Quantitative Population Loss Assessment: Seismic Scenarios for Bucharest Using 2002 Census Data

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Corresponding Author:
iuliaarmas@yahoo.com
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Iuliana Armas[1], Dragos Toma-Danila[1,2], Radu Ionescu[1] and Alexandru Gavris[3]

[1] University of Bucharest, Romania
[2] National Institute for Earth Physics, Magurele, Romania
3 Bucharest University of Economic Studies, Romania

Abstract

In this research, we calculate the probability and scale of population losses that may occur due to earthquake hazard in Bucharest. Losses are quantified in direct relation to the social vulnerability of people who are exposed to an earthquake event. Social vulnerability is based on index construction, using spatial decision rules to assess weights in a criteria tree using the SMCE-module of Ilwis software. To estimate building vulnerability, we used the Improved Displacement Coefficient analytical method in the SELENA software. For the earthquake loss estimation, we used the percentage of severely damageable residential buildings in each census unit (CU). The population loss estimation for the selected earthquake scenarios was obtained by multiplying the complex social vulnerability index with the estimated ratio of severely damageable buildings, for three selected earthquake scenarios and using the population numbers in each census unit. The maps represent the maximum affected population values, per census unit, in percentages. We provide useful estimates of the scale and severity of injuries, and link these with current levels of medical preparedness. In all scenarios, the CUs forming the Rahova neighbourhood revealed high loss values, due to significant problems in terms of the built environment and social vulnerability.

Keywords:

index construction, Improved Displacement Coefficient analytical method, quantitative loss estimation on urban population, seismic hazard, earthquake injuries

1 Background

One of the largest seismic hazard hotspots in Europe is in Romania: the Vrancea Seismic Source (Figure 1), which is located at the contact between the East-European Plate and the Intra-Alpine and Moesian Subplates, at a bend of the Carpathian Mountains. Since 1900, 4 major earthquakes with moment-magnitude (Mw) ≥ 7 have occurred here, at depths of between 94 and 150 km (NIEP, 2016).

Vrancea earthquakes pose major risks to the densely-populated urban area of Bucharest, located approximatively 130 km from the epicentres of this seismic source. This is due mainly to poor building quality: many buildings are old and do not conform to seismic design codes and standards, but the risk is also due to local effects (such as seismic wave amplification). Bucharest is the EU's most vulnerable capital (Cioflan et al., 2016) in relation to seismic risks and, as such, should be the subject of complex risk-mitigation analyses and effective measures. Paradoxically, databases providing risk-relevant statistic indicators are fairly limited and access to them is extremely difficult, making quantitative loss assessments for Bucharest challenging.

Another challenge is the need to increase resolution for the analysis of losses in an earthquake situation (Lang et al., 2012). In this paper, we contribute towards improving the situation for Bucharest by introducing building vulnerability modelling at census unit level (CU). At this resolution, we work with socio-economic variables, housing quality attributes, hazard maps and building characteristics (structure, materials, age and height), making the analysis relevant at neighbourhood scale.

