CrossMark

ORIGINAL RESEARCH PAPER

Insights into the possible seismic damage of residential buildings in Bucharest, Romania, at neighborhood resolution

Dragoş Toma-Danila[1,2] · Iuliana Armaş[2]

Abstract Seismic loss estimation analysis for large cities is a very demanding yet necessary task; the modelling of such complex systems requires first of all insightful input data at good resolution, referring to local effects, buildings and socio-economic aspects. Also, the implementation of less empirical estimation methods is needed. Until recently, these requirements could not be fulfilled for Bucharest, the capital city in the European Union which is most at risk due to earthquakes. Based on 2011 and 2002 census data, standardized according to the framework of the Near-real time System for Estimating the Seismic Damage in Romania (SeisDaRo) through a unique approach, and on relevant hazard scenarios, we estimate for the first time the building damage at census tract scale. The methodology applied relies on 48 vulnerability curves for buildings, on the Improved Displacement Coefficient Analytical Method included in the SELENA software for computing damage probabilities and on deterministic seismic hazard scenarios, including the maximum possible earthquake. By using overlay analysis with satellite imagery and a new methodology integrated in GIS we show how results can be enhanced, reflecting more localized characteristics. Best practices for seismic risk mapping are also expressed. The results are promising and contribute to mitigation efforts in Bucharest.

Keywords Seismic loss estimation · Urban risk · Building vulnerability · Bucharest · Vrancea earthquakes

1 Introduction

The effects of earthquakes on big cities like Kobe (The Great Hanshin earthquake, 1995), Istanbul (Izmit earthquake, 1999), Bam (Bam earthquake, 2003), Port-au-Prince (Haiti earthquake, 2010) or Kathmandu (Nepal earthquake, 2015) revealed that cities are hotspots

✉ Dragoş Toma-Danila
toma@infp.ro

[1] National Institute for Earth Physics, Magurele, Romania

[2] Faculty of Geography, University of Bucharest, Bucharest, Romania

for disasters and also significant differences (both in terms of ground motion and damage) can be noticed from one area of a city to another. Explaining the cause of this difference and modelling the possible effects of future earthquakes is of major interest and is the goal of urban seismic risk analysis. The main problems in analysis at urban level is the poor understanding and expression of the local effect implications (soil amplification, lique-faction, etc.), the means to quantify seismic vulnerability for multiple buildings at once, the lack of detailed statistical data at a high resolution or the modelling methods for such complex systems, with multiple dependencies. It is clear that as urban areas continue to develop, the risk growth is directly proportional (Chang et al. 2012); urbanization (de-termining rapid and many times careless growth of urban areas) and population growth lead to a greater exposure to natural hazards, and without urban seismic risk analysis, much required mitigation actions can not be effective.

In the field of study, one of the major breakthroughs was the development of analytical methods (Molina et al. 2010) like the Capacity-Spectrum Method and their implementation within the HAZUS software, first version being released in 1997. These methods enabled a refined, less empirical modelling of the buildings' seismic behavior (Erdik et al. 2014) and a better consideration of the influence of ground motion parameters; intensity was replaced by acceleration, as seismic parameter. The HAZUS methodology showed a more consistent way of analyzing loss estimates and risk at urban scale, as long as detailed enough data regarding building characteristics (depending on key parameters like construction material, period or height), occupancy and economic aspects can be provided (Silva et al. 2015). The fact that HAZUS was intimately related to the USA specifics and dependent on ArcGis software (acknowledging the role of GIS in the analysis, as tool for considering the spatial dimension) was later compensated by the development of other seismic loss estimation software, with added capabilities (more analytical methods, consideration of other seismic design regulations like Eurocode8), customizable, and with fewer dependencies. Among these software instruments we mention CAPRA, DBELA, ELER, MAEViz, OpenQuake, OPENRISK or SELENA. A detailed comparison between most earthquake loss estimation software packages can be found in Lang (2012), Daniell (2011) or Strasser et al. (2008).

In the last two decades seismic loss estimation methodologies and tools have evolved considerably (significant advances were made in modelling more comprehensively the seismic behaviour of buildings due to seismic action). However, due to the difficulty of obtaining detailed enough datasets at a resolution capable of revealing differences from one neighbourhood to another, not many urban studies at within city scale are available worldwide. Among the published studies we mention Bharwani (2014), Boukri et al. (2014), Eleftheriadou et al. (2014), Lang et al. (2012), Mansouri et al. (2010) or Bal et al. (2008). For each of these studies, the applied methodologies had to be specific, due to the characteristics of the hazard and vulnerability data. Another problem is, in many areas, the lack of vulnerability functions for regionally characteristic buildings.

Through our study we aim to estimate the seismic building damage of Bucharest, capital of Romania, a city with 2 million inhabitants that can be considered the most endangered capital in Europe due to earthquakes (modified statement from Barlakowski et al. 2006, where Istanbul is mistakenly considered as capital) and in the European Union (Fig. 1). Bucharest was and will be affected by earthquakes, as hazard studies at global and regional scale like Giardini et al. (2003, 2013) and Jimenez et al. (2001) show. The main seismic source that can affect the city is Vrancea Source Zone (Fig. 1), where intermediate-depth earthquakes with moment-magnitudes (Mw) of up to 7.7 occur, at a statistical rate of 2–3 events with Mw > 7 per century, as shown by the Bigsees Catalog (NIEP 2016).
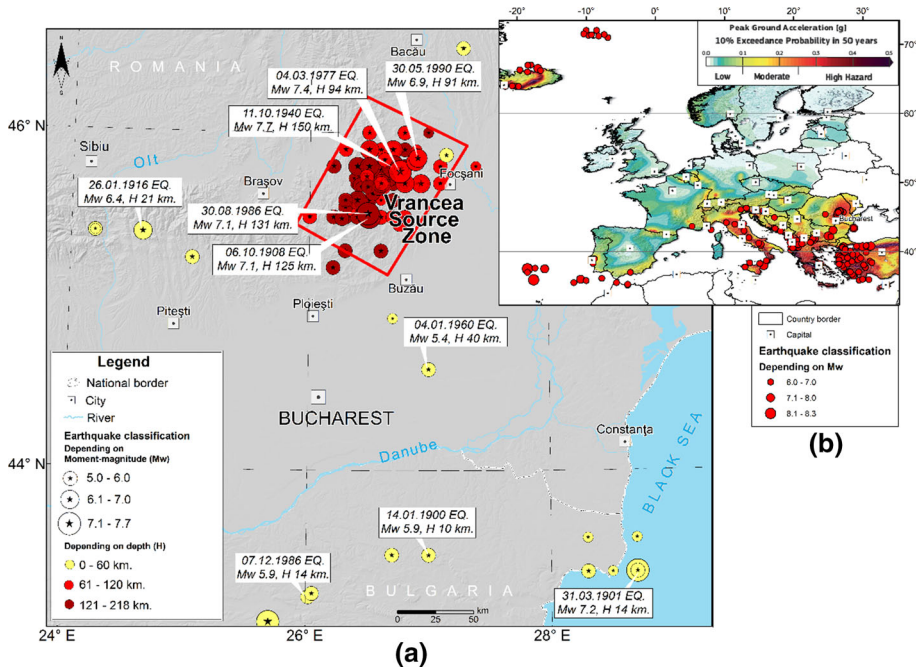
Fig. 1 Maps showing the exposure of Bucharest to earthquakes: **a** epicenters for earthquakes with Mw ≥ 5, between 1900 and 2014, according to Bigsees Catalog (NIEP 2016) **b** overlay of the Share Project hazard map (Giardini et al. 2013), earthquakes according to the Sheec Catalog (Grünthal et al. 2013) and European capitals

One of the particularities of the Vrancea Source Zone is the fact that it produced earthquakes in the past that were able to cause considerable damage over a wide area (for the 1940 earthquake, MSK intensities of IX for Bucharest and greater than VI, 300 km away from the epicentre) especially towards NE and SW (Georgescu and Pomonis 2012); Bucharest is located SW of the source (120–170 km epicentral distance), and it has experienced ever increasing losses, as can be seen in Table 1. The city itself is located on thick quaternary sediments with thicknesses down to 300 m caused by the presence of the Dambovița and Colentina rivers crossing the city. The soft near-surface soil materials have a clear impact on local soil amplification effects (Bala 2013). Since many major cities are built on soft soils, caused by the need for water resources, local seismic site effects have to be in general a fundamental component of the urban risk analysis. Besides seismic hazard variability from various city areas, vulnerability also plays a significant role. Historically, most damage has occurred in the city centre, where many old, medium and high rise buildings collapsed due to construction flaws (no seismic design considerations, inadequate construction materials). Due to the challenging political situation of the times when the 1940 and 1977 earthquakes occurred, we still don't know what the true damage extent on smaller houses was—there is no available map with complete damage on buildings to compare with our simulations. Nevertheless, we compiled from various data sources (such as earthquake reports) a map with medium and high rise buildings that were affected during the 1940 and 1977 earthquakes (Fig. 2).

