SEISMIC RISK ANALYSIS FOR EXTRA-CARPATHIAN AREA OF ROMANIA, CONSIDERING VRANCEA INTERMEDIATE-DEPTH SOURCE

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ABSTRACT

Given the dramatic aging of civil building stock and the necessity to efficiently design buildings with long duration of use, seismic risk analysis is the solution that leads to an increasing resilience in modern society. Research in this field will help for a better understanding of the major earthquake impact and to set priorities for earthquake mitigation.

Seismic risk in Romania is one of the highest in Europe, due to the high rate of occurrence of destructive earthquakes near a dense populated area with significant high vulnerability buildings.

The extra-Carpathian area is the most populated area in Romania - approximately 14.5 million people live here (more than 70% of total population). Large cities, such as Bucharest (2 million inhabitants), Constanta, Iasi, Craiova, are located in this area.

In this paper, we applied different recently developed analytical methods and techniques for the estimation of potential seismic losses in the extra – Carpathian area. As a basis for these computations we used the available information on seismic hazard and vulnerability of buildings as well as the analysis of strong historical events effects.

For the seismic hazard, in order to provide a balanced input that can reflect different damage states in the risk analysis we used beside specific ground motion prediction equations (Sokolov et al., 2004 [11] and Sokolov et al., 2008 [12]), data from microzonation studies (Marmureanu et al, 2010 [13]) and real data recorded for March 4, 1977, August 30, 1986, May 30 & 31, 1990 and October 27, 2004 events.

Data obtained from the DACEA Project (Danube Cross-border System for Earthquake Alert) [4] is used to describe the vulnerability of the built environment, including 48 main building typologies with associated capacity and fragility curves.

For the building's damage assessment, we used methods like the Modified Acceleration-Displacement Response Spectrum Method (MADRS) and the Improved Displacement Coefficient Method (I-DCM) that are included in the SELENA open-source software [8]. The spectral content of the records is taken into consideration by using peak ground acceleration values and spectral acceleration values at 0.3 and 1 seconds. The resolution of the seismic risk analysis is at administrative

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unit level (commune or city). The population casualty estimates are computed through the basic HAZUS methodology [15].

INTRODUCTION

Romania is a country affected periodically by strong earthquakes. Over the time, a significant number of events has been observed and documented, in written archives or earthquake catalogues. The present day catalogue of the National Institute for Earth Physics (Romplus, Oncescu et al, [10]) contains earthquakes since 984 updated to the present, with 38 events with $M_w > 7$. With one exception, all the events are originating in the Vrancea area, which can be well distinguished in Figure 1, at the curvature of the Carpathian Mountains, where the East European Plate and the Intra-Alpine and Moesic Subplates are in contact (continental collision). Vrancea seismic source presents a high concentration of events in a well-defined volume located at intermediate depth ($60 < h < 200$ km), and statistically 2-3 events with damaging effects ($M_w > 7.0$) are generated each century (Radulian et al., 2000 [9]).

![Figure 1: Epicenters of the earthquakes in Romplus Catalogue with moment-magnitude $\geq$ than 3. Vrancea area is easily identified and the total number of earthquake produced in this area is more than a half of the total number of earthquakes in the catalogue [13].](image)

The major earthquakes in the last century (October 6, 1908, $M_w=7.1$; November 10, 1940, $M_w=7.7$; March 4, 1977, $M_w=7.4$; August 30, 1986, $M_w=7.1$; May 30, 1990, $M_w=6.9$ and October 27, 2004, $M_w=6.0$) showed systematically stronger effects in the extra-Carpathian area, in contrast with the effects observed in the inner Carpathian area (on the Intra-Alpine Subplate).

The earthquake on March 4, 1977 ($M_w=7.4$) was one the most damaging events that affected this area. In Romania, a high number of human casualties were recorded: 1,570 deaths and over 11,300 injured. The total number of the buildings that were destroyed and seriously damaged was 33,000 and 182,000 had lesser damage. The total cost of damage was over 2 billion US dollars (Balan et al., 1984 [1]).
INPUT DATA AND METHOD

The goal of this paper is to analyze the seismic risk and its elements: seismic hazard and vulnerability. For hazard, to have a proper input for the analysis of seismic loss, it was necessary to generate maps in terms of peak ground acceleration (PGA) and spectral acceleration (SA) for 0.3 and 1 second periods for different major earthquakes with damage potential.