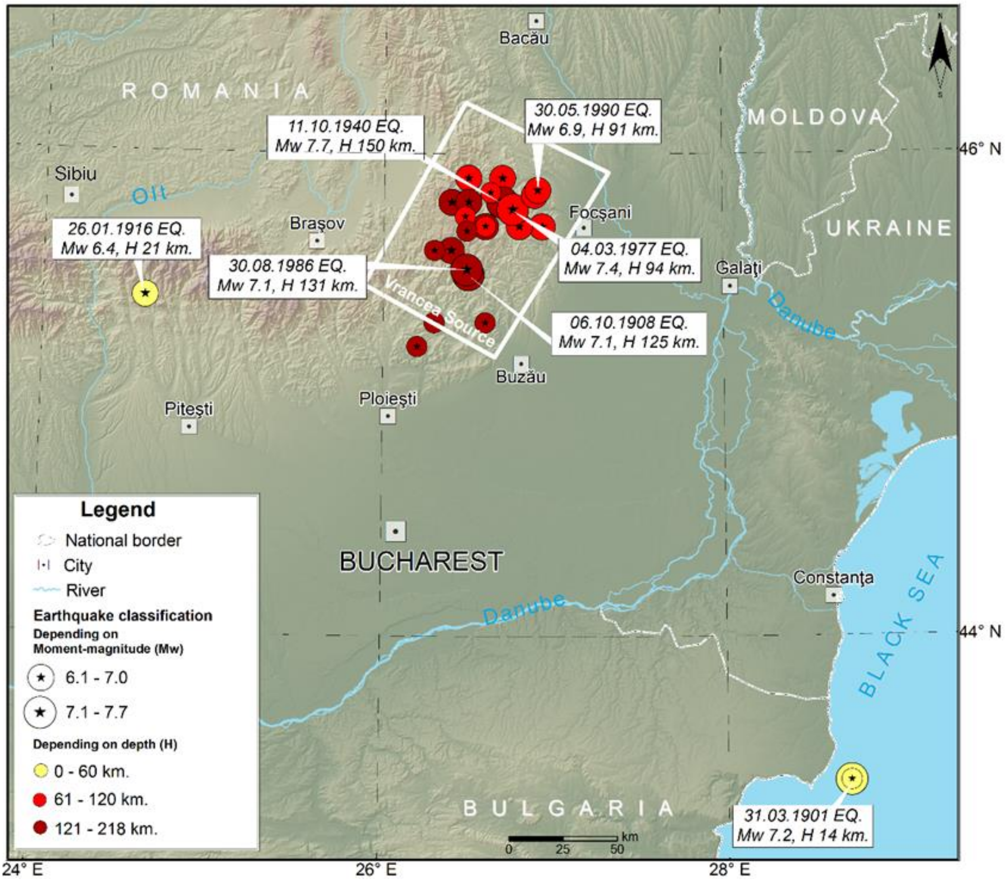

Figure 1: The Vrancea Seismic Source in relation to Bucharest (data source: NIEP, 2016)

We calculated the probability of losses that might occur, for different elements-at-risk, in credible earthquake scenarios. Three different hazard scenarios were used, representing good correspondents for different probabilistic seismic hazard return periods (Table 1). Losses were quantified in direct relation to the vulnerability of the elements-at-risk. In this paper, we focus on people who are exposed to, and could be affected by (injured or killed), an earthquake event. People's vulnerability was understood in a manner similar to the concept of social vulnerability proposed by Blaikie et al. (1994). We assumed that major events can easily destabilize the precarious equilibrium established in areas with high social vulnerability. From this perspective, social vulnerability creates a potential instability that results from a scarcity of resources (material and non-material) identifiable in an area.

Table 1: Hazard scenarios used in the study

Scenario/return period	Mw	Depth (km)	Lat.	Long.	Justification
1. Similar to the 1990 earthquake Return period: 30 years	6.9	91	45.83	26.89	The results can be compared with reality: 2 people died, few buildings were damaged (Georgescu & Pomonis, 2012). We consider this a good scenario for testing the index value at the least dangerous boundary.
2. Similar to the 1977 earthquake Return period: 50 years	7.4	94	45.77	26.76	The results can be compared to the damage implications that were recorded in reality: ~1,424 people were killed and ~7,598 were injured (Georgescu & Pomonis, 2012).
3. Microzonation map of the maximum possible (worst-case) scenario Return period: 475 years	7.8	150	45.8	26.7	The most recent and detailed microzonation map for Bucharest (Marmureanu et al., 2010), based on nonlinear seismic response evaluation to a synthetic signal from a point source with a mechanism similar to the one of the 1940 earthquake (the most powerful earthquake in Vrancea in the 20th century).

