PROBABILISTIC SEISMIC RISK ASSESSMENT IN THE BALKAN REGION

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ABSTRACT

The Balkan region is characterized by an active seismic zone, which has experienced several destructive earthquakes over the centuries. The significant human and economic losses that resulted from these events highlight the need for a reliable seismic risk model for the region. A detailed exposure model has been developed at the municipality level for 12 countries: Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Greece, Kosovo, Republic of Macedonia, Montenegro, Romania, Serbia and Slovenia. The residential building stock of each country has been classified according to a set of building classes that account for the main vulnerability attributes: construction material, lateral load resisting system, number of floors, age of construction and the seismic design level. The datasets used are based on the latest national housing census of each country and have been further refined based on expert judgment from local researchers. Vulnerability functions have been derived by the Global Earthquake Model (GEM) Foundation as part of a global effort to develop a database of fragility and vulnerability functions. The seismic hazard component uses the recently released 2013 European Seismic Hazard Model (ESHM13). The three components have been combined within the OpenQuake-engine, the open-source software for seismic hazard and risk analysis supported by GEM and a number of risk metrics have been generated for each individual country, including average annual losses and exceedance loss curves. These datasets and models are currently being improved and modified within the scope of the H2020 European project SERA.

Keywords: Seismic risk; Balkans; OpenQuake; Earthquake; Average annual loss

1. INTRODUCTION

The Balkan Peninsula is one of the most seismically active regions in Europe, where destructive earthquakes have caused high human and economic losses throughout the history. The 1977 M7.4 Vrancea Earthquake caused the collapse of 32 buildings, killing over 1500 people only in Bucharest, the capital and the largest city in Romania (Bala and Toma-Danila 2016). In Bulgaria, the same earthquake caused the collapse of three blocks of flats and damaged many other buildings, killing more than 100 people. In Greece, the Mw=6 earthquake of September 7, 1999 that occurred near the capital of Athens, resulted in 143 casualties from 27 collapsed buildings and approximately 1600 injuries. This earthquake became the costlier natural disaster in Greece’s recent history, reaching approximately 3% of the country’s GDP (economic losses around 4 billion Euro) (Pomonis 2002).

The significant economic and human losses observed in Southern Europe propelled several collaborative research projects and have encouraged many researchers to study the different components of earthquake risk in the region (hazard, exposure and vulnerability). In September 2007, the SFP 983054-Harmonization of Seismic Hazard Maps in Western Balkan Countries Project (BSHAP) was launched with the main objective to prepare new seismic hazard maps of the Western Balkan Countries using modern scientific methodologies. The 2013 European Seismic Hazard Model (ESHM13) was a collaborative project supported by the European Commission within the Framework Program 7 (FP7) with the goal to develop a comprehensive community-based seismic hazard model for the European territory and Turkey (Woessner et al. 2015, ESHM13 - www.share-eu.org). Within the NERA project

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(NERA - www.nera-eu.org), a European residential building inventory database was developed, mainly using information collected from the latest, at the time of the project, national building censuses of each country, coupled with the experts’ opinion from local practitioners. The project covered 45 European countries, including Turkey, and provided dwelling fractions in urban and rural areas at a regional scale (Crowley, Ozcebe, Baker, Foulser-Piggott and Spence 2014). Regarding structural vulnerability, the last component of seismic risk, SYNER-G was a European collaborative research project that developed a framework for the assessment of the physical seismic vulnerability of buildings, transportation and utility networks and critical facilities at urban and regional level (SYNER-G - www.vce.at/SYNER-G).

In addition to the aforementioned European projects, several researchers have studied the different components of seismic risk in the Balkan countries, with hazard being the most studied component (e.g., Lee and Trifunac 2017, Markušić et al. 2016 and Pavel et al. 2016). However, limited studies go through all the steps of seismic risk, from hazard, vulnerability and exposure to the calculation of earthquake losses. To exemplify, Pomonis and Gaspari (2014) conducted loss estimation scenarios for the town of Pylos in south-western Peloponnese (Greece) and further conducted a cost-benefit analysis for three different seismic retrofitting programmes.