Within the BIGSEES Project [2], a comprehensive waveform database was compiled from various sources (accelerometers in the networks of National Institute for Earth Physics (NIEP), National Institute for Research and Development in Construction, Urban Planning and Sustainable Spatial Development “URBAN-INCERC” and Technical University of Civil Engineering Bucharest (UTCB) with recordings of major Vrancea earthquakes. This database allowed a reconsideration of the ground motion parameters, enhancing the previously processed ShakeMap simulations at NIEP. However, because the density of the stations was still unsatisfactory, a ground motion prediction equation (GMPE) had to be used for distant points.

In order to better preserve the real recordings at the seismic station sites and around them, we tried a different approach to the biasing procedure of ShakeMap. We created a 0.2 decimal degrees buffer around each station, and then we interpolated the GMPE’s proposed by Sokolov et al. (2004) [11] and the real recordings through the Inverse Distance-Weight Method. The resulted raster was used for extracting values directly at each loss assessment point (geounit), making the ShakeMap grid format unnecessary.

The prediction equations of Sokolov et al. 2004 [11], for PGA, PGV, SA and MSK intensity, were constructed using the stochastic technique on the basis of the regional Fourier amplitude spectrum (FAS) source scaling and attenuation models, and the generalized site amplification functions. This model is described in a GEM report (Douglas et al. 2011[5]) as the only one that “passes the selection criteria of Cotton et al. (2006) [3] for areas of deep focus non-subduction earthquakes’. The Sokolov equations come in two forms: for mean and mean+1, the last one providing an estimation of the upper boundary of PGA values. After making the comparison between the real data and data obtained through GMPE’s of Sokolov et al. (2004) [11], we noticed that the real data are a mean between mean and mean+1.

In this analysis we used real data recorded for four events with $M_w \geq 6$: August 30, 1986, $M_w = 7.1$; May 30, 1990, $M_w = 6$ and October 27, 2004, $M_w=6.0$ (see table 1).

For the maximum possible earthquake that can be produced in Vrancea intermediate-depth source, we took into consideration those proposals made by Marmureanu et al. (2010) [13] and Cioflan (2006) [14], that the next big earthquake can have the magnitude $M_w=7.8$ and depth 120 km. For Peak Ground Acceleration (PGA) we combined the Sokolo’s GMPE (Sokolov et al. 2008 [12]) with the real recordings from accelerometers (represented with white triangles), for the 1986 and 1990(1) earthquakes (figure 2). For the 1977 and maximum possible earthquakes the PGA was calculated using the proper form of the Sokolov’s GMPE (figure 3).

Table 1: Description of the hazard data used in this study

<table>
<thead>
<tr>
<th>Event</th>
<th>Magnitude (Mw)</th>
<th>Depth (km)</th>
<th>Hazard data used for obtaining parameters for PGA, SA at 0.3 and 1 seconds</th>
</tr>
</thead>
<tbody>
<tr>
<td>1977 earthquake</td>
<td>7.4</td>
<td>94</td>
<td>Sokolov GMPE’s (average between mean and mean+1 equations, in order to match the only recorded value – 0.2 g in Bucharest)</td>
</tr>
<tr>
<td>1986 earthquake</td>
<td>7.1</td>
<td>131</td>
<td>Real data recorded at accelerometers and Sokolov GMPE’s (mean equation)</td>
</tr>
<tr>
<td>1990(1) earthquake</td>
<td>6.9</td>
<td>91</td>
<td>Real data recorded at accelerometers and Sokolov GMPE’s (mean equation)</td>
</tr>
<tr>
<td>(30 May 1990)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1990(2) earthquake</td>
<td>6.4</td>
<td>87</td>
<td>Real data recorded at accelerometers and Sokolov GMPE’s (mean equation)</td>
</tr>
<tr>
<td>(31 May 1990)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2004 earthquake</td>
<td>6</td>
<td>98</td>
<td>Real data recorded at accelerometers and Sokolov GMPE’s (mean equation)</td>
</tr>
<tr>
<td>Maximum possible</td>
<td>7.8</td>
<td>120</td>
<td>Sokolov GMPE’s (mean+1 equation)</td>
</tr>
<tr>
<td>earthquake (Marmureanu</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>et al. 2010 [13] and</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cioflan, 2006 [14])</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
In the DACEA Project [4], a near real-time system for estimating the seismic damage in the Romanian and Bulgarian cross border region was developed and implemented at NIEP. This system, which started to operate in 2011, is based on the open-source software SELENA (SEimic Loss Estimation using a logic tree Approach, ©NORSAR) together with a direct link to the ShakeMap system.

