Real-Time Earthquake Damage Assessment in the Romanian-Bulgarian Border Region

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SUMMARY
A near-real-time damage assessment system that computes damage and loss estimates for the Romanian-Bulgarian border region has been installed at the facilities of the National Institute of Earth Physics (INFP) in Bucharest, Romania to provide a rapid damage assessment to the emergency management agencies immediately after a major seismic event.
The system implemented at the INFP uses shake-maps that are generated automatically after an earthquake. Based on these shake-maps and the built-in exposure and vulnerability information, the structural damage estimates inflicted by the ground shaking are obtained.
Damage estimates are provided at two separate levels. In the first level, the estimated damage to the general building stock of seven Romanian counties along the Bulgarian border is provided.
The second level of the system focuses on buildings that are critical in case of an earthquake disaster including city halls, schools, governmental buildings and hospitals.

Keywords: Real-time, Damage assessment, Shake-map, Emergency management

1. INTRODUCTION

A system that computes damage and loss estimates in near real-time for the Romanian-Bulgarian border region has been installed at the facilities of the National Institute of Earth Physics (INFP) in Bucharest, Romania. The aim of the installed system is to provide a rapid damage assessment to the emergency management agencies immediately after a major seismic event. After a damaging earthquake, communication systems often fail and flow of reliable information about the sustained damage and potential casualties is hampered. As such, it is of significant importance to provide the emergency management agencies with objective and reliable estimates on the spatial damage distribution as quick as possible in order to support efficient rescue and recovery efforts.

The system implemented at the INFP facilities uses shake-maps that are generated by an automated system. The shake-maps provide estimations of ground-motion parameters that include peak ground acceleration (PGA), peak ground velocity (PGV) and spectral accelerations at multiple periods at a grid of 10 by 10 km immediately after an earthquake. Based on these ground-motion parameters and the built-in exposure and vulnerability model, estimates of structural damage are obtained on the level of communes.

Damage estimates are provided at two separate levels. In the first level, the estimated damage to the general building stock of seven Romanian counties along the Bulgarian border is provided. The damage estimates are provided at the level of the smallest administrative unit, i.e. ‘commune’ and are computed using the core methodology of HAZUS-MH®. As a result of the damage assessment, the percentage of buildings that are expected to be in a damage state that is potentially life-threatening to the occupants at each commune is depicted on regional maps. The estimated damage is obtained using the open-source earthquake damage and loss assessment tool, SELENA (Molina *et al.* 2009; Molina *et*

al. 2010).
The second level of the system focuses on buildings that are critical in case of an earthquake disaster such as city halls, schools, governmental buildings and hospitals. Damage estimates for each individual building are obtained using the capacity spectrum method (CSM; Freeman *et al.* 1975, Freeman 1978, ATC 1996) and fragility functions applied to different building typologies. As in the case of the first level assessment, the seismic demand is represented by a hazard response spectrum scaled to spectral acceleration values taken from the ground motion shake-maps. Predicted damage is obtained using a computer code that was especially developed for this purpose. The expected damage state of each critical building is depicted on a city map to be distributed to local and regional emergency management agencies.

This article only focuses on the first level of the system, which provides damage estimates for the general building stock.

So far, the system has been tested for deterministic shake-map scenarios simulating the 1977 and 1986 Vrancea Earthquakes (Oncescu et al. 1999, Mândrescu and Radulian 1999). The obtained results were found to be in accordance with the observed damage. The system is expected to support the rapid response capabilities of emergency management agencies and the activity of search-and-rescue units after future earthquakes.

