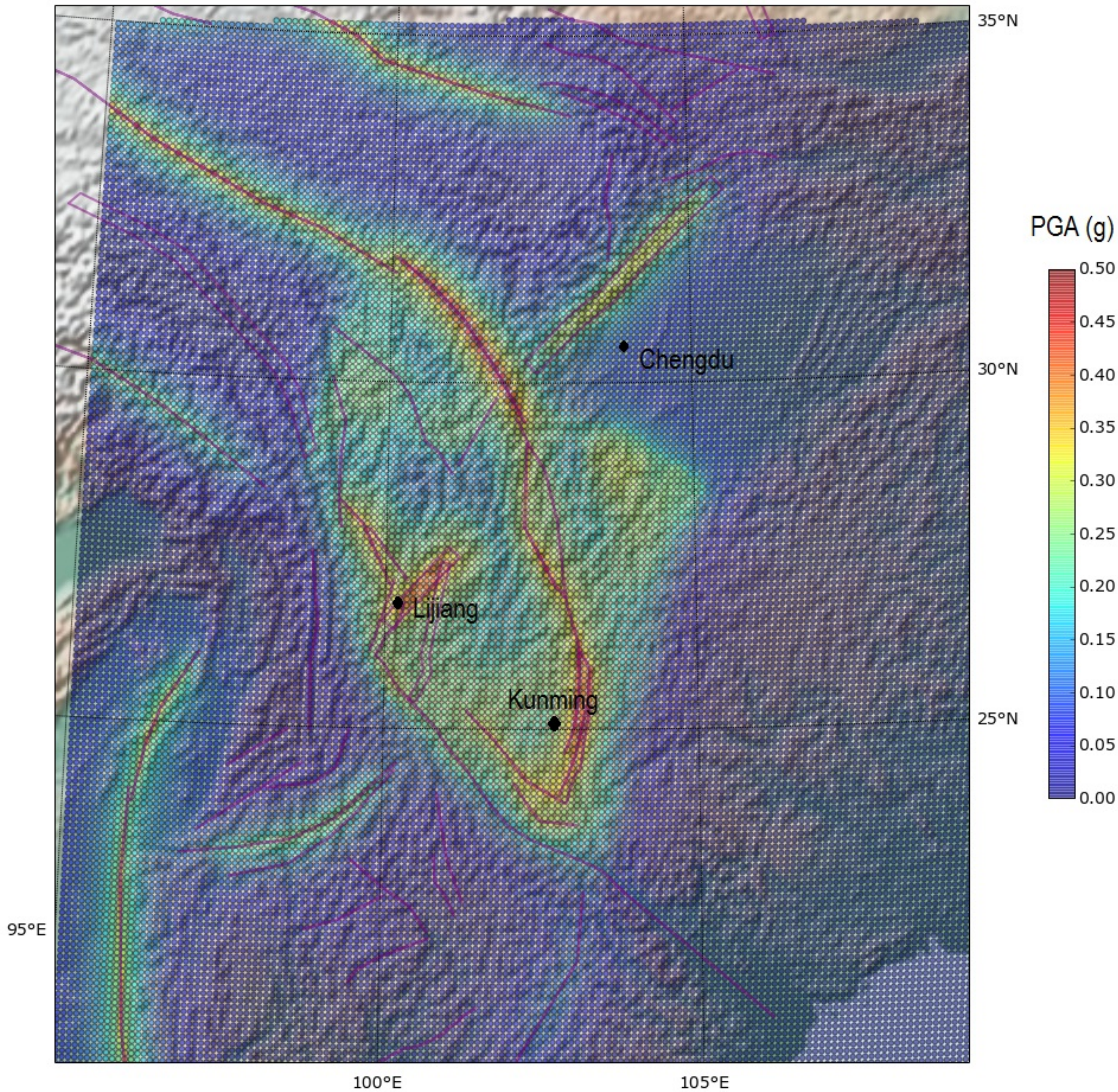


Fig. 4 – Exemplary seismic hazard map (PGA, in g, with 10% probability of exceedance in 50 years) of southwest China.