SELENA is a multi-hazard risk assessment tool that has been developed during the SAFER Project (Seismic Early Warning for Europe) [16]. This software is based on the HAZUS (©FEMA) [15] methodology and is using new analytical methods (MADRS, I-DCM) [3].

SELENA computes the probability of damage in each one of the four damage levels (slight, moderate, extensive, and complete) for the given building types.

The basic idea behind SELENA and all analytical software, like HAZUS and its derivates, is that any building (generally defined as a single degree of freedom system - SDOF) is structurally damaged by the displacement and not by the acceleration itself. For each building, the inter-story drift is a function of the applied lateral force that can be analytically determined and transformed into building capacity curves, based on yield or ultimate points (Erduran et al., 2012 [6]). A performance point, generally defined by the spectral displacement coordinate of the intersection between the median capacity spectrum and the median inelastic demand spectrum in ADRS format (figure 4), is used to further translate the building behavior into probability of damage. For this, fragility functions (curves) are developed based on observed behavior of the structures in real situations or after
computer-based analysis (numerically simulated seismic response). Usually, the damage is characterized by specific damage states, like none, slight, moderate, extensive and complete (as in FEMA, 2004 [15]). For each building typology, a specific damage probability is obtained by plotting on the fragility functions the spectral displacement coordinates of the performance point.

Figure 4: General schema of capacity-spectrum method workflow, in order to obtain probabilities for a building to be in a certain damage state (FEMA, 2004)

The analytical methods used in this study for obtaining building damage estimates were the Modified Acceleration-Displacement Response Spectrum Method, type 2 (Stiffness Degrading Model) (MADRS2), and the Improved Displacement Coefficient Method (IDCM), because of their recent development and slightly different approach.

For defining the vulnerability of the buildings in the southern counties of Romania, a specific database was collected and processed by NIEP and UTCB, together with the NORSAR Institute. Vulnerability curves for each building typology were defined, according to the SELENA requirements. In table 2, it can be seen what curves were associated to what type of buildings, depending on construction material, height and construction year.

Table 2: Structure of the buildings database and associated vulnerability curves (48 in total)

<table>
<thead>
<tr>
<th>Construction material</th>
<th>Material Code</th>
<th>Height class</th>
<th>Construction code</th>
<th>Vulnerability curves</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adobe</td>
<td>M2</td>
<td>L</td>
<td>PC, LC, MC, HC</td>
<td>URM-L-PC</td>
</tr>
<tr>
<td>Unreinforced masonry bearing walls with flexible floors</td>
<td>M3_1</td>
<td>L</td>
<td>PC, LC, MC</td>
<td>URM-M-PC</td>
</tr>
<tr>
<td>Unreinforced masonry bearing walls with rigid floors</td>
<td>M3_2</td>
<td>L</td>
<td>PC, LC, MC</td>
<td>URM-M-LC</td>
</tr>
<tr>
<td>Reinforced or reinforced masonry bearing walls or retrofitted (overall strengthened) masonry buildings</td>
<td>M4</td>
<td>L, M, H</td>
<td>HC</td>
<td>M3-2, M3-4, M3-6</td>
</tr>
<tr>
<td>Wood structures</td>
<td>W</td>
<td>L</td>
<td>PC, LC, MC, HC</td>
<td>W3-PC(LC, MC, HC)</td>
</tr>
<tr>
<td>RC</td>
<td>RC2</td>
<td>L, M, H</td>
<td>PC, LC, MC, HC</td>
<td>C2-1(MH)-PC(LC, MC, HC)</td>
</tr>
<tr>
<td>Concrete frame with reinforced masonry infill walls</td>
<td>RC3</td>
<td>L, M, H</td>
<td>PC, LC, MC, HC</td>
<td>C3-1(MH)-PC(LC, MC, HC)</td>
</tr>
<tr>
<td>Precast concrete walls</td>
<td>RC5</td>
<td>L, M, H</td>
<td>PC, LC, MC, HC</td>
<td>PC5-1(MH)-PC(LC, MC, HC)</td>
</tr>
</tbody>
</table>

Height Class abbreviations: L = Low – 1-2 stories; M = Medium – 3-5 stories; H = High – 6+ stories

Table 2: Structure of the buildings database and associated vulnerability curves (48 in total)

After the end of the DACEA Project, the number of units analyzed was further extended on the Romanian side, comprising now the area represented in figure 4, analyzed also in this study. The database that delivered the building and population data was collected during the 2002 census, and it’s general characteristics can be seen in figure 5 and figure 6.
RESULTS

The results obtained for the extra-Carpathian area using real recordings and using Sokolov’s GMPE’s are presented using two indicators: estimated number of buildings with complete damage (Completely Damaged buildings/Total Number of buildings * 100) and estimated number of severe injuries, which represent a sum of severity grades 3 (severe injuries) and 4 (deaths).