Previous loss estimation studies for Bucharest were performed. The most recent and relevant ones used analytical methods (Lang et al. 2012; Toma-Danila et al. 2015a),

Table 1 Casualties produced by Vrancea earthquakes in the twentieth century (modified from Georgescu and Pomonis 2012)

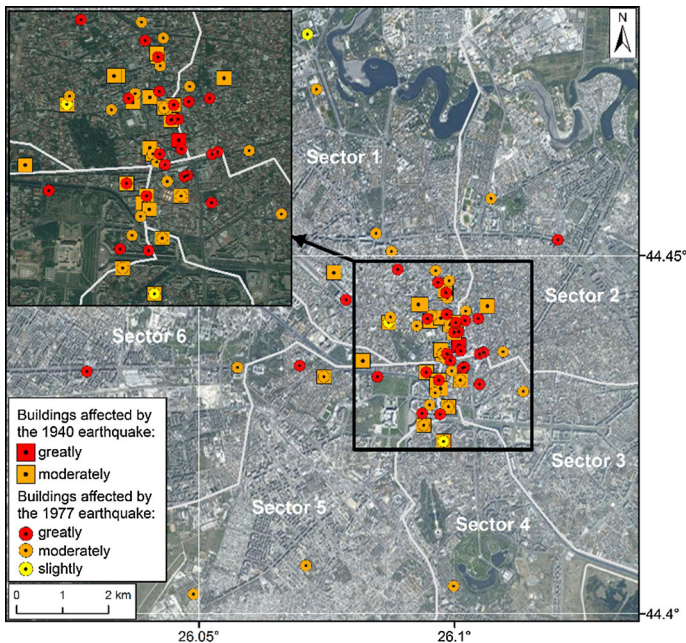| Earthquake	Local hour	Lat	Lon	Mw	Depth (km)	Epicentral/ hipocentral distance to Bucharest (km)	Damaged homes	Fatalities (total)	Fatalities (only in Bucharest)
1940.11.10	03:39	45.8	26.7	7.7	150	225/270	60,000	593	140
1977.03.04	21:22	45.77	26.76	7.4	94	223/242	35,000	1578	1424
1986.08.31	00:28	45.52	26.49	7.1	131	177/220	55,000	8	
1990.05.30	12:40	45.83	26.89	6.9	91	237/254		9	2

Fig. 2 Map of the buildings and monuments in Bucharest, affected partially or completely by the 1940 and 1977 earthquakes

however they were limited to the 6 sectors of the city and they used statistical data from up to 1999. For this study, recently collected census data from 2011 was used, at census tract (CT) level (128 CTs for all Bucharest), reclassified according to the specifications of the Near-real time System for Estimating the Seismic Damage in Romania—SeisDaRo (Toma-Danila et al. 2015b). In the same manner the census data from 2002 (for 154 CTs) was also analysed, allowing a good comparison. In order to consider the influence of local site effects, earthquake scenarios relying on strong motion recordings were chosen and, for the maximum possible, a scenario based on a new microzonation map published by Marmureanu et al. (2010) was chose. As building loss estimation analytical method we used the Improved Displacement Coefficient Method (IDCM). By combining multiple

approaches from seismology, earthquake engineering, statistics and geography, we were able to map Bucharest city areas that can be affected more or less by strong earthquakes, leading therefore to better targeted mitigation actions. The study presents an example of applying recent seismic loss estimation methods to urban environments and also provides new ideas on how missing data can be approximated through the use of expert knowledge and spatial analysis, how uncertainties can be considered or how GIS can be used to refine the analysis. The results of the study are of great interest for disaster management authorities, scientists and the population in Bucharest. The overall methodology and the way GIS was used is also of great interest for other studies at urban scale, regardless of the region and vulnerability database characteristics.

2 Methods and data characteristics

2.1 Modelling building behaviour

In all societies, the main concern regarding the impact of earthquakes refers first of all to the impact on human lives. Considering that most people are not directly affected by the ground motion, but rather by the failure of buildings they live or work in, it is evident that any urban seismic risk analysis has to comprise the evaluation of building damage probability.

When it comes to analysing a certain building, different methods can be applied: push-over analysis, computer modelling and testing, shake-table tests, sensor monitoring, vibration analysis, etc. These all can offer a detailed insight into the seismic behaviour of the analysed building, however they are time and cost consuming, and an analysis at city-scale would be impossible through a building by building approach. Giving that almost every building is different, the analysis of, for example, each of the 31,430+ residential buildings in Bucharest (according to the 2011 census) that were constructed before any seismic code (before 1945), just cannot be an option. Table 2 reveals the current progress of the individual building evaluation. This table shows only a glimpse of what the damage might be after a major earthquake.

The development of analytical methods and the integration within earthquake loss estimation tools provides a means of simplification to the quantification of building loss estimates, having as starting point statistical data. Although the damage estimates can be rough, being obtained based on vulnerability functions that simplify the behaviour of buildings representative for a certain typology (therefore not recommended for small areas or individual buildings), they can reveal the possible general trend right after an earthquake

Table 2 Number of Bucharest residential buildings individually evaluated by experts in order to establish their seismic risk class (*Data source*: Bucharest General Municipality 2016)

Category	Total number	Built until 1945	Built between 1946 and 1977
Individually evaluated buildings	824	700	121
Buildings (still) in the seismic risk class I (most vulnerable)	354	340	14
Buildings that were consolidated	69	68	1

or simulated scenario, and are therefore very useful for emergency intervention, mitigation and planning purposes. The roughness of loss estimation can derive also from the number of building typology classes selected or from the spatial resolution of the statistical data.

The analytical methods are considered performance-based engineering methods that rely on nonlinear static analysis procedures for prediction of structural demands. They essentially involve the comparison of the capacity of a structure, modelled as a single degree of freedom system (SDOF). This system is structurally damaged at different points by displacement rather than acceleration, with the seismic demand represented by an acceleration displacement response spectrum (Mahaney et al. 1993). The 'performance point' of a model building type is obtained from the intersection of the capacity spectrum and the demand spectrum, and is later used with fragility curves. Fragility curves represent the probability distributions of the damage within the building type to determine a specific damage probability, for a certain damage state (low, medium, extensive or complete damage).

2.2 The improved displacement coefficient method (IDCM)

One of the basic analytical methods is the Capacity-Spectrum Method (CSM), implemented in HAZUS since 1997. After CSM, new methods providing improvements were developed. One of them is IDCM, used in this study due to well received reviews (Gencturk and Elnashai 2008; FEMA 2005), consistency with the use in SeisDaRo (Toma-Danila et al. 2015b), and an observed good fit with expected damage in Bucharest (Toma-Danila et al. 2015a). This method implies the modification of displacement demand for the equivalent SDOF, by multiplying it with a series of coefficients, in order to generate an estimate of the maximum displacement demand of the nonlinear oscillator (Molina et al. 2010), as expressed in Fig. 3. During our tests we found that this method does not generate results significantly different than when using other recommended analytical methods such as the Modified Capacity Spectrum Method (MADRS). The most important aspect when using analytical methods is the selection of relevant building typologies that properly define the multitude of buildings within an area. The capacity and fragility functions—obtained from literature or custom modelled, have to reflect the mean characteristics of a specific type of building that can be easily defined through generic, non-invasive parameters such as height, age or material, that are collected by censuses, for example.

In this study we used the SELENA open-source software in order to apply the IDCM method and to obtain for different hazard scenarios the estimated number of buildings in different damage states (Molina et al. 2010). Buildings (drawn from the 2002 and 2011
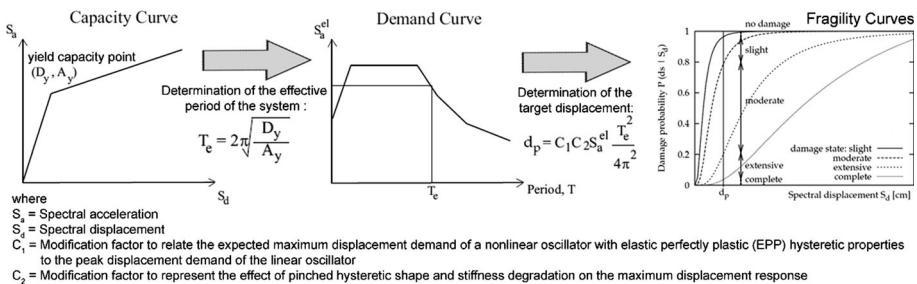

Fig. 3 Schematic illustration of IDCM process used for obtaining building damage probabilities (modified Molina et al. 2010)

Romanian censuses) were divided into typologies associated with 48 individual vulnerability functions (presented in subchapter 2.3), and three representative hazard scenarios were selected. The methodology allows real-time implementation, if ground motion parameters (calculated for a grid or each analysis point, in systems like ShakeMap) are available.

2.3 Seismic hazard considerations

The Vrancea Seismic Source, located at the intersection between the East-European Plate and the Intra-Alpine and Moesian Subplates, at the bend of the Carpathian Mountains (Fig. 1), is responsible for the high seismic hazard of Bucharest. However, there is still some uncertainty left regarding the size of the hazard generated by this source. The reasons are mainly that Vrancea is an intermediate-depth source, very confined spatially but difficult to analyse due to its depth, the different particularities from an earthquake to another (Sokolov et al. 2004), and its moderate activity, which did not allow to fully capture its true nature in the instrumental period of seismology. Since 1984, 37 major earthquakes with moment-magnitude (Mw) ≥7 are believed to have occurred between 94 and 150 km depths, as shown by the Romplus Catalogue (2015), although for the period before 1800, the magnitude and depth estimates are affected by large errors (Sokolov et al. 2004). If we consider earthquakes with Mw ≥ 6.5, the upper depth limit becomes 75 km. The reality is that any major earthquake could occur at any depth, probably between 60 up to 180 km depth. Recent seismic activity showed that even at 40 km depth moderate earthquakes can occur (the 22 November 2014 earthquake, with Mw 5.4—an event no one expected). Although Fig. 1 shows that close to Bucharest moderate crustal earthquakes were recorded (the Făgăraș-Câmpulung area in Romania or Shabla in north-eastern Bulgaria), these never produced damage in the city and are not considered as sources with this potential. As such, they are not taken into consideration in this study.