5. Conclusions

We developed a new method to construct ESMs for seismic hazard calculations. In the new method, we defined large seismic source zones, and used TGR distribution to describe the earthquake magnitude-frequency distribution for each zone. Then, we distributed the earthquakes rates defined by the TGR to fault sources and background seismicity. The new method integrates historical earthquake catalogs, geodetic strain rates, and geological faults. Historical earthquake catalogs were used to determine GR *a*- and *b*-values. Geodetic strain rates define the upper bound of seismic moment rates and thus were used to constrain the corner magnitude of TGR distributions for source zones. Earthquake activity on the faults were modeled based on fault parameters such as their length and slip rate. Background seismicity was captured by the smoothed seismicity method. The traditional way of constructing ESMs usually requires the knowledge of all the active faults in a study region. Using the method presented herein, we can construct ESMs for the regions where we only have parameters for some of the active faults, such as China. We illustrated the workflow using southwest China as an example.

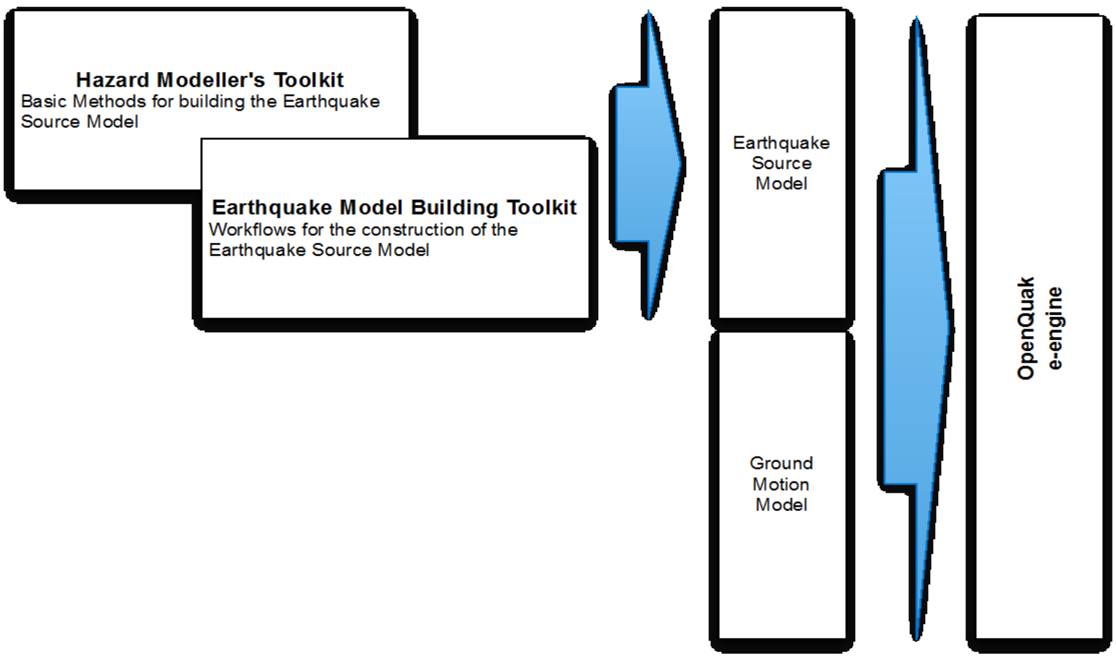


Fig. 5 – Schematic showing the relationship between the OpenQuake Hazard Modeller's Toolkit, the OpenQuake Earthquake Model Building Toolkit, and the OpenQuake-engine.

We proposed the development of an open-source toolkit for constructing such source models. The toolkit will be built on top of the oq-hmtk, and its output will serves as the input for OpenQuake to perform seismic hazard calculations (Fig. 5). The goal of developing this suite of tools is to make the seismic hazard modeling process more transparent, and to promote the development of new methodologies for seismic hazard assessment.

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