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GIS in seismology: contributions to the evaluation of seismic hazard and risk

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Abstract. In this paper we highlight the capabilities and advantages of GIS, through an explicit analysis of its contribution within different studies of seismic hazard and risk assessment. These studies are related to Romania – one of Europe's countries with the highest seismic risk, mainly due to intermediate-depth earthquakes originating in the Vrancea Zone. We provide examples of how GIS contributes and enhances the evaluation of seismic hazard, the development of vulnerability spatial datasets, multicriteria analysis, real-time estimation of seismic risk, assessment of road network failure susceptibility and implications, mapping or others. The role of free data and contribution capabilities are discussed. In recent projects such as Bigsees and Ro-Risk, GIS was one of the elements that lead to innovation, and we aim to present the experience and results. Another important aspect is referred to: the importance of GIS to a research dissemination with great impact.

Keywords: *GIS, seismic hazard, earthquake, maps, Romania*

1. INTRODUCTION

GIS (Geographic Information System) is a fundamental tool that exploits the spatial dimension and its links with other dimensions, allowing to model and represent processes that are representative to the world we live in. GIS can find its place in almost all fields of study.

In seismic (and all types of) hazard and risk assessment, the need of considering location is embedded in the very definitions of the terms. But GIS can do much more than providing distance measurements and solutions for mapping. Among its numerous practical applications (Bonham-Carter, 2014) we mention that it can:

- allow a complex modelling of the data (both spatially and temporally);
- provide spatial and geostatistical analysis tools;
- provide filtering capabilities (text or location based)
- enable overlay analysis;
- have the function of an all-in-one platform, with database management, code development, automation and sharing capabilities;
- be the proper tool for disseminating the results (publicly or privately).

As reflected by more and more studies (such as Leonard *et al*. 2002, ESRI 2007, Rivas-Medina *et al*. 2013, Toma-Danila *et al*., 2017a), the role of GIS became major in seismology – a geoscience in need of geographical instruments. The Generic Mapping Tool (GMT) or QGIS have been and are still being widely used by seismologists (they are open source), but other commercial software such as ArcGis (under which HAZUS-MH operates) are also of great reference.

In this paper, we will show and interpret different maps (which are a basic product of GIS) that were obtained not only by representing data specific to seismology (such as earthquake epicenters), but also by analyzing and modelling data. By doing so, we aim to highlight that GIS is not only for cartographic purposes, but also for data processing, spatial and geostatistical analysis and automation of tasks.

2. ENHANCING SEISMIC HAZARD ANALYSIS THROUGH THE USE OF GIS

2.1. Processing earthquake catalogues

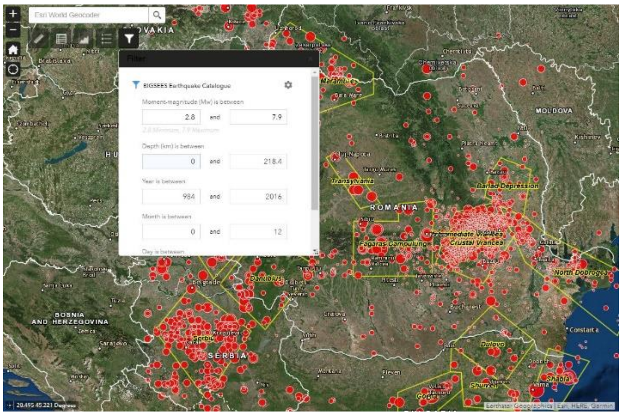
Earthquakes do not respect national boundaries; that is why national earthquake catalogues might not be completely useful when assessing seismic hazard in near-border regions. But also, as our experiences showed, national catalogues are more precise for the area they focus on (when also trying to consider earthquake with small or moderate magnitudes). A compilation between multiple sources is the best solution for a more reliable seismic hazard assessment. GIS has the right tools to allow the identification of earthquakes with impact on a specific area and the compilation of multiple catalogues. We used these tools when creating the Bigsees Earthquake Catalog – by combining the ROMPLUS Catalog (NIEP, 2016) with the SHEEC Catalog (Grunthal *et al*. 2013) and more recent EMSC-CSEM data. Among the choices we made were the following:

- for Romania, we chose mostly earthquakes from the ROMPLUS Catalog (noticing that the other sources of data provide in some cases events located completely wrong or with unreliable magnitude and depth);
- for near-border regions, we compared the locations provided by different data sources and made an expert based selection (removing duplicates);
- for more distant areas (seismic sources in Serbia, Dulovo and Shabla, that were considered to have capability of influencing the seismic hazard within Romanian borders) we used the SHEEC Catalog.

Without GIS it would have been considerably difficult to identify duplicate or misplaced earthquakes, and to see how far to go beyond national borders, in the effort of assessing overall national seismic hazard. The aforementioned Bigsees Earthquake Catalog was also easily integrated in a webGIS app (Figure 1) which allows visualization, filtering and download capabilities, disseminating this product in a way of impact for the general public, stakeholders and the scientific community. The past webGIS problems related to the speed of plotting multiple points in the same time on a map (more than 6600 events in the case of the Bigsees Earthquake Catalog) are now overpassed, since dynamic point clustering or pre-filtering techniques are available).

Earthquake catalogs are essential in seismic hazard analysis (whether probabilistic or deterministic). One of the initial steps in preprocessing catalogs is to decluster them, meaning the removal of foreshocks, aftershocks or swarms. There are several more or less empirical ways to do this (methods such as Gardner and Knopoff 1974 or Musson 1999), based on time and distance windows. GIS works with these dimensions, allowing automatic implementation of declustering algorithms and the development of new ones, which consider additional aspects such as fault plane solutions and spatially (and 3D) distributed patterns of the analyzed earthquakes.

In the effort of determining maximum magnitude, overlaying geological, tectonic, faults, focal mechanisms, crustal models and earthquake catalogues on a map can provide the basis for an insightful assumption. The same map setup can be used for determining the spatial extent of the seismogenic areas.



Moment-magnitude (Mw) is between 2.8 and 7.9
2.8 Minimum, 7.9 Maximum
Depth (km) is between 0 and 218.4
Year is between 984 and 2016
Month is between 0 and 12
Day is between

Figure 1 *WebGIS app presenting the Bigsees Earthquake Catalog and the seismic sources defined through the use of GIS; (Source: bigsees.infp.ro/Results.html)*

2.2. Ground motion distribution analysis

Seismic hazard analysis provides, ultimately, ground motion estimates for different plausible earthquake scenarios or return periods. These can have various distributions, depending significantly on the choice of ground motion prediction equation (GMPE) and its properties and variables, and can be more or less compatible as trend with actual recordings. By bringing all data into GIS, a visual or geostatistical analysis can be performed, in order to check values, their distribution and effects of soil type consideration, their intra and inter-event variability, modifications from a GMPE to another or fit with real data.

The Vrancea intermediate-depth seismic source in Romania is known to produce large earthquakes (statistically, two or three earthquakes with moment-magnitude Mw > 7 occur per century), which can cause high intensities over a wide area, producing significant damage. It is also known that the extracarpathic area is more prone to high acceleration and intensity values than the intracarpathic (Transylvanian) Basin, due to specific earthquake mechanisms and geologic conditions (Marmureanu *et al*. 2016). Although GMPEs were developed specifically for this source, the uncertainty of the output is still significant; the number of real records from high magnitude earthquakes, which contributed to the GMPE determination, was small and values showed great variability. By using GIS we are able to analyze the results of GMPEs (also implement their equations), and make best fit selections, as shown in Figure 2.

In Toma-Danila and Cioflan (2017b) we used GIS capabilities to generate ShakeMaps (depicting peak ground accelerations right after an earthquake, based on real recordings and GMPEs) through a new approach: by choosing automatically the GMPE with the best fit for a certain azimuthal interval (45 degrees wide). The results are shown in Figure 2. GIS is also fundamental when trying to determine local soil effects or Vs30 values – through methods such as topographic slope (Allen and Wald, 2007). Interpolation methods also are a part of GIS, and their selection is highly important, depending on the type of seismic data used; for acceleration values, probably the best is to use natural neighbor or inverse distance weight, in order not to alter the real-recorded values. Kriging is better to be used with macroseismic intensity values, which are much more subjective and need a better smoothing.