Studies like Kienzle et al. (2006) estimate for Vrancea a 50 years return period for an earthquake with Mw ≥ 7.4. The maximum credible Mw is considered to be 7.8, according to Lungu et al. (1999) and Marmureanu et al. (2010). However, magnitude is not entirely explanatory for the seismic hazard; hypocentral distance, together with ruptured area migration Marmureanu et al. (2008), focal mechanism, directivity and local site effects (Sokolov et al. 2004) also play an important role in determining different ground motion patterns, therefore they must be considered as parameters in each scenario. In order to show what hazard values are to be expected for Bucharest, a comprehensive list with peak ground acceleration (PGA) values obtained from different probabilistic studies, for different return periods, is presented in Table 3. However, these PGA values are general and are subjected to considerable uncertainties (as shown by the Sokolov et al. 2004 data—due to factors like the inter-event variability of real recorded data used for ground motion prediction equations—GMPE and few recordings of major earthquakes), failing also to reflect the variations throughout the city. That is why we chose to use for our analysis scenarios based on real recordings and a recent microzonation map for the city (Table 3); these choices allowed us to make hazard distinctions between different areas of Bucharest. The PGA values resulted from these scenarios fall within the intervals provided in Table 3.

The fact that PGA is not entirely representative for structural designers or seismic risk evaluators was highlighted in multiple studies, such as Marmureanu et al. (2008) or Manea et al. (2016). Especially in case of Bucharest the need for an even more detailed description of the hazard, through the integration of spectral acceleration (SA) values, is required. This

Table 3 PGA hazard for various return periods calculated for Bucharest (modified from Sokolov et al. 2004)

Area	Return period (years)	PGA (cm/s^2)	Soil effect considerations	Source of data
Bucharest	100	240	No	Lungu et al. (2003)
	100	120–200 (180–310[b])	Yes	Sokolov et al. (2004)
	225	294	Yes	UTCB (2013)
	475	290	No	Mantyniemi et al. (2003)
	475	240–420[a] (360–600[b])	Yes	Sokolov et al. (2004)

[a] Values may be overestimated, because the site response is considered to be linear during large earthquakes

[b] Mean + 1 standard deviation amplitudes of site response were used

is due to the phenomenon of long predominant periods in the 1–2 s domain, explained by the non-linear behaviour of clay deposits during strong earthquakes (Sokolov et al. 2004), by the presence of Quaternary deposits estimated to be up to 300 m deep (Bala 2013) and evidenced in real recordings like the one of INCERC station for the 1977 earthquake. We chose to use in this paper the IBC2006 design spectrum (rather than Eurocode8), since it provides a better coverage of the spectra for the 1977 and 1990 earthquakes (as shown in Fig. 4), allowing the provision of custom SA values at 0.3 and 1 s periods, beside PGA. Of great interest would be the consideration of the P100/2013 Romanian seismic design spectrum (UTCB 2013) for Bucharest (presented also in Fig. 4), however the implementation methodology is at the moment uncertain.

The scenarios used for Bucharest, together with the justifications for their selection, are shown in Table 4. Due to the study goal, the accent was mainly on creating the possibility to compare the results with real situations, to test boundary condition scenarios and to make use of the high resolution vulnerability dataset. The use of GMPEs can be an option, however during our tests we noticed that they cannot make a distinction between various areas of the city with different soil amplifications (reflected by real recordings), although considering VS30 values (which do not vary considerably throughout the city).
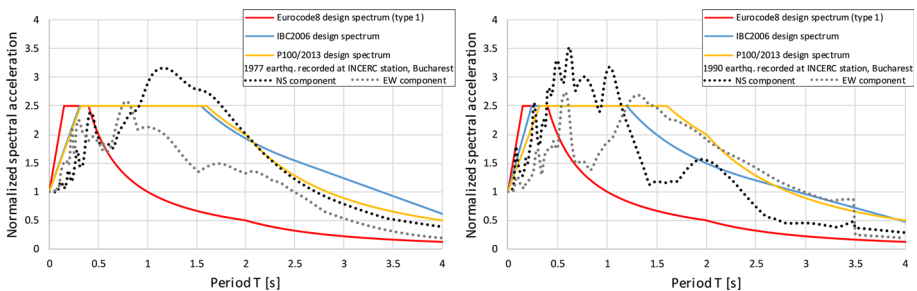

Fig. 4 Normalized elastic design spectra as computed by Selena, following the provisions of Eurocode 8 (EC8 type 1) and IBC2006 for already amplified PGA and SA values recorded at the INCERC station in Bucharest during the 1977 and 1990 earthquakes, overlaid with the correspondent response spectra (5 % damping) for horizontal components and the Romanian P100/2013 design spectra for Bucharest (generalized for surface)

Table 4 Hazard scenarios used

Scenario	Data used	Choice justification
1. For the 1990 earthquake (Mw 6.9, 91 km depth)	Real recorded strong motion data, from 10 stations in Bucharest and 4 nearby (Fig. 5). The data is recorded at surface, in free field conditions	Estimates can be compared with the real damage: few buildings were completely damaged (Georgescu and Pomonis 2012). We consider that it is a good scenario at the limit of real damageability
	Through inverse distance weighting interpolation we obtained a raster that was used to calculate the mean values in each CT	We chose this scenario instead of one based on the 1986 earthquake (Mw 7.1, 131 km depth), because for Bucharest, real recordings had higher values
	The maximum PGA value for a CT is 0.13 g	
2. For the 1977 earthquake (Mw 7.4, 94 km depth)	The only recording in Bucharest, at the INCERC station (eastern Bucharest), with PGA of 0.21 g, SA at 0.3 s of 0.37 g and SA at 1 s of 0.57 g, used for all of Bucharest. Data is recorded at surface, in free field conditions	Estimates can be compared with the size of the real damage (keeping in mind that since 1977 the building stock changed)
3. Microzonation map of the maximum possible (worst-case scenario), considered for Mw of 7.8 and depth of 150 km	The map by Marmureanu et al. (2010), shown in Fig. 6	The most recent and detailed microzonation map for Bucharest, obtained 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 biggest in the twentieth century as Mw)
	For SA we computed the values through the Sokolov GMPE (Sokolov et al. 2008), for corresponding PGA values from the map	

2.4 Residential buildings vulnerability data

One of the main issue when trying to use analytical methods is the difficulty of having a detailed and regionally-specific buildings dataset, consisting of the number of buildings in each typology and the corresponding capacity and fragility curves. In order to advance toward risk estimates, the number of residents, the economic value of the properties or the reconstruction values for the buildings are additionally needed. Due to the generalized approach, the use of analytical methods and earthquake loss estimation software is not recommended for a small number of buildings, being intended for larger units like census tracts or entire cities. Therefore, buildings and population censuses are an important piece of the puzzle. For Romania and Bucharest, these censuses are performed approximately
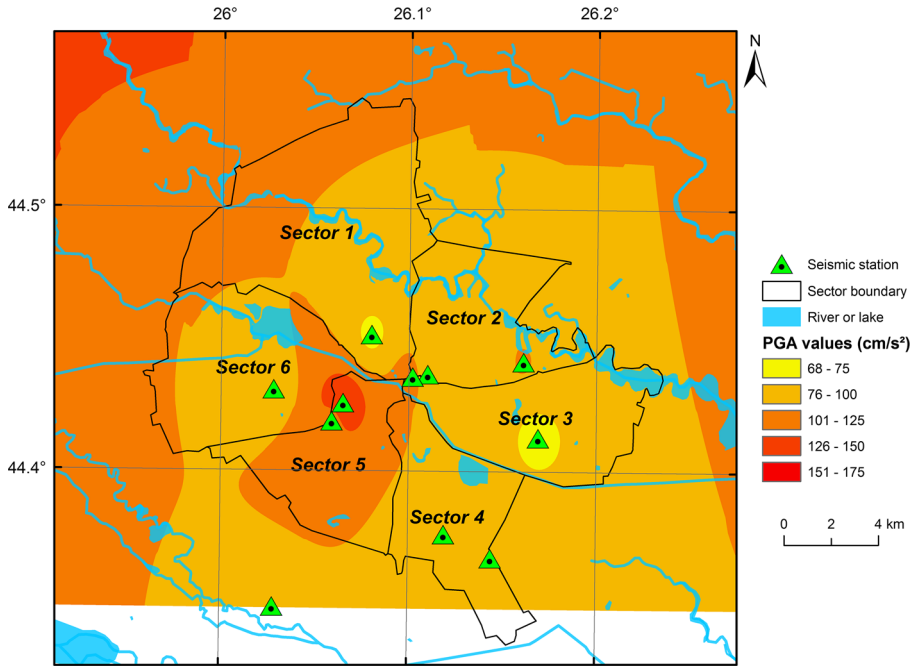
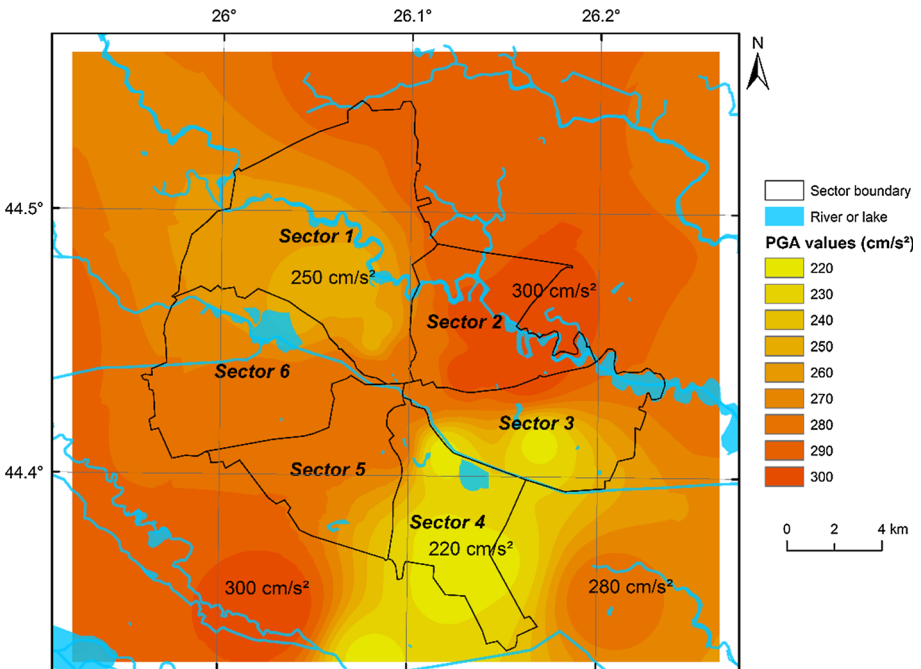**Fig. 5** Interpolation map of the PGA values recorded by seismic stations during the 1990 earthquake