Measurement of societal features enabled aggregation of results in a complex social vulnerability index, using spatial decision rules to assess weights in a criteria tree, as described in Armaș & Gavris (2013). We investigated 154 census units covering the entire administrative area of Bucharest, representing 228 km2 (with a CU average of 1.5 km2 and a range of 0.11 to 24.5 km2); the built-up areas represented slightly over 70% of the total CU area. The data included consisted of inventories of population characteristics, economic data, and data on housing conditions (Table 2). (For the detailed methodological steps of index construction, see Armaș & Gavris, 2013.)

Table 2: Indicators used to assess social vulnerability in Bucharest (after Armaș & Gavris, 2013)

Sub-indices	Computed statistical indicators (2002)	Symbol
Social Vulnerability	Ratio of elderly population (over 65 yrs)	N_e
	Ratio of female population in total population	N_f
	Ratio of children (under 5 yrs)	N_c
	Ratio of widows in female population	N_{wi}
	Housing density	N_h
	Average number of wage earners per household	N_{we}
	Minimum level of education	N_{me}
	Women with 3 children or more	N_{w3}
	Ratio of dependent people in total population	N_d
Economic Vulnerability	Ratio of unemployed	N_u
	Ratio of low incomes	N_l
	Ratio of high incomes (women)	N_{hw}
	Ratio of high incomes (men)	N_{hm}
Housing Quality (Security)	Room occupancy per household	N_o
	Average dwelling area in census unit	N_{ra}
	Density of dwelling residents in census unit	N_{dp}
	Average no. of private/owned dwellings with 5 or more rooms on census unit	N_{05}
	Average room area per person in census unit	N_{pa}

The population loss estimation was calculated by multiplying the complex social vulnerability index with the estimated ratio of severely damaged buildings for the selected earthquake scenarios and with the total number of people living in a census unit.

For the estimation of building damage (residential buildings only), we used a procedure previously applied within the Near Real-Time System for Estimating the Seismic Damage in Romania (SeisDaRo) and described in detail in Toma-Danila et al. (2015a). We relied on the SELENA open-source software (Molina et al., 2010), on the Improved Displacement Coefficient analytical method, on the IBC2006 demand spectrum, and on census data with information regarding building construction materials, height and construction period, reclassified according to the SeisDaRo specifications (and therefore associated with 48 individual capacity and fragility curves). The methodology had previously been applied successfully for Bucharest, but for analysis at the level of local administrative areas (sectors) (Lang et al., 2012; Toma-Danila et al., 2015b).

For the consideration of hazard, we used the three scenarios presented in Table 1. For the quantification of earthquake loss estimates, for this study we used only the percentage of severely damaged buildings out of the total number of buildings in each census unit ('severely' in this context means 'completely destroyed', as defined within SELENA; otherwise, results seem to be overestimated).

For each census unit, we calculated the maximum affected population value (i.e. people killed or injured) as a percentage. The ratio of mortality to morbidity is particularly important for assessing the strain on those systems responsible for post-disaster intervention. This ratio is generally expressed as the index R = 100*D/I, which for one death (D) for every three injured (I) would be R = 33.3. The 1:3 ratio holds for earthquakes in the 6.5–7.4 range on the Richter scale. Higher intensities provoke more serious damage and the ratio tends to increase, with the number of injured nearing that of those killed (Alexander, 1985). Given that two of our scenarios fall within the 6.5–7.4 range, giving a 1:3 ratio, we used this to look in further detail at how many deaths and injuries could occur, and what this would entail for emergency and medical services. In line with the reasoning above, for the worst-case scenario we decided to use a 1:1.5 ratio.