This paper presents the preliminary results of a probabilistic seismic risk model for the residential building stock of 12 European countries covering the Balkan region. This work features part of the initiative of the Global Earthquake Model (GEM, https://www.globalquakemodell.org/) to develop an open earthquake risk model at a global scale by the end of 2018. Within this framework, an exposure database was generated for the 12 countries using the latest housing census data available, identifying the most common building classes, their structural characteristics and replacement costs. Vulnerability functions, were derived by GEM as part of the global risk modelling effort, while the seismic hazard component uses the recently released ESHM13. The three components were combined within the OpenQuake-engine (Silva, Crowley, Pagani, Monelli and Pinho 2014), the open-source software for seismic hazard and risk analysis supported by GEM and harmonized risk metrics were developed across the countries. The datasets used herein will be continuously updated based on experts’ contributions, in order to benefit the community and engage local experts into the further enhancement of the resulting model. In particular, the ongoing H2020 project SERA (Crowley et al. 2018) features specifically activities related with the derivation of exposure and vulnerability models for the European territory.

2. PROBABILISTIC SEISMIC HAZARD MODEL – ESHM13

In the present study, the OpenQuake-engine was used to calculate seismic hazard at the locations of the residential building stock, using the ESHM13.

The ESHM13 was a collaborative initiative supported by the European Commission within the Framework Program 7 (FP7) to develop a probabilistic community-based seismic hazard model, with the participation of several institutions and experts throughout Europe. The study area considered by the ESHM13 included highly diverse tectonic regimes. To account for the uncertainty associated with the latter, the ESHM13 used a logic tree to account for multiple ground motion prediction equations per tectonic regime and three independent seismic source models (an area source model (AS-model) based on the definition of areal sources for which earthquake activity is defined individually; a kernel-smoothed zonation-free stochastic earthquake rate model that considers seismicity and accumulated fault moment (SEIFA-model); and a fault source/background seismicity model (FSBG-model), based on the identification of large seismogenic sources using tectonic and geophysical evidence) (Woessner et al. 2015).

The datasets used and the results are publicly available through the European Facilities for Earthquake Hazard and Risk (EFEHR - www.efehr.org) or the ESHM13 project website (ESHM13 - www.share-eu.org). Figure 1 presents the seismic hazard map in terms of peak ground acceleration (PGA) for a probability of exceedance of 10% in 50 years (which is equivalent to a return period of 475 years). It can be observed that the Balkan region is amongst the areas with the highest seismic hazard estimates,
with PGA values greater than 0.40 g along the western coast of Greece to the northern coasts of Albania.

Figure 1. European Seismic Hazard Model (ESHM13) results of PGA for a 475 year return period and a reference rock condition of Eurocode 8 type A (Vs30 = 800m/s).

The effect of local soil conditions on the seismic ground motion characteristics very often causes considerable increase of the damage level during an event (Poggi and Donat 2016). To consider the amplification effects due to soil conditions, a site model was implemented using $V_{S,30}$ proxy values. Herein, a $V_{S,30}$ layer covering the whole territory of the Balkan region and Cyprus was created using the topographic proxy proposed by Wald and Allen (2007). The latter methodology is based on the assumption that steep mountains indicate rock and consequently high shear wave velocities, while nearly flat basins indicate soil (lower-velocities). The limitations of such approach are well recognized, as indicated by several researchers. For example, Lemonie et al. (2012) concluded that such method should only be employed for first-order studies and only in the absence of other more detailed information (e.g., actual measurements, microzonation studies and investigations based on geology). Also, within the scope of the aforementioned SERA project (Crowley et al. 2018), a more detailed approach will be followed, which will consider not just the topographic slope but also geological maps.

3. DEVELOPMENT OF AN EXPOSURE MODEL FOR THE BALKAN REGION

In order to perform a risk assessment an exposure model that describes the spatial distribution, building classification and replacement cost of the building stock is required. Depending on the availability of the datasets and resources, different approaches can be followed to develop an exposure model. Herein, solely publicly available data were considered and the primary source of information was the national housing databases of each individual country. The exposure model that will be presented in this study, will be continuously improved based on local experts’ opinion (e.g., SERA exposure workshop in March 2018).