Fig. 6 Seismic zoning map for Bucharest, for the maximum predicted Vrancea earthquake with Mw of 7.8 and depth of 150 km (modified from Marmureanu et al. 2010)

every 10 years, with the last ones in 2002 and 2011. The characteristics of 2002 and 2011 census datasets that were available for this study are presented in Table 5 and in Fig. 7.

As it can be seen in Table 5, the census attributes that we could use are significantly different from 1 year to another; this is in general a major problem of national censuses in Romania: the lack of continuity and standardization of measurements. One of the major downsides of the data we used was the lack of provisions regarding the building material for residential buildings according to the 2002 census—in fact, a fundamental aspect when trying to estimate building damage through analytical methods. This problem was overcome by using previously collected detailed data from 1999 (at sector level), described in Toma-Danila et al. (2015b) and included in SeisDaRo, and also expert knowledge. The procedure is described in Fig. 8. For the 2011 census there are references to buildings that

Table 5 Structure of the 2002 and 2011 census datasets for residential buildings

| 2002 census data characteristics	2011 census data characteristics
112,039 buildings in total	131,875 buildings in total
154 census tracts (CT) for all Bucharest	128 census tracts (CT) for all Bucharest
For each CT, number of residential buildings according to	
Construction period: <1940, 1940–1959, 1960–1989, 1990–2002 (years)	Construction period: <1919, 1919–1945, 1946–1960, 1961–1989, 1990–2002, 2003–2011 (years)
↘ For each construction period building height <2S, 2-4S, 5-7S, 8-10S, >10S (S = Storeys)	↘ For each construction period building height <2S, 2-4S, 5-7S, 8-10S, >10S (S = Storeys)
↘ All buildings classified	↘ 40,000 buildings unclassified
No info regarding building material	Construction material reinforced concrete, precast concrete, masonry with concrete floor, masonry with wooden floor, wood, adobe, other materials, mixt materials
	↘ 20,156 buildings unclassified
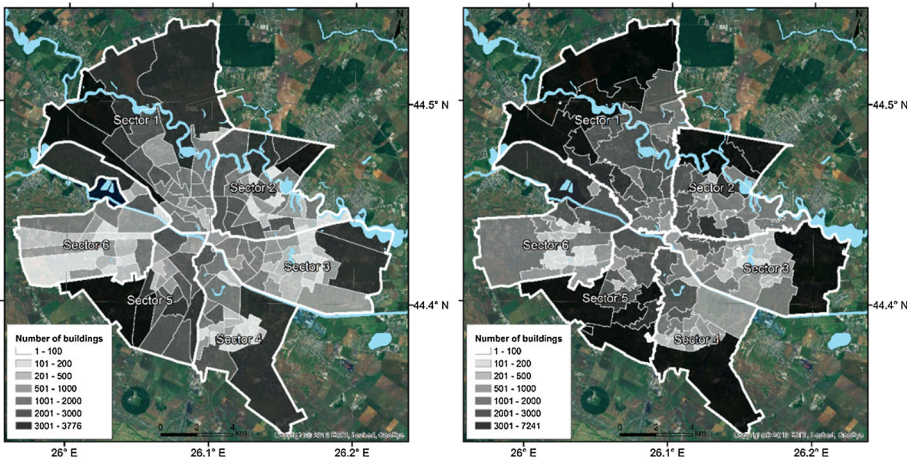
Fig. 7 Maps of the total number of residential buildings in each census tract, according to the 2002 (*left*) and 2011 (*right*) censuses. Legends have comparable intervals, but the shape of census tracts vary
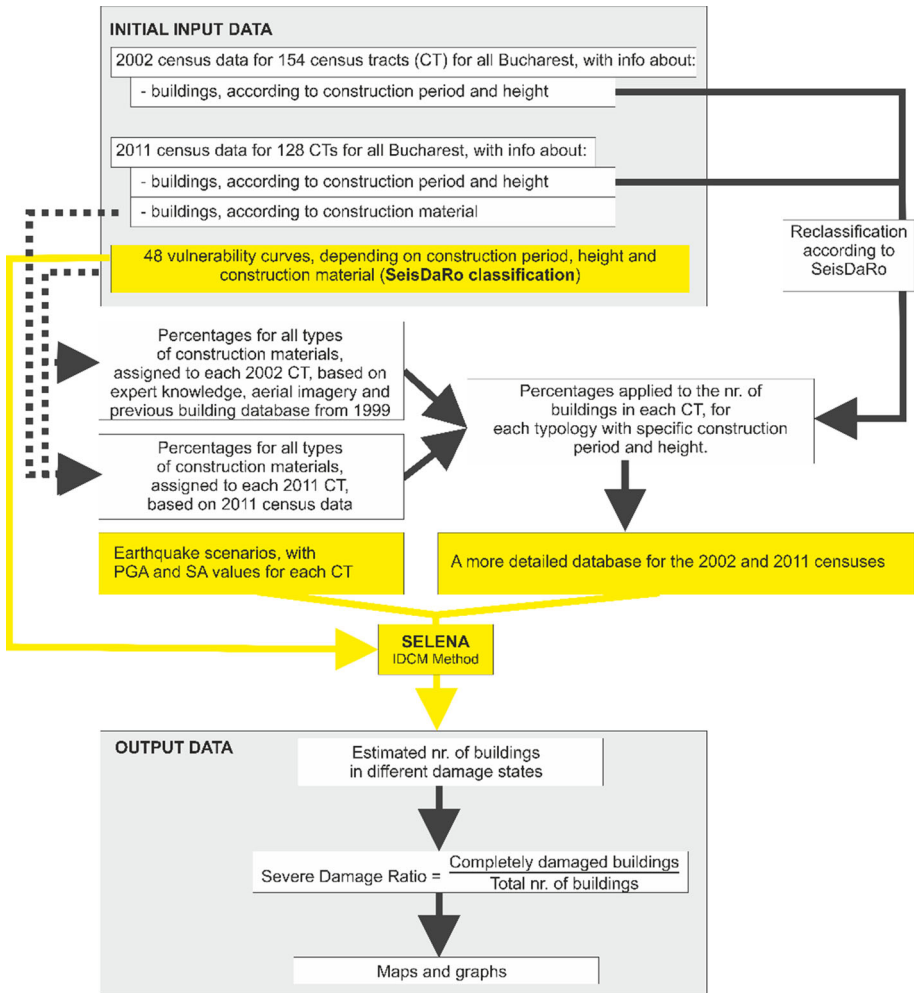
Fig. 8 Scheme used for converting 2002 and 2011 census data to the SeisDaRo format (presented in Table 6) and for obtaining building loss estimates. *Yellow boxes* represent final computational elements used for obtaining the output

could not be classified in any typology; apparently, for the 2002 census there were no unclassified buildings. The difference of almost 20,000 buildings, between the total number of buildings in 2002 and 2011, is plausible and explainable by the construction boom in Bucharest. As seen in Fig. 7, the number and shape of CTs is different between the two censuses. Still, for a relevant comparison between censuses, CTs can be merged according to sector boundaries (which are the lowest official administrative territorial unit for Bucharest). We presented all these issues, since they play an important role in the way we computed damage estimates. In order to adapt the 2002 and 2011 census data to a standardized classification (of SeisDaRo), a compromise had to be made, with no other options available.