Not all injuries require the same level of attention and resources, and it should be noted that there is considerable variation for the ratios of different-severity injuries of people affected by severe earthquakes. In general, a breakdown would point to: Fatalities (20–30%), Injuries requiring first aid/outpatient treatment (50–70%), Injuries requiring hospitalization (5–10%), and Injuries requiring major surgery (1–2%) (Coburn & Spence, 2003). Drawing on these numbers, if we focus just on the injuries we can extract two scenarios: one of lesser severity (first aid 90%, hospitalization 9%, and major surgery 1%), and one of greater severity (first aid 85%, hospitalization 12%, and major surgery 2%).

The spatial aggregation of losses at census level was examined using the Geoda software (Anselin et al., 2006). This software allowed us to explore the spatial self-correlation characteristics of the possible losses indicated by the proposed scenarios, and therefore to identify areas where the elements targeted by analyses clustered. Subsequently, these clusters were statistically evaluated to determine whether their spatial distribution was random or the result of the particular variable selected.

2 Results

Simulations of the physical environment component revealed different loss scenarios at population level. In the loss analysis, we took into consideration only buildings that would be seriously damaged in each of the three earthquake scenarios. The spatial distribution of buildings that would be severely damaged in these scenarios underlined the differences in losses at population level, for different areas. The results of spatially associating the losses gave us a Moran score ranging between 0.39 and 0.76 (Figure 2). This suggests that the distribution of the clusters is not random, with building vulnerability characteristics influencing the losses significantly. We interpreted this spatial association as resulting from the historical building patterns of the built environment.

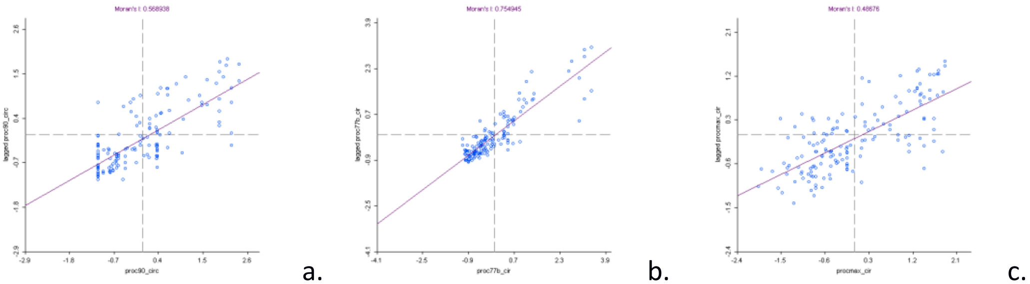

Figure 2: Moran's I Scatterplots for losses (%) in (a) the 1990 earthquake scenario; (b) the 1977 earthquake scenario; (c) the worst-case earthquake scenario

The CUs showing associations of the various loss components differ from one scenario to another, yet there are common hotspots. CUs in the Rahova neighbourhood, in the west of the city, are present in all scenarios as having significant problems in terms of the built environment. This is also an area of low income and educational level, high birth rate, and a high number of socially assisted individuals (Armaș & Gavris, 2013) (Figure 3). The physical environment of Rahova is characterized by apartment blocks built with medium to low levels of comfort in mind, alongside numerous houses with rural characteristics which have survived the city's expansion. The scenario for 1977 shows that the highest concentration of spatially-associated human losses occurred in the Rahova area (Figure 4). Other areas with high loss values, such as Giulesti-Sarbi, Crangasi and Bucurestii Noi, are also defined by a combination of many vulnerable buildings (low-quality buildings built prior to the 1977 earthquake) with high social vulnerability.