2. TECHNICAL OVERVIEW OF THE SYSTEM

Figure 1 presents the flowchart of the implemented system. The system consists of three main tasks. In the first task, a *"shake-map server"* prepares the shake-maps using the ground motion data recorded in real time by the national seismic network and Sokolov *et al.* (2009) ground motion prediction equation. In a second step, the *"risk server"* conducts the intrinsic damage assessment using the static inventory database the shake-maps prepared by the shake-map server and provides georeferenced damage and loss estimates. In order to do the risk computation, the SELENA–*RISe* Open Risk package (http://selena.sourceforge.net/) is applied which is installed on the risk server. In task 3, maps of the study region that depict the damage and loss estimates are prepared and automatically transmitted to the emergency management agencies.

2.1. Methodology of SELENA

SELENA is based on the HAZUS methodology that has been developed as a multi-hazard risk assessment tool for the United States (FEMA, 2003). While the HAZUS approach is attractive from a scientific/technical perspective, the fact that it is tailored so intimately to U.S. situations and to a specific GIS software makes it difficult to be applied in other environments or geographical regions.

Aware of the importance of a reliable seismic risk estimation, NORSAR (Norway) and the University of Alicante (Spain), has developed a software in order to compute the seismic risk in urban areas using the capacity spectrum method named SELENA (SEimic Loss EstimatioN using a logic tree Approach). The user supplies the inventory data in terms of model building types, ground motion parameters, soil maps and corresponding ground-motion amplification factors, capacity curves and fragility curves corresponding to each of the model building types and finally cost models for building repair or replacement. This tool computes the probability of damage in each one of the four damage states (slight, moderate, extensive, and complete) for the given building types. This probability is subsequently used with the inventory data to express the results in terms of damaged area (square meters) or number of damaged buildings. Finally, using a simplified economic model, the damage is converted to economic losses in the respective input currency and human casualties in terms of different injury types and casualties are computed (Molina *et al.* 2010).

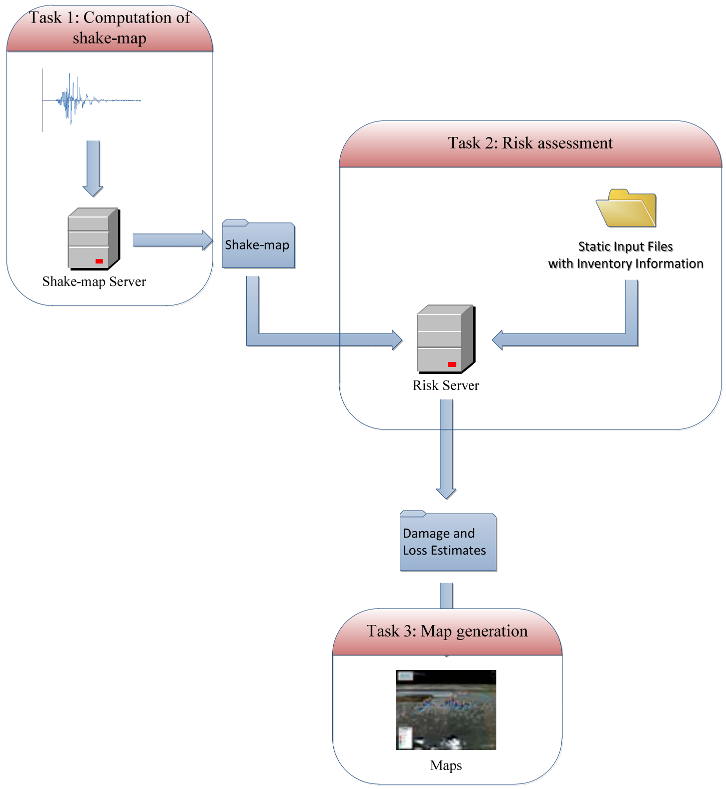


Figure 1. Flowchart illsutrating the various worksteps of the implemented system.

The algorithm is transparent in preparing and loading the input files and getting the final results. One main innovation of this tool is the implementation of the computation under a logic tree scheme, allowing the consideration of epistemic uncertainties related with the different input parameters to be properly included, and the final results are provided with corresponding confidence levels.