In the last years, within the 'Danube Cross-border system for Earthquakes Alert (DACEA)' Project (2010–2013) a residential building database at city/commune scale was

compiled and used in SeisDaRo (Erduran et al. 2012). Experts from the Technical University of Civil Engineering, Bucharest (Romania) and NORSAR Institute (Norway) worked on defining building typologies with specific capacity and fragility curves (48 in total) for the dataset. The resulted classification is presented in Table 6. This classification was found to provide a credible estimation of the possible damage within southern and eastern Romania (Toma-Danila 2012) and Bucharest (Toma-Danila et al. 2015a), although the local construction specifics are considered partial in nature. In order to also have continuity with previous analyses, we investigated ways to adapt the 2002 and 2011 census datasets to the SeisDaRo already defined typologies.

One of the major discrepancies consisted in the lack of data regarding the building construction material for the 2002 census and the unlinked information between construction material and building height and age data for the 2011 census (not allowing for example to know the number of buildings that are older than 1963 and are made of masonry). This problem was overcome through the use of an empirical estimation model, presented in Fig. 8. The model relies on determining construction material profiles for each CT (based for the 2002 census on data from a more complete dataset from 1999, at sector level, on expert knowledge or aerial imagery), and then applying these profiles to the datasets arranged according to construction period and height of the buildings. Profiles

Table 6 Structure of the DACEA project buildings database and associated vulnerability curves (48 in total), used within SeisDaRo (modified from Toma-Danila et al. 2015a)

Construction material	Height class	Construction period	Vulnerability curves
Adobe	L	PC, LC, MC, HC	URM-L-PC[1]
Unreinforced masonry bearing walls with flexible floors	L	PC, LC, MC	URM-L-PC[1]
Unreinforced masonry bearing walls with flexible floors	M, H	PC, LC, MC	URM-M-PC[1]
Unreinforced masonry bearing walls with rigid floors	L	PC, LC, MC	URM-L-LC[1]
Unreinforced masonry bearing walls with rigid floors	M, H	PC, LC, MC	URM-M-LC[1]
Reinforced or confined masonry bearing walls or retrofitted (overall strengthened) masonry buildings	L, M, H	HC	M7-2, M7-4, M7-6[2]
Wood structures	L	PC, LC, MC, HC	W1-PC(LC, MC, HC)[1]
Concrete shear walls	L, M, H	PC, LC, MC, HC	C2-L(M,H)-PC(LC,MC,HC) fragility curve[1] + modified capacity curve (by UTCB)
Concrete frame with unreinforced masonry infill walls	L, M, H	PC, LC, MC, HC	C3-L(M,H)-PC(LC,MC,HC) fragility curve[1] + modified capacity curve (by UTCB)
Precast concrete walls	L, M, H	PC, LC, MC, HC	PC2-L(M,H)-PC(LC,MC,HC)[1]

Height class abbreviations *L* low—max 2 storeys, *M* medium—3–5 storeys, *H* high—min 6 storeys; construction period abbreviations *PC* PreCode—older than 1963, *LC* LowCode—1963–1977, *MC* ModerateCode—1978–1991, *HC* High Code—after 1991

Sources: [1]FEMA (2014), [2]Cattari et al. (2004)

were used as percentages, determining, for example, that in a CT with 200 low rise buildings built in the PreCode period, there is a probability that 20 % are reinforced concrete, 50 % masonry and 30 % adobe. This method most certainly induces uncertainties, however it was considered to be the best option to compensate for the missing data and allow the use of analytical methods. Another issue was the lack of homogeneity between datasets; in order to respect the SeisDaRo classification, it was decided that some census fields will be considered as alike (like in the case of 2–4 and 5–7 story high buildings, which were considered as belonging to the Medium Height typology in Table 6). Others will be divided empirically (such as the 1960–1989 construction period interval for the 2002 census that was split in two, in order to obtain LowCode and ModerateCode SeisDaRo typologies).

The final data arrangement was included in the required SELENA format (within the input file numbuild.txt), allowing the use of vulnerability curves already assigned from SeisDaRo. The point coordinates for each CT were set inside each polygon, however their relevance is not important due to the fact that for each coordinate we associated ground motion values obtained by computing mean values for each built area of the polygons (for the 1990 and maximum possible scenarios where hazard values were in raster format), at the exact location, therefore making the interpolation in SELENA unnecessary.

Due to the fact that CTs are not equally sized or of similar shape from one census to another, for a one-to-one comparison of the results and a better highlight of the damage dispersion we chose to compute an additional indicator to the number of damaged buildings (in different states), which is Severe Damage Ratio (SDR). This normalized indicator is a simplified Mean Damage Ratio (as described in Lang et al. 2012), computed as the ratio between the estimated number of completely damaged buildings and total number of buildings. The terminology 'Severe' was chosen due to the fact that we found the term 'Complete' to be often misinterpreted when disseminating results to emergency intervention authorities.

Furthermore, we tried a new approach in order to enhance the resolution of the urban analysis and the mapping of residential buildings loss estimates. CTs are defined as contiguous polygons that define all of Bucharest. However, they also comprise of areas where there are actually no residential buildings. By removing these areas—parks, water bodies, industrial areas, streets, etc., a more precise depiction of the areas with possible seismic damage can be revealed. Even more, by isolating areas where only reinforced concrete multi-storey buildings are present (many neighbourhoods specific to the communist area and easily distinguishable from aerial imagery) and determining their loss estimates only for the corresponding typologies (medium and high rise reinforced concrete buildings), we were able to tell more about the zonal differences. For other areas without these kind of flats, we determined loss estimates based on the sum of the other typologies. The usefulness of this new methodology can be easily seen when comparing the original CTs in Fig. 7 with the maps in the result section.

3 Results and discussions

Before presenting and discussing the results of loss estimations for the selected scenarios, we want to highlight a simplified conclusion based on the actual state of affairs in Bucharest. Based on the raw census data, we summarized in Table 7 the total number of buildings, in all of Bucharest and in its sectors, which were built prior to any seismic

Table 7 Number of residential buildings corresponding to the construction period in Romania in which there were no seismic design regulations (prior to 1940). These types of buildings and especially medium and high-rise buildings proved to be considerably vulnerable during strong Vrancea earthquakes (at least 32 collapsed during the 1977 earthquake)

Bucharest	2002 Census Construction year ≤ 1940 39,077, out of which 35,779—Low rise (<2 storeys) 3142—Medium rise (2–7 storeys) 156—High rise (>7 storeys)	2011 Census[a] Construction year ≤ 1945 31,430, out of which 27,831—Low rise (<2 storeys) 3511—Medium rise (2–7 storeys) 88—High rise (>7 storeys)
Sector 1	12,390	9617
Sector 2	10,781	8707
Sector 3	2977	2771
Sector 4	3649	3121
Sector 5	7668	5818
Sector 6	1612	1396

[a] 20,783 buildings unclassified in any construction period; if classified, they would probably contribute to a better fit with the 2002 values

design code (the first seismic design code was developed after the 1940 earthquake). Although these buildings are not to be mistakenly considered as doomed (after all they endured the 1940 and 1977 major earthquakes), many of them, especially medium and high rise buildings (an example is in Fig. 9), could have serious problems—most buildings expertized and classified in the seismic risk class I according to Bucharest General Municipality (2016) belong to this category. What determined us to present this situation is the large number of buildings in this typology. Damage estimates may seem to be relative, but these values offer a more direct view of the vulnerability situation and show that the old building stock can be a major issue for Bucharest.

In the following figures we present the results for the three deterministic scenarios earlier presented (1990, 1977 and maximum possible earthquake). First we compare, in Figs. 10, 11 and 12, the estimated number of buildings with complete damage at sector

Fig. 9 Typical PreCode masonry buildings in the Historical Centre of Bucharest (still inhabited)

level, between the 2002 and 2011 datasets and additionally with results from a previous recent study (Toma-Danila et al. 2015a), which used another building dataset from 1999, considered to be more accurate in its description (but limited to a maximum resolution of sector level). These figures show that:
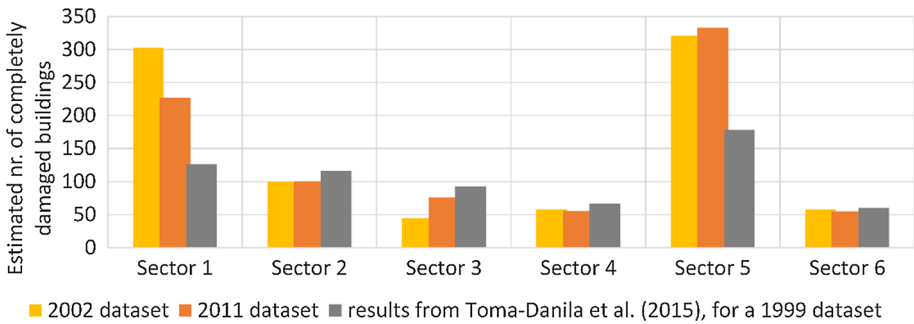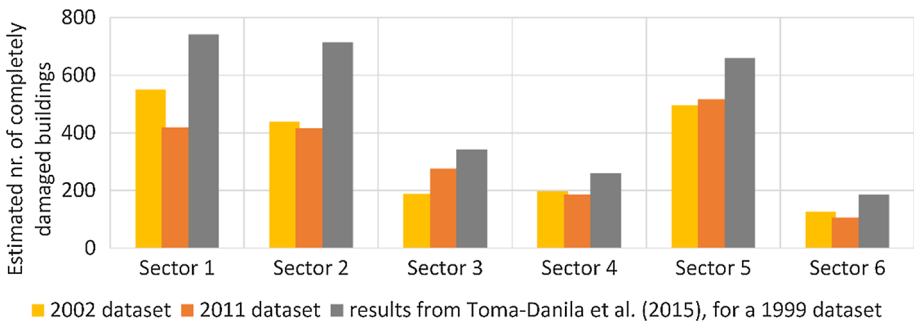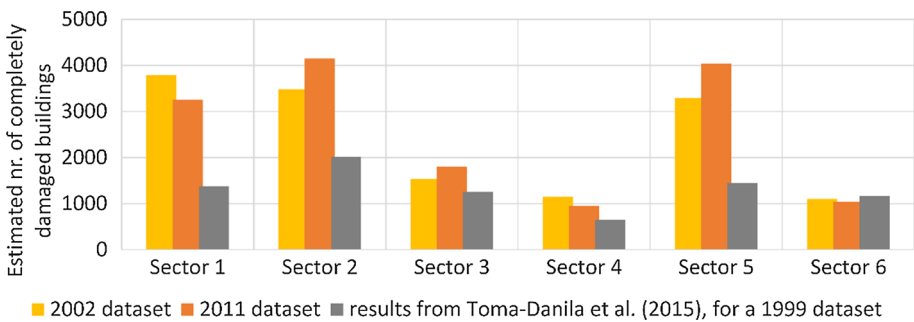