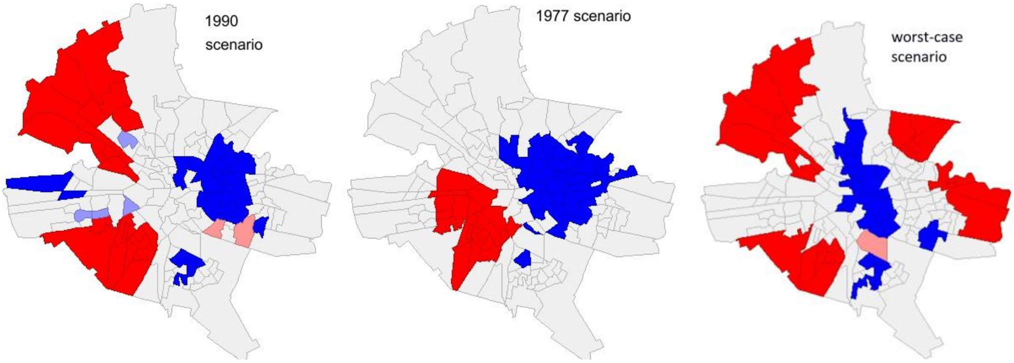

Figure 3: LISA cluster maps for the three earthquake loss scenarios; red clusters are vulnerable while blue clusters are resilient.

The association of resilient zones is characterized by numerous differences across different hazard scenarios. The picture that emerges from the scenarios is that areas in sectors 2, 3 and 4 seem least likely to suffer major losses. For different scenarios, the resilient clusters stretch north and east from the central area.

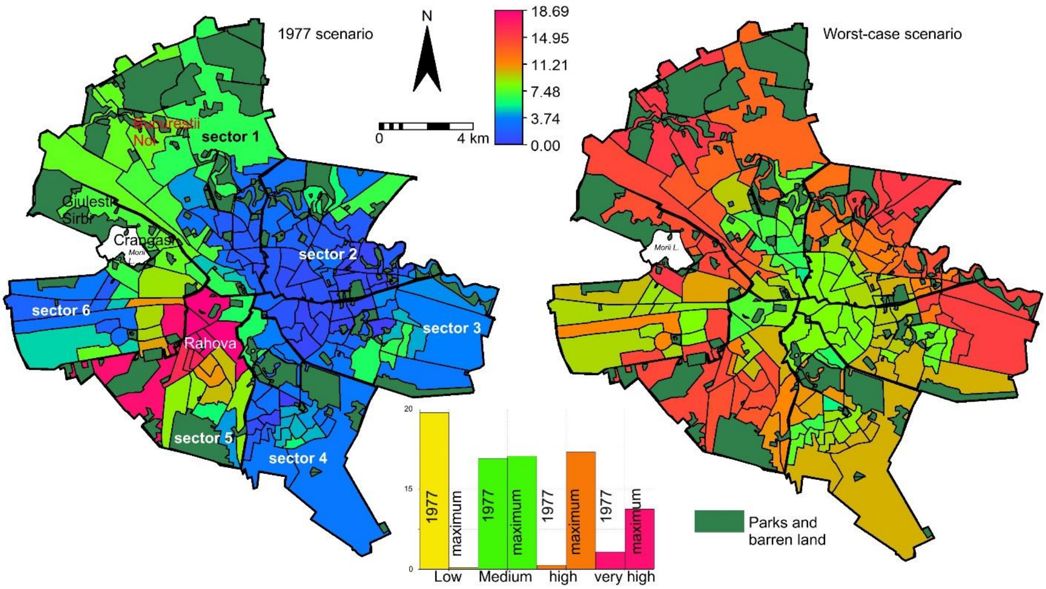

Figure 4: Spatial distribution of losses for the 1977 and the worst-case earthquake scenarios