SELENA is a tool based upon the analytical approach for earthquake risk assessment and it combines the ground motion input in terms of response spectra (see, for example, the spectral acceleration versus spectral displacement illustrated in **Figure 2(a)**) with the building's specific capacity curve (see the example shown in **Figure 2(b)**).

The philosophy behind is that any building is structurally damaged by the displacement (and not by the acceleration itself). For each building and building type, the inter-story drift (relative drift of the stories within a multistory structure) is a function of the applied lateral force that can be analytically determined and transformed into building capacity curves. Building capacity curves naturally vary from building type to building type, and also from region to region reflecting local building regulations as well as local construction practice.
The building capacity curve is defined through three control points: Design, Yield and Ultimate capacity (**Figure 2(b)**). Up to the yield point, the building capacity curve is assumed to behave linearly elastic. From the yield point to the ultimate point, the capacity curve changes from an elastic to a fully plastic state (curved form), and the curve is assumed to remain fully plastic past the ultimate point. A bi-linear representation (two linear parts) is sometimes used to simplify the model shown in **Figure 2(b)**. The fragility functions are developed as log-normal probability distributions of damage from the capacity curves **(Figure 3)**.

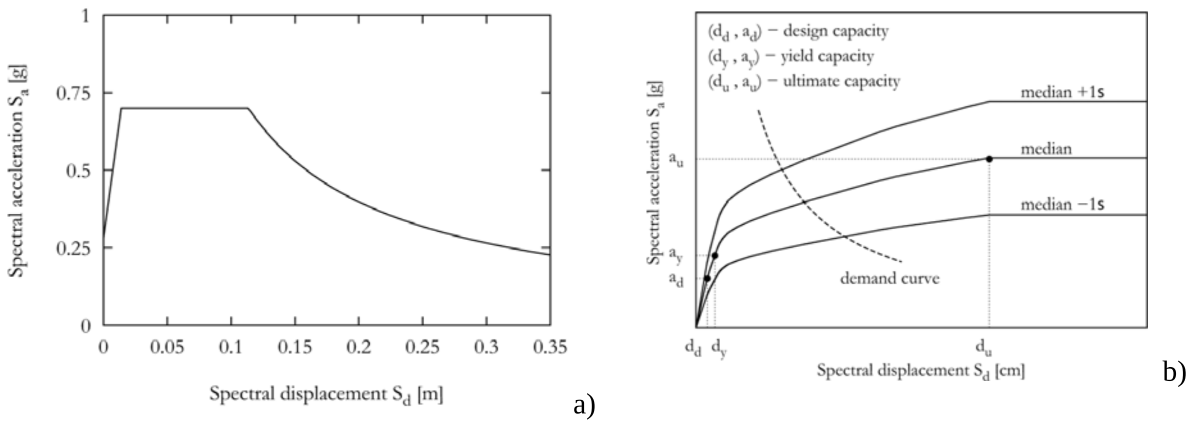


Figure 2. (a) The methodology is based on presenting the ground-motion response spectral ordinates (at given damping levels) of spectral acceleration versus spectral displacement, (b) the principle of the building-specific capacity curve intersected by the load curve representing the seismic demand.

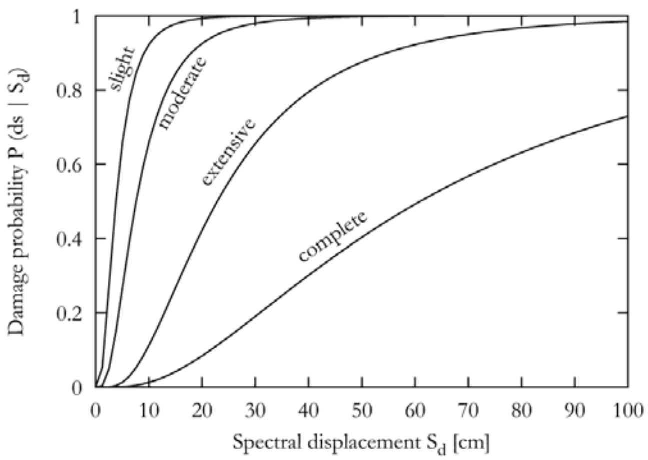


Figure 3. Example fragility curves showing the probabilities $P(d_s \mid S_d)$ of being in or exceeding the different damage states, d_s, for building type C1M as given in HAZUS (FEMA 2003).