Fig. 10 Estimated number of completely damaged buildings for different datasets (including results from Toma-Danila et al. 2015a), for Bucharest's sectors and the 1990 earthquake scenario

Fig. 11 Estimated number of completely damaged buildings for different datasets (including results from Toma-Danila et al. 2015a), for Bucharest's sectors and the 1977 earthquake scenario

Fig. 12 Estimated number of completely damaged buildings for different datasets (including results from Toma-Danila et al. 2015a), for Bucharest's sectors and the maximum possible earthquake scenario

- the 2002 and 2011 estimates are comparable between each other,
- for the 1990 and maximum possible earthquake scenarios they vary considerably with results from the Toma-Danila et al. (2015a) study—especially for Sector 1 and 5. This is explainable due to the way small houses are considered, as typology: the 1999 dataset indicates that many small houses (most of them being in Sector 1 and 5) are adobe buildings, and the 2002 and 2011 datasets considers them as masonry buildings, therefore the vulnerability functions are different and reflected as such in damage estimates.
- Another problem with the comparison for the two aforementioned scenarios is the fact that estimates are based on hazard values that are attributed at CT level individually, for the 2002 and 2011 datasets (important local differences being considered), and not at sector level, uniformly as a mean (as in the case of the 1999 dataset).
- The fact that the 1977 scenario, which has the same PGA and SA values for all Bucharest, shows very similar estimates gives us the hint that by considering more specific local hazard effects and datasets, a better and significantly different loss estimation can be obtained.

The following maps (Figs. 13, 14, 15) show the results of the three scenarios, for the 2002 dataset (maps on the left) and the 2011 dataset (maps on the right). The legend has similar intervals within each figure and due to the use of the SDR, all figures are directly comparable. For the 1990 scenario, due to the small (as expected) SDR values, legend intervals are fewer than in the case of the other figures.

Figures 13 and 14 exhibit a particularity: there are areas mostly consisting of flats with very high SDR values for the 2002 map, and 0 SDR values (no damage) for the 2011 map. By looking into the data behind the maps, we noticed the cause of this difference. The classification based on the statistical data and our conversion methodology associates to these areas many buildings belonging to the precast concrete walls material, low and moderate code period and high-rise typology for the 2002 dataset. These are considered by the loss estimation method as having great damage potential (due to the associated
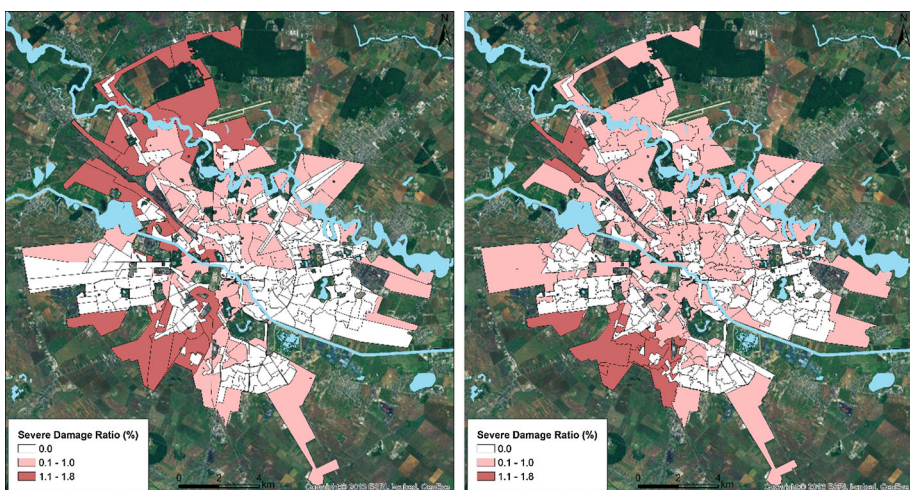

Fig. 13 Maps with SDR estimates for the 1990 earthquake scenario, for the 2002 (*left*) and 2011 (*right*) Bucharest residential building datasets
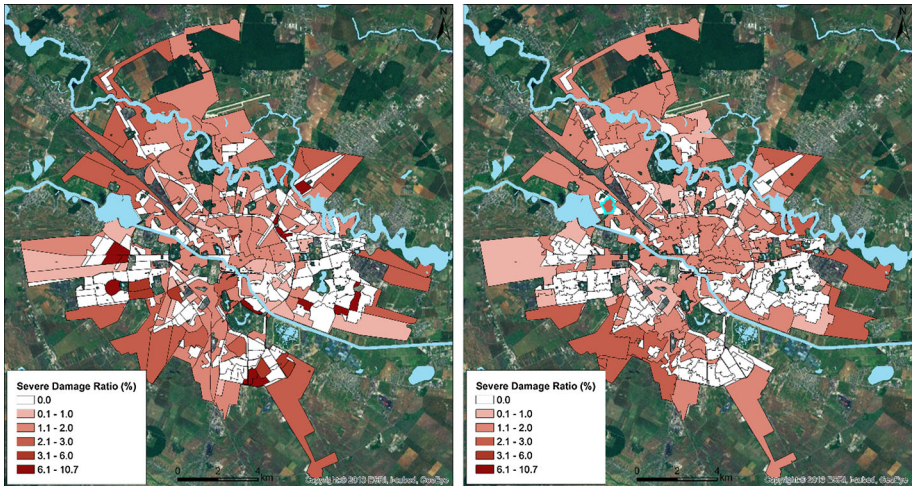
Fig. 14 Maps with SDR estimates for the 1977 earthquake scenario, for the 2002 (*left*) and 2011 (*right*) Bucharest residential building datasets
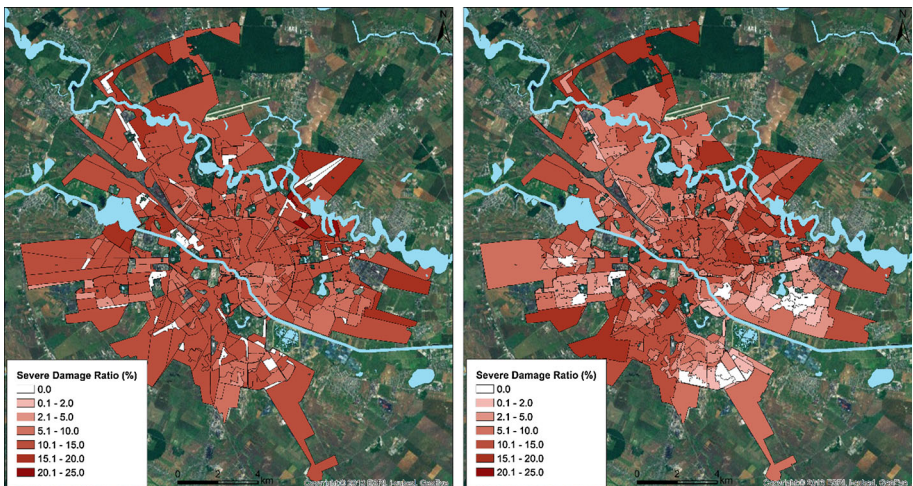

Fig. 15 Maps with SDR estimates for the maximum possible earthquake scenario, for the 2002 (*left*) and 2011 (*right*) Bucharest residential building datasets

vulnerability functions, which might be slightly inappropriate). For the 2011 dataset, buildings are classified in other typologies of reinforced concrete material, which are less vulnerable. Since for the 2002 dataset the association of construction material was performed using a less accurate approximation, we recommend taking more into consideration the maps based on the 2011 dataset.