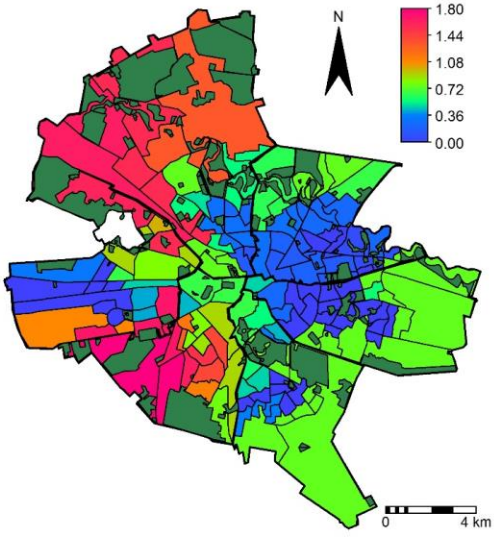

Figure 5: Spatial distribution of losses for the 1990 earthquake scenario

Preparations for an earthquake affecting Bucharest need reasonable forecasts of the number and condition of the victims. We have therefore drawn on a ratio of one death for every three injuries requiring attention for scenarios one and two, and a ratio of one death for every 1.5 injuries in scenario three (worst-case). We found that while the number of deaths in the 1977 scenario would be considerably lower than in the worst-case scenario (25,000 as opposed to 81,000), the number of injured people would be very difficult to manage, at 76,000 (Figure 6).

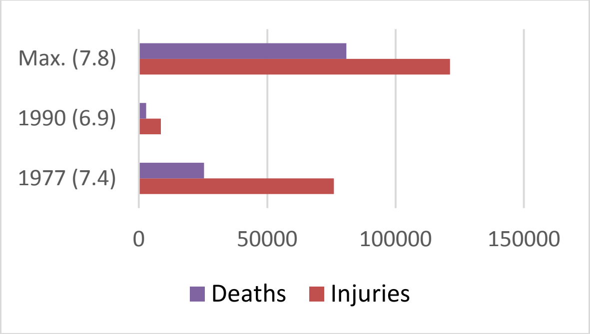

Figure 6: Numbers of deaths and injuries across scenarios

We also looked at the types of injuries and what they would entail for the hospital system. Considering that the Bucharest-Ilfov region has around 17,874 hospital beds, with a usage of 80.1%, on a typical day there will be approximately 3,557 hospital beds available (Health Ministry, 2013). While having empty beds is generally perceived as inefficient health management, bed availability is of direct significance in managing post-disaster hospitalization. The findings are summarized in Table 3. An earthquake similar to that of 1990 would be manageable from a health perspective. Even in a more severe scenario, where there is a greater proportion of people in need of hospital treatment, there would be about 1,200 people requiring a hospital bed. Again, the number would be manageable. The same cannot be said for the other two scenarios, irrespective of their injury severity ratios. For the worst-case scenario, we estimate around 17,000 people requiring hospitalization. This is slightly less than 5 times the number of beds available. Even the less severe pairing (1977 values, with lower proportion of serious injuries) would still require hospital attention for 7,500 people – double the availability.

Table 3: Numbers and types of injuries across six scenarios described by earthquake intensity and severity of health impact

	Scenario	1990 (Mw 6.9)	1977 (Mw 7.4)	Worst-case (Mw 7.8)
	Injuries	8,558	76,015	121,210
Less Severe Injuries (90/9/1)	First aid	7,702	68,413	109,089
	Hospitalization	770	6,841	10,909
	Major surgery	86	760	1,212
More Severe Injuries (85/12/2)	First aid	7,274	64,613	103,029
	Hospitalization	1,027	9,122	14,545
	Major surgery	171	1,520	2,424

A dense urban environment has complex characteristics which make it particularly vulnerable to earthquakes. We therefore wanted to see whether the Socio-Economic Vulnerability Index was related to the number of people in each CU. There was a positive correlation between the two variables, r = 0.216, n = 154, p = 0.007. Interestingly, if we examine the scatterplot below (Figure 7), we find that this correlation pertains, by and large, until the population reaches about 13,800 per CU, or a socio-economic vulnerability index of around 0.55. Once vulnerability increases beyond 0.55, the relationship between it and the size of the population for that CU disappears. To further test this, we compared how well the two correlate for CUs with a vulnerability of 0.55 and under, and for those with higher vulnerability. We observe a reasonably strong correlation (r = 0.481, n = 61, p = 0.001) for the ones with an index of 0.55 or under, and no correlation over 0.55.