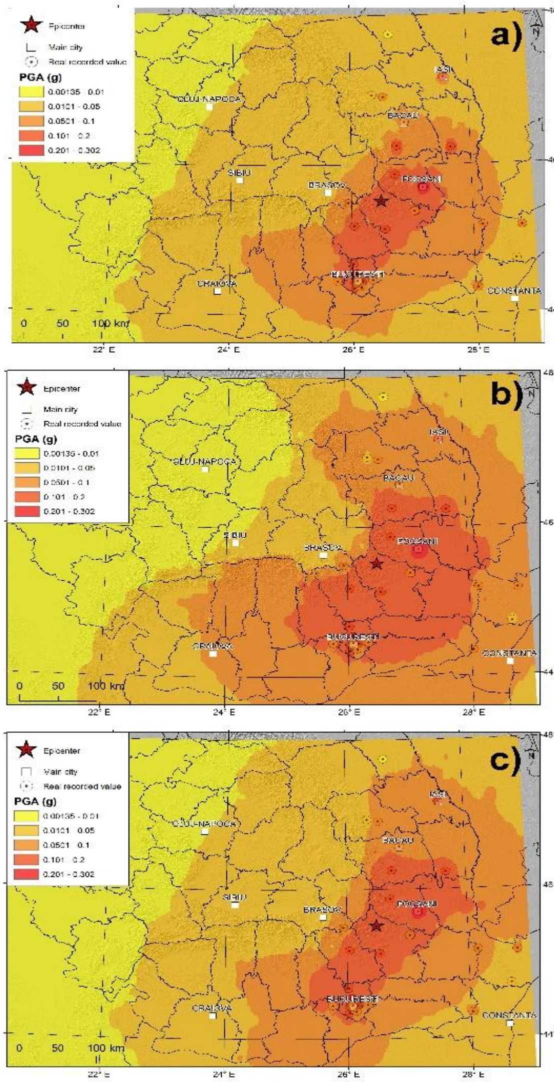


Figure 2 *ShakeMap style representations of Peak Ground Acceleration (PGA) for a scenario of the 30 August 1986 earthquake (Mw 7.1), obtained automatically in GIS based on real-data from 30 stations and on two different GMPEs: Vacareanu GMPE (a) and Sokolov GMPE (b), combined based on azimuthal interval fit (c) using the methodology described in Toma-Danila and Cioflan (2017b)*

3. USING GIS FOR SEISMIC RISK ANALYSIS

3.1. The contribution of GIS within risk evaluations at national level

SeisDaRo (The near real-time system for estimating the seismic damage in Romania) is an automated system installed at NIEP, which estimates minutes after an earthquake the possible damage, in terms of residential buildings affected (at city/commune level) and number of victims. At its core is the SELENA software (Molina *et al*. 2010), which is a Matlab routine that produces tabular results, but not maps. We employed GIS both in preparing the input (geocoding of statistical census tracts with info regarding residential buildings and inhabitants, determination of soil type) and in processing the output, in a way that is useful for representation and dissemination. In Figure 3 we present some of the latest SeisDaRo cartographic products. These types of maps are particularly useful and much appreciated by emergency management experts, although the uncertainties in the estimates need to be clearly stated, through the use of disclaimers. SeisDaRo also provides downloadable GIS data, which is further used in webGIS products that are easy to interrogate, filter and share.