The SDR distribution of the results is somewhat different than what was seen in reality after the 1977 earthquake. After the 1977 earthquake most of the completely damaged buildings were in the city centre (although it is still uncertain what the actual building

damage extent at city scale was due to the secrecy of the communist regime and the importance of moderate and high rise buildings that collapsed in the city centre and caused many causalities). It is expectable that a major future earthquake will produce significant damage in the city centre again (as shown by the distribution of buildings in the seismic risk class I in Fig. 16)—our results do not exclude this aspect, but on our result maps this aspect does not appear as a main characteristic; our residential building damage estimates reveal that considerable property damage (and not necessarily human losses) can be expected in subcentral and peripheral areas where there are many masonry and adobe houses (distinct areas in the south-western Bucharest and in Sector 1). In Sector 2, 3, and 6, where there is a high concentration of reinforced-concrete flats built after the PreCode period, the SDR is minimum. Through Fig. 16 we checked whether this pattern maintains for the 1977 earthquake scenario, for buildings built prior to 1977 (PreCode or LowCode). The pattern is essentially similar, and there is also a relevant fit with the distribution of buildings in the seismic risk class I. Since an evaluation in the peripheral areas was not performed, we do not know how many buildings would belong to the seismic risk class I. The values for the 1990 scenario and for the maximum earthquake scenario show that estimates are in the range of expectations and do not go a great deal further than expected.

Handling errors in seismic damage estimation is an intricate process; multiple uncertainties from all variables accumulated along the way make error quantification very
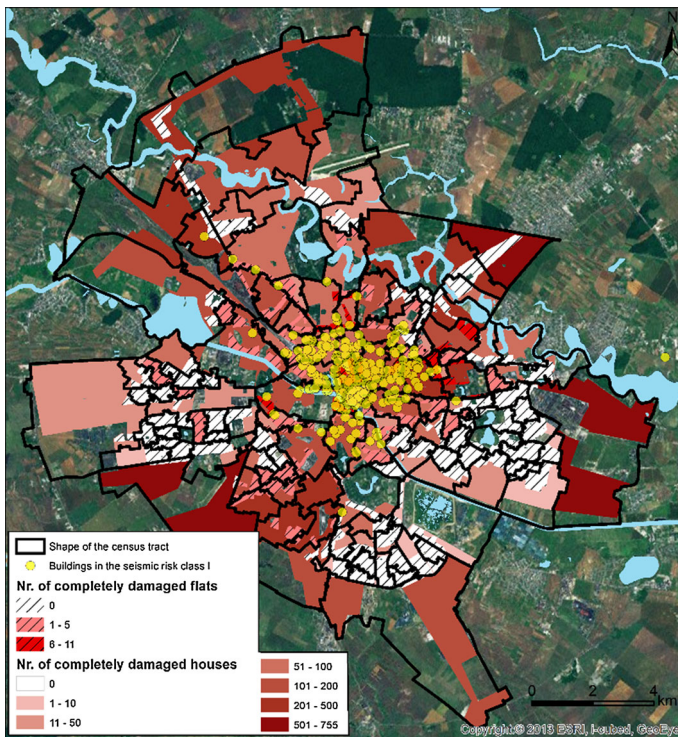

Fig. 16 Map of the estimated number of completely damaged buildings built before 1977 (considered as PreCode and LowCode), for the maximum possible earthquake scenario. The map also shows the locations of the buildings individually assessed and considered as being in the seismic risk class I, according to Bucharest General Municipality (2016)

Table 8 Qualitative analysis of the main error sources in this study

| Error source	Impact on the results
Hazard scenarios	*Moderate* The 1990 scenario is the most detailed and certain at city scale; the 1977 scenario is limited to one recorded value and results are not differentiated according to local ground motion effects; the map of the maximum earthquake scenario was obtained through complex simulations, however it is a rough approximation of the values that might be recorded
2002 and 2011 Census datasets for residential buildings	*High* Census data is the basis of damage estimation. Due to the fact that census datasets in Romania have limited continuity in their criteria, the collecting phase is significantly subjective (for fields referring to building properties) and CTs are variable, high errors—difficult to quantify, are induced. In the case of our study, an additional impact was the lack of construction material data for the 2002 census. The methodology for adapting census data to the SeisDaRo structure further induced uncertainties
Vulnerability functions	*Moderate* Very few vulnerability functions are available for Romanian specific buildings, therefore we had to rely mostly on borrowed vulnerability functions. However, these associations can provide a good fit with expected damage (Toma-Danila et al. 2015a)
Damage estimation methodology	*Moderate* One of the possible error sources in the HAZUS/SELENA methodology is the design spectrum consideration; the integration of the Romanian design spectrum for Bucharest is considered to decrease the uncertainties (as stated also in Lang et al. 2012). The results for the 16 and 84 % fractiles are not considerable
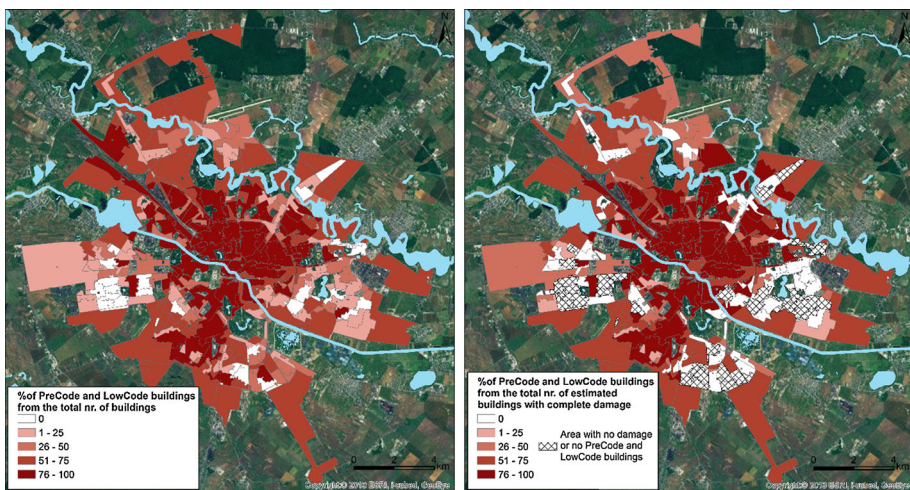
Fig. 17 Maps showing the percentage of old buildings (PreCode and LowCode) from the total number of buildings (*left*) and from the estimated total number of buildings with complete damage (*right*), for the 2011 dataset and the maximum earthquake scenario

difficult and hard to model. For the part depending on analytical methods a proper option is the consideration of the method already integrated in SELENA, in which the results are multiplied by their corresponding weights and then are fitted to a normal distribution in

order to get the median values as well as the 16 and 84 % fractiles (Molina et al. 2010). But for the other parts (like the hazard and vulnerability data characteristics) an additional consideration has to be made. In order to show the error sources in our study and their impact on the final results, we performed a qualitative analysis, presented in Table 8.

Figure 17 is designed to show how much of the total complete damage is due to buildings belonging to the PreCode and LowCode construction periods. Data for the maximum earthquake scenario and the (more reliable) 2011 dataset is used. A high percentage (on the map on the right) means that old buildings are more responsible for the estimated damage. As expected, in the city centre PreCode and LowCode buildings can cause most of the damage, but also in peripheral areas they can represent more than 25 % of the total damage. Due to the fact that both maps are very similar we can conclude that PreCode and LowCode buildings do not appear to be considerably more vulnerable than newer building, in our estimates. This gives us a good sense regarding the influence of vulnerability function selection, but the validation will require further research and real event observations. As a fact, newer building can also be considered as vulnerable—during the 1977 earthquake there were three relatively new buildings that collapsed, in different areas of the city: Lizeanu, OD16 and the Computer Centre of the Ministry of Transport buildings.

4 Conclusions

This study represents a first attempt at quantifying the potential seismic damage of all residential buildings in Bucharest, at census tract level—for more than 128 areas of the city. Through the use of analytical methods (IDCM), multiple census datasets from different years (2002 and 2011), a recent definition of building typologies in Romania (integrated within SeisDaRo), with correspondent vulnerability functions and relevant hazard scenarios, we obtained building loss estimates that can be of great use for highlighting the high seismic risk of Bucharest and besides this, of great aid in prioritizing much required mitigation actions. Our research lead to the development of a new methodology for converting raw census data into SeisDaRo compliant data (applicable also to other urban areas world-wide characterized by inconsistent datasets), and introduced a new GIS based approach for enhancing the resolution of the analysis (through the removal of non-relevant elements and separation of areas with different typologies).

The results obtained for the three earthquake scenarios show that significant damage could occur not only in the Bucharest centre, where the percentage of old buildings built without or with low seismic design considerations is more than 76 %, but also in other areas towards the periphery (in Sectors 1 and 5 more specifically), where there is a considerable number of vulnerable small buildings. The SDR representations offer a better glimpse of the building damage patterns, from one CT to another; for the 1990 and 1977 earthquake scenarios, CTs that have mostly medium and high rise reinforced-concrete flats have a very low SDR (many have 0 SDR). We can conclude that these areas could be safer during a major earthquake; however, it must be considered that the socio-economic losses could be far greater if a single 10 story flat collapses (which is what happened during the 1977 earthquake), compared to the collapse of 50 small houses.

Although the procedure of obtaining the results is promising and the maps look ready-to-use for potential beneficiaries such as Emergency Intervention Institutions, we insist on making it clear that each single step in seismic loss estimation is subjected to significant

uncertainties which have to be considered when analysing and using the final results. For example, we are aware of the limitations induced by the use of an elastic spectrum that does not focus on the 1–2 s interval for Bucharest (which is of great significance for intermediate-depth Vrancea earthquakes), on the uncertainty of the acceleration values for the maximum possible earthquake scenario or on the census dataset limitations and subjective selection of vulnerability functions. We ask our readers to do the same. In further studies we will investigate more thoroughly the intricate process of estimating seismic damage at city scale. The results based on the 2011 census data can be considered more reliable than the ones for 2002, due to the availability of data regarding the construction material.