The development of the present exposure model followed four main steps: 1) definition of building classes; 2) mapping census data to building classes; 3) mapping dwellings to buildings; and 4) estimation of replacement cost.
3.1 Definition of building classes

The residential building stock of the Balkan region has been classified according to a set of building classes that describe the structural characteristics and expected performance to ground shaking. The attributes that were used to define the building classes in this study were: 1) the material of the external walls (e.g., concrete, brick, stone); 2) the number of the floors (low, medium, high-rise buildings); 3) the construction age (which is linked to the seismic provisions and consequently to the ductility level; non-ductile, low, medium and high ductility); and 4) the structural type of the lateral load resisting system (e.g., dual system, infill walls). The identification of the most common building classes across the 12 countries in the Balkan region was performed using existing studies and projects (e.g., NERA), housing reports from the World Housing Encyclopedia (WHE), peer-reviewed publications, Google Street View and UN-HABITAT studies. The main structural types that were finally adopted consist of: 1) bare reinforced concrete frames; 2) infilled concrete frames; 3) concrete walls; 4) reinforced concrete dual frame-walls; 5) precast reinforced concrete walls; 6) confined masonry; 7) reinforced masonry; 8) unreinforced masonry; 9) wood panels; and 10) steel frames. In addition, according to the National Institute of Statistics of Romania, almost 33% of the residential buildings are constructed using a material named “chirpici”. It was found that a “chirpici” house is constructed with wooden stud and mud, mixed with straw infill walls. This is a particular vulnerable structure that comprises a considerable fraction of the residential buildings in Romania and therefore was assigned a separate building class. The different combinations of the above structural types with the number of floors and the ductility level led to 143 building classes, which follow the GEM Building Taxonomy (Brzev et al. 2013). As an example, Figure 2a indicates a reinforced concrete with a potential soft story, which is commonly found in urban areas in Greece, Figure 2b shows a reinforced concrete with brick infill walls found in Albania and Figure 2c is a precast concrete panel apartment, a common building type built in Romania between the 1960s through the 1990s.

![Figure 2. Common building classes found in Greece, Albania and Romania, respectively.](image)

3.2 Mapping census data to building classes

Housing statistics usually provide information on the number of the dwellings and/or buildings classified according to specific attributes, such as the main material of construction, number of floors and construction age. In this study the latest census databases were used to retrieve the aforementioned attributes of the residential buildings in each country. These attributes were further used to assign a building class to the dwellings/buildings. However, buildings whose exterior wall material is defined as clay brick in the census data could refer to structures of unreinforced masonry, reinforced masonry, confined masonry or even reinforced concrete with brick infilled walls. Therefore, mapping schemes were developed for each individual country, which define the relationship between the attributes found in the census and the list of building classes. The development of the mapping schemes of the 12 countries, closely follows the methodology thoroughly described in Yepes-Estrada et al. (2017). The advantage of this approach is that it can be continuously refined based on additional input from local experts.
3.3 Exposure model and estimation of replacement cost

The last step of the exposure modelling is to convert the dwellings into number of buildings and assign a replacement cost per building type. The Statistical Institutes of some countries, such as Greece or Albania provide both the number of dwellings and number of residential buildings in each municipality. On the other hand, countries such as Montenegro or Serbia provide only the number of dwellings. In order to derive the number of buildings, the amount of dwellings were divided by the average number of dwellings per story times the average number of storeys per building class (Equation 1). The national census databases and expert judgement were used to define the range of number of storeys for each building class and the average number of dwellings per story.

\[
N_{\text{buildings}} = \frac{N_{\text{dwellings}}}{N_{\text{storeys}}^{\text{building}} \times N_{\text{dwellings}}^{\text{storey}}}
\] (1)

Regarding the average replacement costs, three different quality classes per country were defined in order to capture the differences in the replacement cost between the various building typologies. Specifically, each of the 143 building classes was assigned to a lower, middle or high construction quality class, which was then assigned an average built up area and cost of replacement per square meter. Both the average built up area and cost were determined by the census databases of each country or expert’s judgement. Then, the average size and average cost of construction were multiplied to obtain the final replacement cost for each building typology. The total number of the residential buildings in each country, the total replacement cost and the main sources of information are summarized in Table 1. For the sake of clarity, Figure 3 illustrates the results at a country level (although they are developed at the municipality level) and only the distribution of simplified building classes across the countries are depicted (as opposed to the entire set of 143 building classes).