The structural damage states are (as in most other proposed schemes and neglecting the state no damage) divided into four damage states: “slight”, “moderate”, “extensive”, and “complete”. A detailed description of these damage states are found in many places. For example, the description of damage states for reinforced concrete frame buildings are (FEMA 2004):

slight: Flexural or shear type hairline cracks in some beams and columns near joints or within joints.

moderate: Most beams and columns exhibit hairline cracks. In ductile frames, some of the frame elements have reached yield capacity indicated by larger flexural cracks and some concrete spalling. Non-ductile frames may exhibit larger shear cracks and spalling.

extensive: Some of the frame elements have reached their ultimate capacity indicated in ductile frames by large flexural cracks, spalled concrete and buckled main reinforcement; non-ductile frame elements may have suffered shear failures or bond failures at reinforcement splices, or broken ties and buckled main reinforcement in columns which may result in partial collapse.

complete: Structure is collapsed or in imminent danger of collapse due to brittle failure of nonductile frame elements or loss of frame stability. Approximately 13% (low-rise), 10% (mid-rise) or 5% (high-rise) of the reinforced concrete buildings with complete damage is expected to be collapsed.

2.2. Shake-map Generation

Immediately after an earthquake, the ground motion parameters including the peak ground acceleration (PGA) and the spectral acceleration at several periods are computed using the ground-motion prediction equation provided by Sokolov *et al.* (2009) over a grid. The site conditions at each point of the grid are hard-coded in the software and automatically taken into account. The locations of the grid points are plotted in **Figure 4**, where different shapes and colours of the markers indicate different site conditions. The computed ground motion parameter estimates are then corrected using the actual ground motion parameters recorded at several seismic stations that are under operation in the region and run by INFP.

Once the shake-maps are generated, they are automatically transferred to the risk server (**Figure 1**), which are then converted to the format that is required by the SELENA software (Molina *et al.* 2010) using a MATLAB command. SELENA, then, combines these shake-maps with the static input files that contain information about exposure data and vulnerability, and compute the damage estimates for each predefined building typology at each commune.

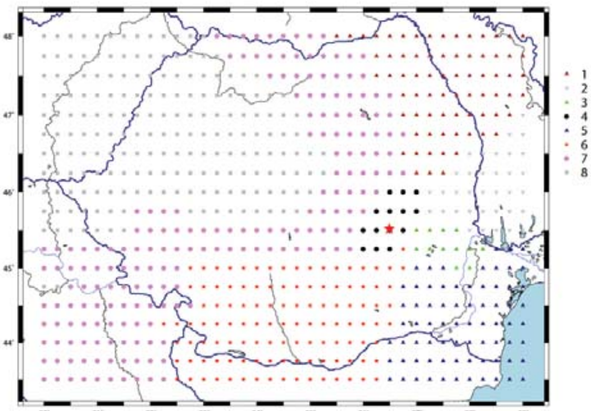


Figure 4. Locations of the grid points, where ground motion parameters are estimated. Different shapes mark different conditions (e.g., soil conditions) that affect the estimated ground motion parameters. These conditions are hard-coded in the shake-map software and, thus, implicitly considered.

2.3. Static Input Files

2.3.1. Available Inventory Database

An inventory database for Romania is available, which is based on the most recent census from the year 1999 (Marmureanu 2007). This inventory database is the most recent to be available and, though significant changes have taken place over the past 10 years, it is still regarded as adequate, though not arguably optimal (Lang *et al.* 2012). For Bulgaria, a similar database is also achieved from the authorities reflecting the number of the 2009 census. However, the Bulgarian database is cruder than its Romanian counterpart providing information at the municipality level.