References

Bal IE, Crowley H, Pinho R (2008) Displacement-based earthquake loss assessment for an earthquake scenario in Istanbul. J. Earthq. Eng 11(2):12–22

Bala A (2013) Modelling of seismic site amplification based on in situ geophysical measurements in Bucharest, Romania. Rom. Rep. Phys. 65(2):495–511

Bartlakowski J, Wenzel F, Radulian M, Ritter JRR, Wirth W (2006) Urban shakemap methodology for Bucharest. Geophys Res Lett 33:L14310. doi:10.1029/2006GL026283

Bharwani HM (2014) Earthquake risk assessment, loss estimation and vulnerability mapping for Dehradun city, India. Master thesis. Faculty of Geo-Information Science and Earth Observation of the University of Twente

Boukri M, Farsi MN, Mebarki A, Belazougui M, Amellal O, Mezazigh B, Guessoum N, Bourenane H, Benhamouche A (2014) Seismic risk and damage prediction: case of the buildings in Constantine city (Algeria). Bull Earthq Eng 12(6):2683–2704

Bucharest General Municipality (2016) List of buildings technically expertise, classified into seismic risk classes. www.pmb.ro/servicii/alte_informatii/lista_imobilelor_exp/docs/Lista_imobilelor_expertizate.pdf. Accessed 29 Jan 2016

Cattari S, Curti E, Giovinazzi S, Lagomarsino S, Parodi S, Penna A (2004) Un modello meccanico per l'analisi di vulnerabilita del costruito in muratura a scala urbana. In: 11th Conference "L'ingegneria Sismica in Italia", Genoa, Italy, 2004

Chang SE, Gregorian M, Pathman K, Yumagulova L, Tse W (2012) Urban growth and long-term changes in natural hazard risk. Environ Plan A 44(4):989–1008

Daniell JE (2011) Open source procedure for assessment of loss using global earthquake modelling software (OPAL). Nat Hazards Earth Syst Sci 11:1885–1900

Eleftheriadou A, Baltzopoulou A, Karabinis A (2014) Seismic risk assessment of buildings in the extended urban region of Athens and comparison with the repair cost. Open J Earthq Res 3:115–134

Erdik M, Sesetyan K, Demircioglu MB, Zulfikar C, Hancilar U, Tuzun C, Harmandar E (2014) Rapid earthquake loss assessment after damaging earthquakes. Chapter in perspectives on european earthquake engineering and seismology. In: Ansal A (ed), vol 1. ISBN 978-3-319-07118-3

Erduran E, Lang DH, Lindholm CD, Toma-Danila D, Balan SF, Ionescu C, Aldea A, Vacareanu R, Neagu C (2012) Real time earthquake damage assessment in Romanian-Bulgarian border. In: Proceedings of the 15th World Conference on Earthquake Engineering, Lisbon, Portugal

FEMA—Federal Emergency Management Agency (2005) Improvement of nonlinear static seismic analysis procedures, applied technology council (ATC-55 Project). Federal Emergency Management Agency, Washington, DC

FEMA—Federal Emergency Management Agency (2014) HAZUS-MH: multi-hazard loss estimation methodology. http://www.fema.gov/hazus. Accessed 21 Feb 2016

Gencturk B, Elnashai A (2008) Development and application of an advanced capacity spectrum method. Eng Struct 30:3345–3354

Georgescu ES, Pomonis A (2012) Building damage versus territorial casualty patterns during the Vrancea (Romania) earthquakes of 1940 and 1977. In: 15th World Conference on Earthquake Engineering, Lisbon, 24–28 September 2012

Giardini D, Grünthal G, Shedlock KM, Zhang P (2003) The GSHAP global seismic hazard map. In: Lee W, Kanamori H, Jennings P, Kisslinger C (eds) International handbook of earthquake & engineering seismology., International Geophysics Series 81 BAcademic Press, Amsterdam, pp 1233–1239

Giardini D, Woessner J, Danciu L, Crowley H, Cotton F, Grünthal G, Pinho R, Valensise G and the SHARE consortium (2013) SHARE European seismic hazard map for peak ground acceleration, 10 % exceedance probabilities in 50 years. doi: 10.2777/30345, ISBN-13, 978-92-79-25148-1

Grünthal G, Wahlström R, Stromeyer D (2013) The SHARE European earthquake catalogue (SHEEC) for the time period 1900–2006 and its comparison to the European-Mediterranean earthquake catalogue (EMEC). J Seismol 17(4):1339–1344

Jimenez MJ, Giardini D, Grunthal G, SESAME Working Group (2001) Unified seismic hazard modelling throughout the Mediterranean region. Boll Geog Teor Appl 42:3–18

Kienzle A, Hannich D, Wirth W, Ehret D, Rohn J, Ciugudean V, Czurda K (2006) A GIS-based study of earthquake hazard as a tool for the microzonation of Bucharest. Eng Geol 87:13–32

Lang D (2012) Earthquake damage and loss assessment—predicting the unpredictable. Dissertation for the degree of Dr. philos, University of Bergen, Norway. http://bora.uib.no/handle/1956/6753. Accessed 28 May 2016

Lang D, Molina-Palacios S, Lindholm C, Balan SF (2012) Deterministic earthquake damage and loss assessment for the city of Bucharest, Romania. J Seismol 16:67–88

Lungu D, Cornea T, Nedelcu C (1999) Hazard assessment and site dependant response for Vrancea earthquakes. In: Wenzel F, Lungu D, Novak O (eds) Vrancea earthquakes: tectonics, hazard and risk mitigation. Kluwer, Dordecht, pp 251–268

Lungu D, Aldea A, Demetriu S, Craifaleanu I (2003) Seismic strengthening and seismic instrumentation—two priorities for seismic risk reduction in Romania. In: Papers of First International Conference on Science and Technology for Safe Development of Lifeline Systems, Sofia, 4–5 November 2003

Mahaney JA, Freeman SA, Paret TF, Kehoe BE (1993) The capacity spectrum method for evaluating structural response during the Loma Prieta earthquake. In: Proceedings of the 1993 National Earthquake Conference, Memphis

Manea E-F, Michel C, Poggi V, Fäh D, Radulian M, Balan F (2016) Improving the shear wave velocity structure beneath Bucharest (Romania) using ambient vibrations. Geophys J Int. doi:10.1093/gji/ggw306

Mansouri B, Ghafory-Ashtiany M, Amini-Hosseini K, Nourjou R, Mousavi M (2010) Building seismic loss model for Tehran. Earthq Spectra 26(1):153–168

Mantyniemi P, Marza VI, Kijko A, Retief P (2003) A new probabilistic seismic hazard analysis for the Vrancea (Romania) seismogenic zone. Nat Hazards 29:371–385

Marmureanu G, Cioflan CO, Marmureanu A (2008) New approach on seismic hazard isoseismal map for Romania. Rom Rep Phys 60(4):1123–1135

Marmureanu G, Cioflan CO, Marmureanu A (2010) Researches on local seismic hazard (Microzonation) for metropolitan Bucharest area. Tehnopress Ed. 2010. ISBN: 978-973-702-809-9, 470 p

Molina S, Lang DH, Lindholm CD (2010) SELENA—An open-source tool for seismic risk and loss assessment using a logic tree computation procedure. Comput Geosci 36(3):257–269

NIEP—National Institute for Earth Physics (2016) Bigsees earthquake catalog

Silva V, Marques M, Castro JM, Varum H (2015) Development and application of a real-time loss estimation framework for Portugal. Bull Earthq Eng 13(9):2493–2516

Sokolov V, Bonjer K-P, Wenzel F (2004) Accounting for site effect in probabilistic assessment of seismic hazard for Romania and Bucharest: a case of deep seismicity in Vrancea zone. Soil Dyn Earthq Eng 24:929–947

Sokolov V, Bonjer KP, Wenzel F, Grecu B, Radulian M (2008) Ground-motion prediction equations for the intermediate depth Vrancea (Romania) earthquakes. Bull Earthq Eng 6(3):367–388

Strasser FO, Bommer JJ, Sesetyan K, Erdik M, Cagnan Z, Irizarry J, Goula X, Lucantoni A, Sabetta F, Bal IE, Crowley H, Lindholm C (2008) A comparative study of European earthquake loss estimation tools for a scenario in Istanbul. J Earthq Eng 12(2):246–256

Toma-Danila D (2012) Real-time earthquake damage assessment and GIS analysis of two vulnerable counties in the Vrancea seismic area, Romania. Environ Eng Manag J. 11(12):2265–2274

Toma-Danila D, Zulfikar C, Manea EF, Cioflan CO (2015a) Improved seismic risk estimation for Bucharest, based on multiple hazard scenarios and analytical methods. Soil Dyn Earthq Eng 73:1–16

Toma-Danila D, Cioflan CO, Balan SF, Manea EF (2015b) Characteristics and results of the near real-time system for estimating the seismic damage in Romania. Math Model Civ Eng 11(1):33–41

UTCB—Tehnical University of Civil Engineering, Bucharest, Romania (2013). Seismic design code P100. Part I design provisions for buildings