Table 1. List of the countries considered in the study, along with the total number of residential buildings, the total replacement cost and the main source of information.

<table>
<thead>
<tr>
<th>Country</th>
<th>Residential Buildings</th>
<th>Replacement Cost (USD Million)</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greece</td>
<td>3,245,604</td>
<td>512,516</td>
<td>Hellenic Statistical Authority</td>
</tr>
<tr>
<td>Romania</td>
<td>5,326,972</td>
<td>245,887</td>
<td>National Institute of Statistics of Romania</td>
</tr>
<tr>
<td>Bulgaria</td>
<td>2,071,699</td>
<td>237,280</td>
<td>National Statistical Institute of Bulgaria</td>
</tr>
<tr>
<td>Serbia</td>
<td>2,139,607</td>
<td>125,197</td>
<td>Statistical Office of the Republic of Serbia</td>
</tr>
<tr>
<td>Croatia</td>
<td>1,274,193</td>
<td>77,507</td>
<td>Croatian Bureau of Statistics</td>
</tr>
<tr>
<td>Bosnia and Herzegovina</td>
<td>1,072,231</td>
<td>71,790</td>
<td>Agency for Statistics of Bosnia &amp; Herzegovina</td>
</tr>
<tr>
<td>Cyprus</td>
<td>171,530</td>
<td>71,618</td>
<td>Statistical Service of Cyprus</td>
</tr>
<tr>
<td>Kosovo</td>
<td>251,366</td>
<td>36,095</td>
<td>Kosovo Agency of Statistics</td>
</tr>
<tr>
<td>Macedonia</td>
<td>427,014</td>
<td>34,128</td>
<td>State Statistical Office of the Republic of Macedonia</td>
</tr>
<tr>
<td>Slovenia</td>
<td>463,029</td>
<td>27,026</td>
<td>Statistical Office of Slovenia</td>
</tr>
<tr>
<td>Albania</td>
<td>598,267</td>
<td>16,516</td>
<td>Instat, Institute of Statistics</td>
</tr>
<tr>
<td>Montenegro</td>
<td>136,883</td>
<td>11,980</td>
<td>Statistical Office of Montenegro - MONSTAT</td>
</tr>
</tbody>
</table>
Figure 3. Residential exposure model for 12 countries in the Balkan region and Cyprus in terms of number of residential buildings and main structure type (CR: concrete reinforced, MATO: other (assumed to be informal construction), MCF: confined masonry, MUR: unreinforced masonry, WL1: light wood; ER+W: wooden stud with mud infill walls, UNK: unknown, MR: reinforced masonry).

4. VULNERABILITY ASSESSMENT

Fragility functions establish the probability of exceeding a number of damage states conditional on a set of ground shaking levels. On the other hand, vulnerability functions represent the probability of loss ratio for a number of ground shaking levels. Fragility functions can be converted into vulnerability functions through the employment of a damage-to-loss model (e.g., Yepes-Estrada et al. 2016).

Within this study, the vulnerability functions proposed by Martins and Silva (2018) for regional seismic risk analysis have been employed. These functions were developed following an analytical approach. In this process, a large set of single-degree-of-freedom (SDOF) systems per building class were tested against a set of ground motion records using nonlinear time history analysis. This approach covered the three main sources of uncertainty in vulnerability modeling: building-to-building variability, record-to-record variability and uncertainty in the damage criterion.

The SDOF systems were defined using experimental data, information from technical reports (e.g., past European projects), the outcomes from the PAGER-WHE project, and the findings from existing literature (e.g., Erdik et al. 2003; Kappos et al. 2006; Borzi et al. 2008; Silva et al. 2014). The derivation of the fragility and vulnerability functions was performed using the Risk Modelers Toolkit (Silva et al. 2015) of the GEM Foundation, which uses the open source structural analysis software OpenSees to perform the nonlinear dynamic analysis.