The Romanian inventory database covers residential occupancy for the entire country on different administrative levels: *comuna, municipiu, oras,* and *sectors* (in case of the capital Bucharest). **Figure 5** illustrates the subdivision of the test region into these geographical units. It should be noted that the level of resolution is significantly different for the Romanian and Bulgarian sides of the considered region. This is due to the difference between the detail level of the databases available for respective countries. However, this level of resolution is regarded suitable for the purpose of the current project, since a further refinement of the spatial distribution would lead to a number of geographical units, input and output information that could not be handled anymore.

Population Distribution
Exposure is an integral part of seismic risk assessment. It covers both population and building and infrastructure systems that are exposed to potential seismic shaking. In areas of high population and high population density, expected numbers of casualties are higher than in sparsely populated areas both in absolute and in relative numbers. With respect to **Figure 5**, it can be identified that the respective test region is largely of rural character as only a few geographical units exhibit population numbers greater than 50,000, particularly on the Romanian side of the border. It should be noted that the difference between the population numbers of the Romanian and Bulgarian sides of the border is because the geounits on the Bulgarian side covers a much greater area than their Romanian counterparts. In combination with other parameters such as injury severity levels, collapse ratios etc, numbers of population provided in the inventory database can be used to compute numbers of expected casualties and fatalities.