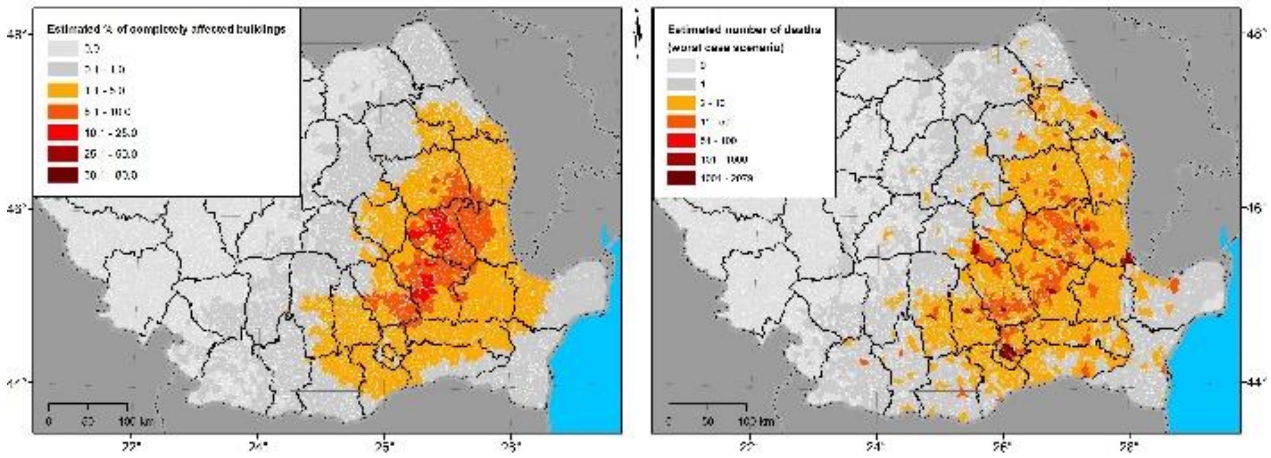


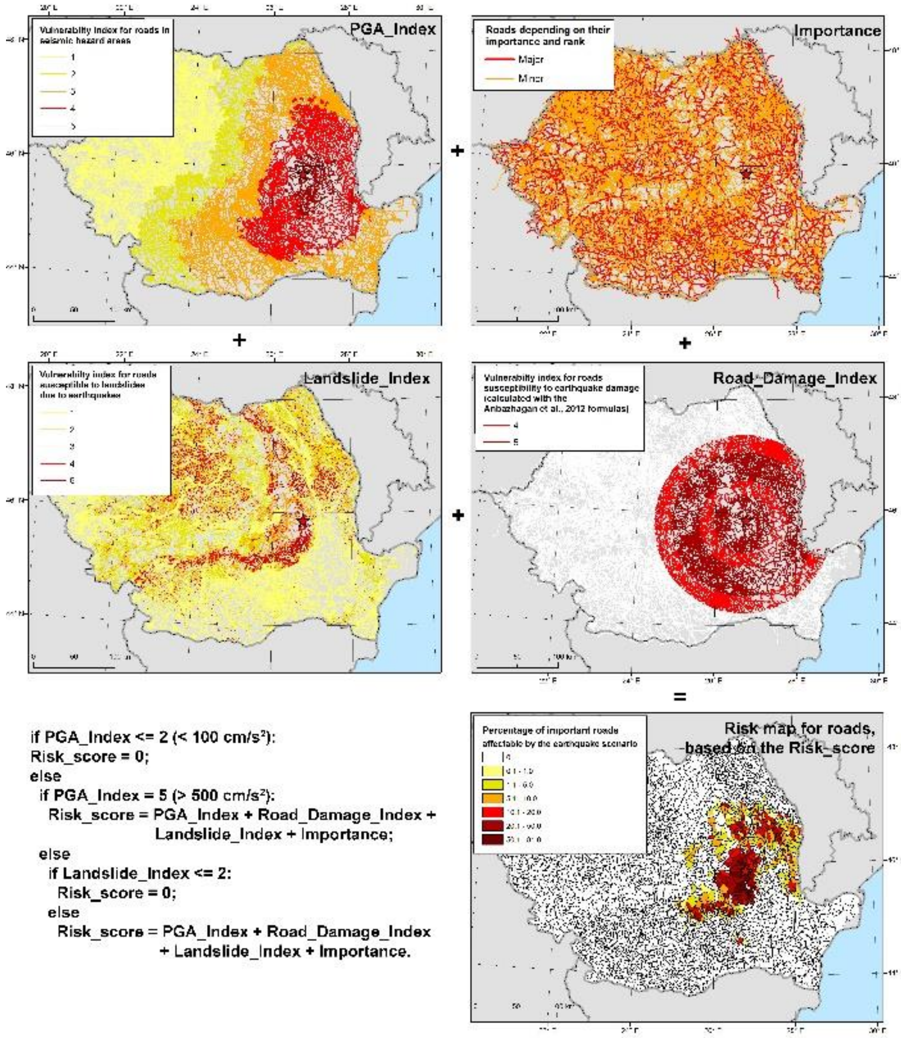
Figure 3 *SeisDaRo maps depicting easy to understand seismic loss estimations, as percentage of completely affected buildings (left) and number of deaths in a worst-case scenario (right), for a Vrancea earthquake scenario with Mw = 7.5*