For the earthquake of May 30, 1990 (Mw=6.9), we observed a small difference in the results between the two methods used. We noticed some differences for the North-West area from Ploiesti City: the estimated percentage of buildings that present life threatening damage is between 5-10 percent for MADRS2 and 2-5 percent for IDCM (figure 7 left). For 1986 earthquake, Mw=7.1, the results obtained by the two methods are almost similar and the maximum damage is estimated as expected in the area of Focsani (see figure 7 right).
When we compared the estimated results with the actual losses produced by the 1986 and 1990 earthquakes we observed that the estimations are overestimating the damage (although building database is for a different period), however not very wide. The most appropriate results are obtained using the IDCM methods.

For the 1977 earthquake, $M_w=7.4$, and maximum possible earthquake, $M_w=7.8$, where we used as an input for Selena only data simulated with Sokolov GMPE’s, we observed that the difference becomes more prominent; for entire area the estimated percentage of buildings that present life threatening damage is varying with 10 - 30 percent between the two models (see figure 8).

For estimated number of severely injured people (see figure 9), in case of 1990 and 1986 earthquakes, the damage is very high in the big cities. In reality, 9 people died in 1990 and only two in the 1986 earthquake [17]. That means that the Selena is overestimating the number of the people for these two earthquakes.

Although the building stock is different then and now, the estimated number of deceased person, in SELENA, for the same parameters of the 1977 earthquake (in which ~ 1420 people died) and for the IDCM method is around 1588, with 0.21098 g for Romania capital (see figure 10). These values, although not desirable, seem to be not very far to what happened in 1977.

We also analyzed the seismic risk with hazard input from smaller earthquakes (1990(2) with Mw 6.4 and 2004 with Mw 6.0), but no damage estimates were obtained. This is a good sign that the analysis does not overestimate the damage losses, because in reality none of the buildings suffered damage in these earthquakes. Therefore, no maps for these earthquakes appear in this section.
Figure 9: Maps for the 1990(1) (left) and 1986 (right) earthquakes, showing the estimated number of severely injured people (HAZUS states S3+S4)

Figure 10: Maps for the 1977 (left) and maximum possible (right) earthquakes, showing the estimated number of severely injured people (HAZUS states S3+S4)

CONCLUSIONS

In this study the objective was to test different recently developed analytical methods and techniques for the estimation of loss scenarios and seismic risk computations for the extra – Carpathian area. For this, we used different earthquake scenarios and two different methods for building analysis, included in Selena: IDCM and MADRS.

As a basis for the computations we used most recently available information on seismic hazard and vulnerability assessment of buildings as well as the analysis of historical events for the extra – Carpathian area.

Real data were provided by the reanalyzed recordings for March 4, 1977, August 30, 1986, May 30 & 31, 1990 and October 27, 2004 earthquakes. For the maximum possible earthquake, we used a relevant scenario, with $M_w=7.8$ and depth=120 km, taking into account the proposals made by Marmureanu et al. (2010) [13] and Cioflan (2006) [14]. To obtain a proper input data for Selena, we used Sokolov GMPE’s combined with a Shakemap - like methodology to obtain PGA values and SA values at 0.3 and 1 seconds.

The maps based on real data recorded in earthquakes showed that the estimated percentage of buildings that present life threatening damage are a little overestimated, however not far from what we should expect and be prepared for. The simulations shown that, for earthquake with magnitudes smaller than 7($M_w$), no significant damage is expected to be recorded.
The comparison between the results obtained with Selena and the real damage and casualty, for 4 March 1977 earthquake, shown a very good fit.

In all the cases, the results obtained with IDCM method were smaller and more credible than the results obtained with MADRS, but the difference among them is not so big.

When analyzing in more detail the building typology that mostly influences in the results with the highest damage probabilities are for adobe buildings, which have an important percentage in the total building stock (more than 30%).

Selena provides a more detailed description of the specific population/building typology relation for each geounit and this level of estimation is the most affected by uncertainties and is based on empirical methods and casualty rates (observed in real earthquakes) that are generally applicable.

More detailed results are expected to be obtained by improving the resolution of the database, together with the use of microzonation maps. The characteristics of the census dataset (dating 2002) did not allow a smaller resolution, which we hope to obtain from the newer available detailed data of the 2011 national census.

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