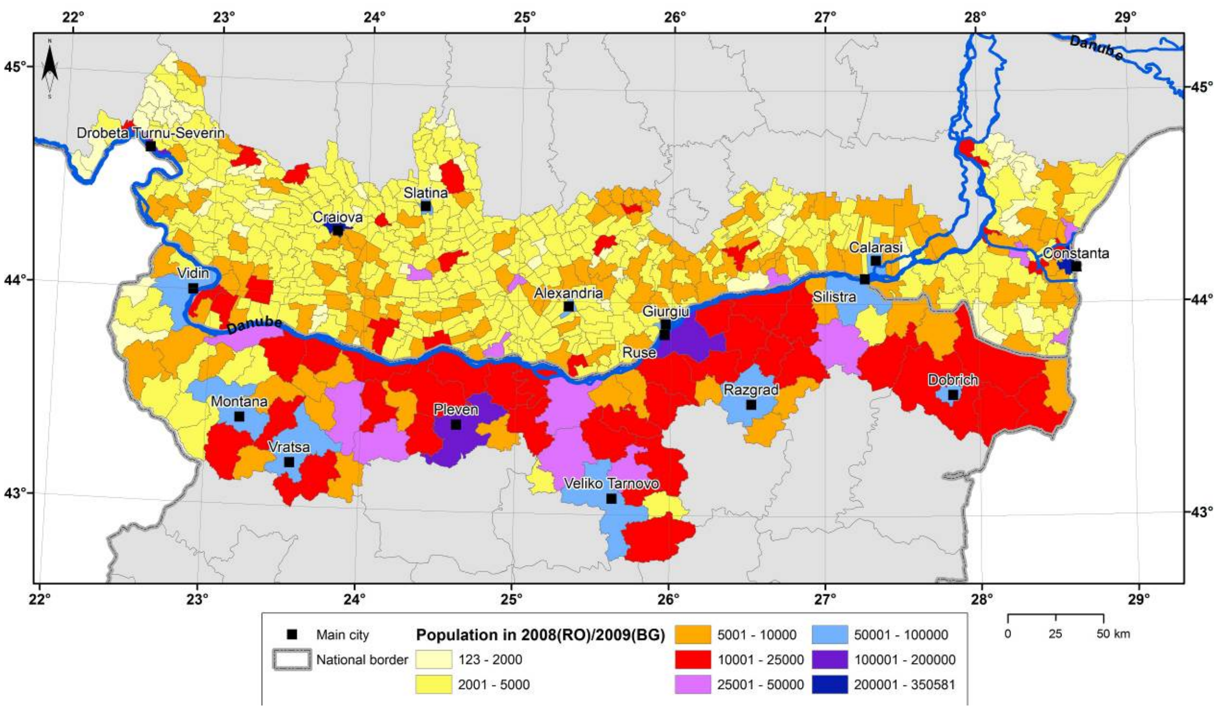


Figure 5. Population numbers in the different communes (Romania) and municipalities (Bulgaria).

Distribution of Building Stock
In general, the composition of the building stock with respect to building typologies strongly varies between rural and urban surroundings. **Figure 6** illustrates this distribution for each geographical unit while the simplified building classification scheme for Romania is applied. Strong differences can be observed between the composition of the building stock between rural and urban areas. It should be noted that the height of the columns in **Figure 6** represents the total number of buildings in the geounit.

2.3.2. Vulnerability Functions

The vulnerability functions are arguably the most important component of a real-time earthquake damage assessment study. As such, it is of utmost importance to use vulnerability functions that represent the peculiarities of the building stock for a reliable earthquake damage assessment. Despite the importance of vulnerability functions in earthquake damage assessment framework, there are very few studies that provide vulnerability functions for earthquake damage assessment. Therefore, selection of vulnerability functions from a limited database that represents the conditions of the study area remains as the most challenging task. For this study, the vulnerability functions that are available in literature have been evaluated in detail and the most suitable ones for each building typology that best represents the available building stock have been selected. It should be noted that, in the damage assessment methodology used herein, vulnerability function for each building typology consists of two sets of curves: capacity curves and corresponding fragility functions. **Figure 7** depicts sample fragility functions for three building-typologies: low-rise URM with rigid floors, low-rise confined masonry and low-rise low-code precast concrete walls. Fragility functions and capacity curves should be compatible for each building typology and one can be derived from another. As such, only fragility functions for selected building typologies are plotted here for brevity.