Within the Ro-Risk Project, NIEP was in charge of assessing the potential loss on road networks, due to earthquakes in Romania. One of the basic inputs for this task is the road network definition, not only by shape, but also by properties such as road type, width, construction material, technical state, traffic values, etc. Unfortunately, in Romania most of this info is unavailable at administrative level (not to mention that an imposed GIS format for data is non-existent). As backup solution, we used OpenStreetMap (OSM) data, which was collected in a vector format from a well-known data repository (http://download.geofabrik.de/). It turned out that the data for important or even smaller county roads is highly accurate. By using the properties of this data together with other layers (landslide susceptibility, peak ground acceleration values or analysis of road damage index based on the work of Anbazhagan *et al.*, 2012) and a Multi Criteria Decision Analysis (MCDA), we obtained a preliminary risk map for road networks (Figure 4). The next step for this map is to integrate it in a GIS network analysis, reflecting also problems such as the impact of loss of connectivity or traffic patterns in a post-earthquake situation.

3.2. Urban vulnerability and risk studies

Urban vulnerability and risk analysis is a great challenge; the intricate relations in this complex environment are difficult to explain and model. There are many aspects to be considered, and overlaying is fundamental.

Recently, we were able to acquire data from the 2011 national census for population and buildings, at census tract level, for Bucharest. We applied the SeisDaRo methodology to these data, also considering seismic microzonation maps (Cioflan *et al.*, 2004; Marmureanu *et al.*, 2010) reflecting differences in amplifications throughout the city (GIS was used to extract PGA in each census tract). Further on, by using overlay analysis with satellite imagery, removing areas like parks, water bodies, industrial areas, streets etc. from contiguous census tracts and isolating areas where only reinforced concrete flats are present, the urban seismic loss estimate map for Bucharest was enhanced (Figure 5).



```
if PGA_Index <= 2 (< 100 cm/s²):
Risk_score = 0;
else
  if PGA_Index = 5 (> 500 cm/s²):
    Risk_score = PGA_Index + Road_Damage_Index +
                 Landslide_Index + Importance;
  else
    if Landslide_Index <= 2:
      Risk_score = 0;
    else
      Risk_score = PGA_Index + Road_Damage_Index
                   + Landslide_Index + Importance.
```

Figure 4 *Maps depicting the datasets used within the Ro-Risk Project to determine the potential seismic damage of road networks; the formula shows the algorithm used to compute the risk score.*