Additional details regarding the structural modeling, uncertainty propagation and selection of the ground motion records can be found in Martins and Silva (2018). All of the input models and datasets are also accessible at a public repository at GitHub (https://github.com/lmartins88). Similarly to what was
indicated for the exposure component, also the vulnerability portion of the risk integral is being further improved within the scope of the H2020 SERA project.

5. PROBABILISTIC RISK METRICS FOR THE BALKAN REGION

The seismic risk analysis of the Balkan region was performed using the stochastic event-based calculator of the OpenQuake-engine. Following the recommendations of Silva (2017), a total of 100,000 events with a 1-year duration were generated per branch of the logic tree. For each earthquake rupture in the stochastic event set, a spatially correlated ground motion field is generated, taking into consideration both the inter- and intra-event variability of the ground motion prediction equations (GMPEs).

The ground shaking at each location of the exposure model along with the vulnerability functions assigned to each asset are used to generate the loss ratios for each ground motion field. The final loss is computed by multiplying this ratio by the associated replacement cost. The average annual loss can be obtained by dividing the sum of the economic losses by the total number of 1-year stochastic event sets, while the rate of exceedance for every observed loss $\lambda(L > l)$ can be calculated as follows:

$$\lambda(L > l) = \frac{1}{n} \sum_{i=1}^{j} I(L_i > l)$$

where $I(L_i > l)$ stands for the number of loss values above $l$, and $j$ is the total number of generated losses.

5.1 Average annual losses

The average annual losses (AAL) for the 12 countries considered in this study are presented in Figure 4. It can be observed that at the national scale Greece, Romania and Bulgaria indicate the highest AAL in absolute values, while Bosnia and Herzegovina and Montenegro have the lowest rank.

Figure 4. Average annual losses for the Balkan region and Cyprus.
5.2 Earthquake loss exceedance curves

The loss exceedance curves indicate the probability of exceeding different loss levels for building portfolios and are critical for the development of risk reduction measures. For example, Figure 5 illustrates that for an event with a 200-year return period, Greece has losses over 10 billion USD, while Albania, Bulgaria, Cyprus and Romania have losses between 1 and 5 billion USD. On the other hand, the rest of the countries, Bosnia and Herzegovina, Kosovo, Croatia, Montenegro, Slovenia, Serbia and Republic of Macedonia, present losses less than 1 billion USD for an event with the same frequency.

6. CONCLUSIONS

This study presented a probabilistic seismic risk model for the residential building stock of 12 countries in Southeast Europe at the smallest administrative level, namely: Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Greece, Kosovo, Republic of Macedonia, Montenegro, Romania, Serbia and Slovenia and the three components of seismic risk (exposure, hazard and vulnerability) were described.

The residential building stock of each country was classified according to a set of 143 building classes that account for the main vulnerability attributes that may influence a building’s response during an earthquake: construction material, lateral load resisting system, number of floors, age of construction and the seismic design level. In addition, the model estimates the replacement cost and average built-up area. The datasets used were based on the latest national housing census of each country and will be further refined based on expert judgment from local researchers and practitioners. The exposure model indicated that Greece has the highest concentration of capital in the residential portfolio amongst the 12 countries with a value of around 512 billion USD, followed by Romania, Bulgaria and Serbia, with 245, 237 and 125 billion USD, respectively. It is observed that reinforced concrete and confined masonry are the most common building classes across all the countries, with the exception of Albania, where almost 50% of the buildings are reinforced concrete and a large fraction (~ 30%) is informal construction.
For what concerns the vulnerability component, at this stage the regional functions proposed by the GEM Foundation as part of the global risk modeling effort were employed. The seismic hazard component used the recently released ESHEM13. The probabilistic event-based calculator of the OpenQuake-engine was used to estimate average annual losses and loss exceedance curves. It was identified that Greece has the highest average annual loss and a loss for the 200-year return period of over 10 billion USD. On the other hand, Montenegro presented the lowest average annual loss with a loss for the 200-year return period of less than 150 million USD. It should be highlighted that the aforementioned results do not include losses due to geotechnical or tsunami effects (liquefaction, faulting, slope instability, etc.), but only losses related to ground shaking.

All of the components of this model are preliminary and are currently being modified and improved within the scope of the European project SERA (Crowley et al. 2018).

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8. REFERENCES