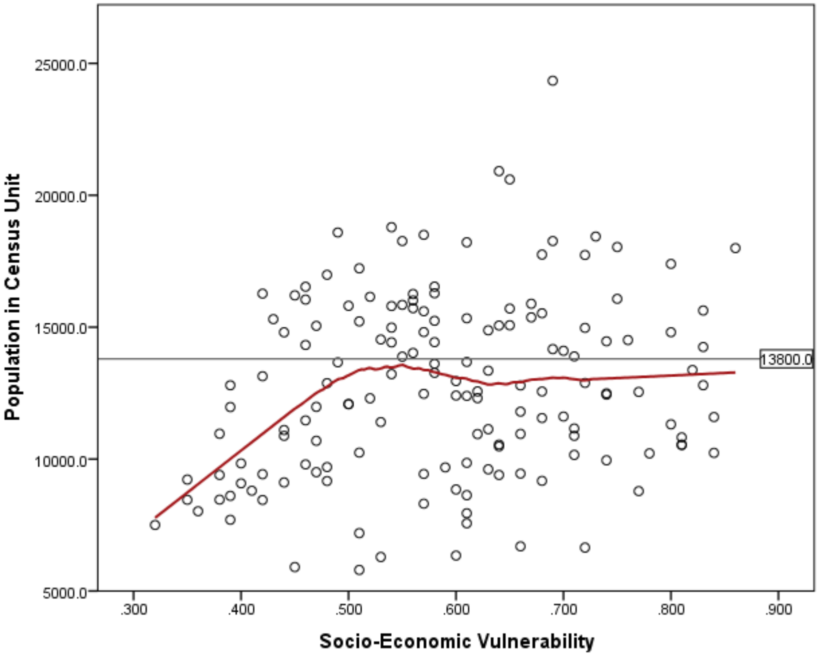

Figure 7: Relationship between socio-economic vulnerability and population size

The way the intensity of a possible earthquake manifests itself across individual scenarios is crucial in identifying high-loss areas. The scenarios show us that we need to take into account not only the resulting clusters but also the conditions found at local CU level. Inconsistencies between scenarios were signalled by Lang et al. (2012). It is precisely these inconsistencies that need to drive future analyses and further scenarios running the latest census data.

3 Conclusions

This paper detailed a quantitative analysis of human losses across three seismic hazard scenarios as a function of social and physical environment vulnerability. We focused on Bucharest and the data provided by the 2002 census in relation to three earthquakes of different magnitudes (the earthquakes of 1977 and 1990, and the worst-case scenario for Bucharest). Multi-criteria and analytical methods, with a focus on spatially-associated losses, show good results and can be drawn on for further similar estimates. Correlation of our results with those of other studies combined with the observation of similarities between clusters could help to foresee potential significant problems in case of future earthquakes. High-loss clusters coincide, as expected, with many densely populated areas. These results clearly indicate the need for future analyses in order to develop risk-mitigation plans. We further need to establish priority zones to limit estimated losses and improve decision making.

The spatial distribution of losses suggests a need for more variables to be included in the model. Our analysis was limited by the socio-economic variables that could be extracted from the 2002 census. At the same time, if capacity curves and fragility functions customized to the construction practice of an individual region (here Bucharest) are unavailable, any earthquake damage and loss study has to rely on alternative functions selected by expert judgement. It will be a major task for future damage and loss assessment studies for Romanian cities to develop damageability functions that are customized to local building conditions.

However, the work presented here illustrates the feasibility of creating pilot projects aimed at reducing the number of future earthquake victims, irrespective of an earthquake's magnitude. This paper underlines the need for multi-disciplinary approaches to scenario evaluation and for deterministic earthquake damage and loss assessments at increasingly local level, in order to better identify the conditions that lead to worsening losses in the complex urban environment.

Acknowledgments

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