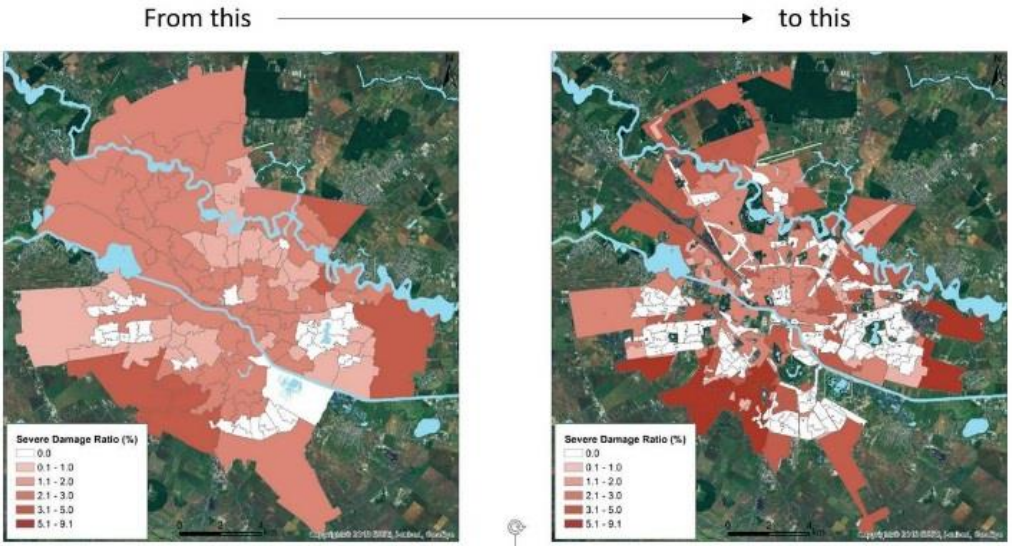


Figure 5 *Maps presenting the Severe Damage Ratio in Bucharest due to an earthquake scenario similar to the 4 March 1977 event (Mw=7.4), in a SeisDaRo approach relying on statistical data (left) and after a GIS enhanced analysis (right) (source: Toma-Danila and Armas, 2017a)*

Figure 6 reflects the results of another seismic urban risk analysis, addressed to determining which are the service areas and times of intervention for emergency hospitals (ambulances) and fire-fighters in Bucharest, considering a potentially damaged road network due to the collapse of high risk buildings and traffic congestion. ArcGIS and its network analysis module was the main framework used for computation, which could also be performed in real-time, contributing to a more efficient resources allocation in case of a disaster.

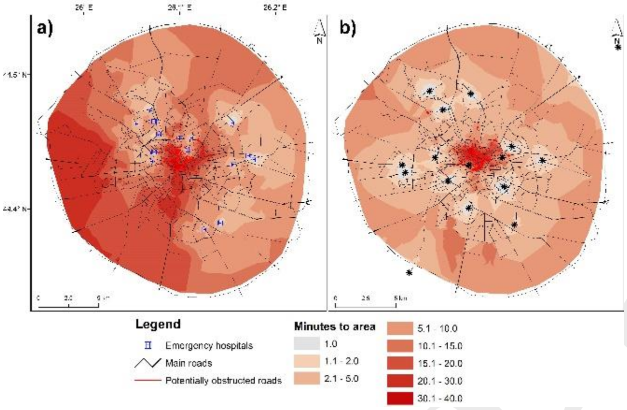


Figure 6 *Maps with service areas (merged), for all emergency hospitals (a) and firefighter units (b) in Bucharest, considering a worst-case road network scenario (all potentially obstructed roads affected) and 8:00 AM Monday typical traffic (source: Toma-Danila, 2017c).*

4. CONCLUSION

GIS is nowadays also a fundamental tool in seismology. It can be used in a wide array of applications, from processing and analyzing earthquake catalogs to seismic hazard and risk analyses or modeling tectonic processes. As shown in this paper, by combining different attenuation models with peak ground records, GIS is capable to generate ShakeMaps to be used as input for seismic damage and loss analyses, in real-time also.

In seismic risk (at national or urban level), GIS can lead to a refined evaluation of potential losses and a more insightful consideration of aspects within the spatial dimension. GIS has to be used not only for its cartographic value, but also for its capability to link layers together, process and model them. The maps shown in this paper are the result of advanced use of GIS in seismology, and we believe that they also reflect best practices in mapping earthquake-related features. As initiatives such as HAZUS or OpenQuake show, the link between GIS and seismology is clear, and future common developments are certain.

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