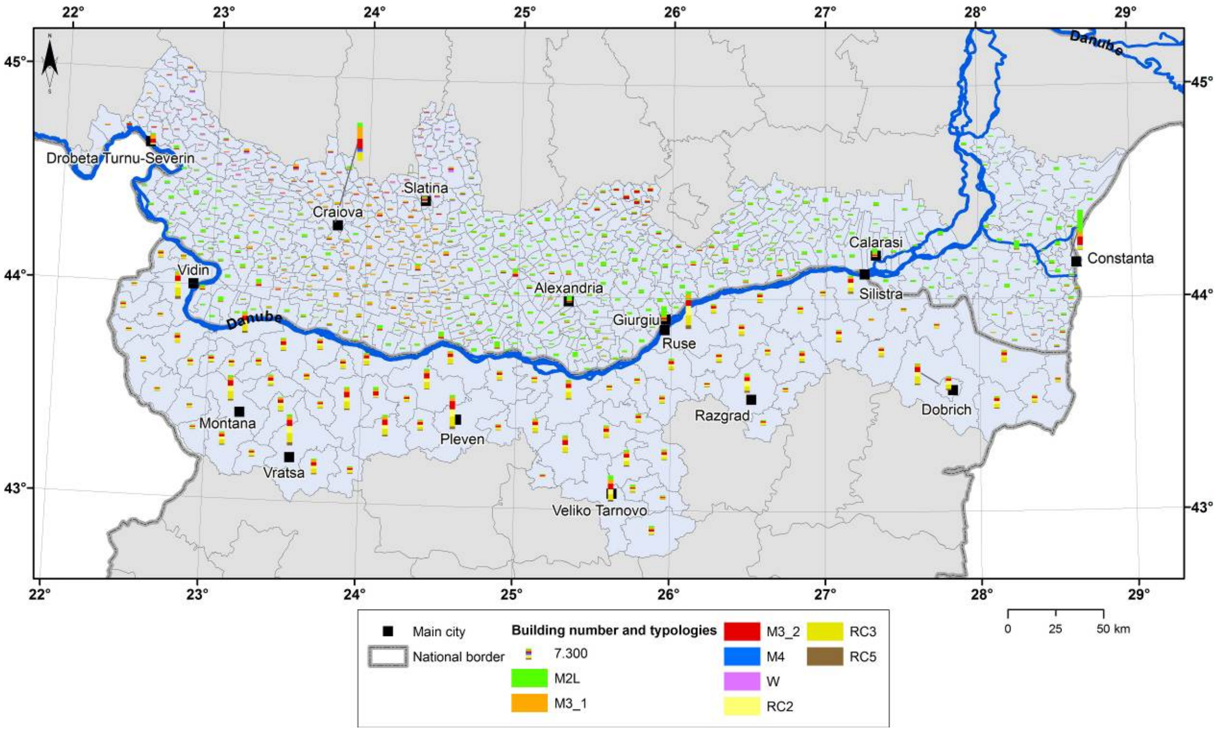


Figure 6. Percentage distribution of building typologies in the geounits.

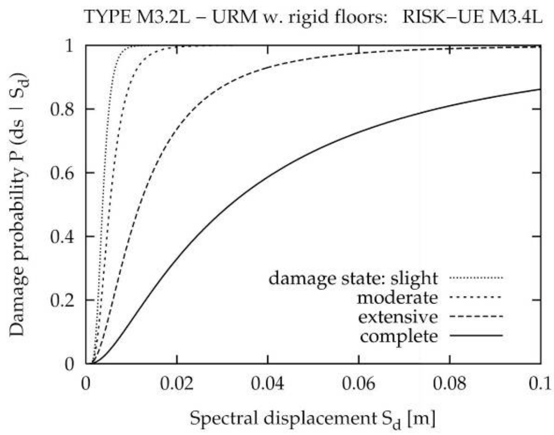
2.4. Map Generation

As part of the third task, maps that depict the estimated damage are automatically generated as soon as the damage assessment is completed. The format and the depicted damage parameter of these maps are crucial for the emergency management agencies. As a result of several discussions with the INFP and UTCB, it was decided that the maps would be prepared in two different formats: *pdf* and *kml*. The *kml* format is the standard format for Google Earth and Google Maps plots and hence can be used to project the damage estimates on the screens in the control room facilities of the INFP.

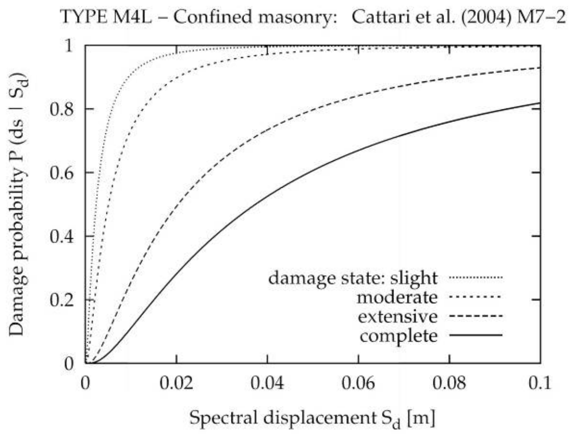
Regarding the damage parameter that will be depicted on the maps, two parameters have been considered. The first one is the *Mean Damage Ratio (MDR)* which is computed assuming a repair cost for all damage states and calculating the total repair cost as a proportion of the reconstruction cost:

$$MDR = \frac{\sum_j \sum_{i=1}^{m} N_j^k DR_j}{N_T} \tag{1}$$

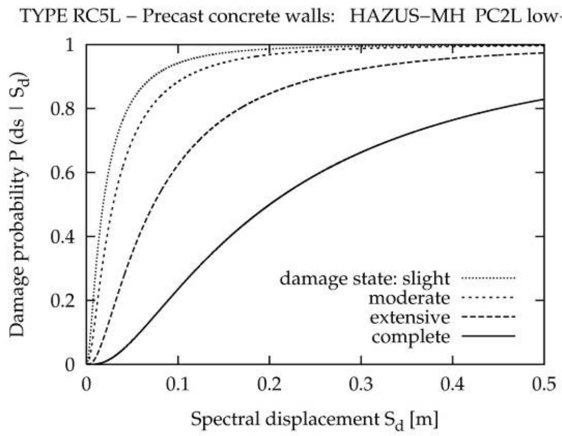
where the subscript j represents one of the four damage states (*slight*, *moderate*, *extensive* or *complete*), N_j^k is the number of buildings or total built area of class k in damage state j, DR_j is the ratio of the repair cost for damage state j to the reconstruction cost, and N_T is the total number of buildings or total built area. In this study, DR values were assumed to be 0.08, 0.33, 1.05, and 1.02 for *slight*, *moderate*, *extensive* and *complete* damage states, respectively. Values greater than 100% of the total cost of the buildings were used for *extensive and complete* damage states, since repair costs for these damage states include not only the reconstruction cost but also costs for demolition and removal of debris.



(a)



(b)



(c)

Figure 7. Fragility functions for (a) low-rise URM with rigid floors (b) low-rise confined masonry (c) low-rise precast concrete walls (low-code).

The second parameter that is also plotted is the percentage of the buildings that are expected to be in a life-threatening damage state in each commune. In this study, extensive and complete damage states were defined as the life-threatening damage states. We believe that, although *MDR* gives a more complete picture of the estimated damage and economical losses, the latter parameter that is depicted in maps, i.e. the percentage of buildings estimated to be in a life-threatening state, is more useful for emergency management agencies since their priority is to save lives.

In addition to the damage estimates in a commune, the total number of buildings in the commune can also be of significant use for emergency management purposes. As a result, in order to be able to depict both parameters on one map, each commune is depicted with a circle. The size of the circle is proportional to the number of buildings in the commune and the color-code presents the ratio of buildings that are expected to be in a life-threatening damage state. **Figure 8** depicts a sample map that is obtained using the 1986 Vrancea earthquake (M7.1) scenario, where most of the damage is expected to be on the Romanian side of the border with no significant damage on the Bulgarian side, which is in accordance with the observed damage.

3. CONCLUSIONS

A reliable and technically sound near-real-time earthquake damage assessment can be a crucial part of the rescue and recovery efforts after a major earthquake. In order to facilitate such a damage assessment system in the Romanian-Bulgarian border region, such a system has been established at the INFP facilities in Bucharest, Romania. The system consists of two parts: The first part computes the ground motion parameter estimates at a predefined grid immediately after the earthquake. These ground motion parameter estimates are then corrected and calibrated with recorded ground motion paremeters at several recording stations distributed throughout the region. These corrected ground motion parameters that include peak ground acceleration and spectral accelerations at several periods are used as the ground motion input for the earthquake damage assessment together with the static input files. The static input files include the exposure database and vulnerability functions. For the exposure database, the databases obtained separately for the Romanian and Bulgarian sides of the border are used. The vulnerability functions are selected carefully from the available functions in literature such that the selected set of functions represents the local building typologies and construction practice as realistically as possible. Earthquake damage assessment is conducted automatically using the SELENA software and the static input files along with the shake-maps generated by the risk server. The results of the earthquake damage assessment are plotted as maps that depict the percentage of buildings that are expected to be in a life-threatening damage state along with the total number of buildings at each commune. These automatically generated maps are then conveyed to the emergency management agencies in order to enable them to make better decisions on how to use their resources for more efficient rescue and recovery efforts.

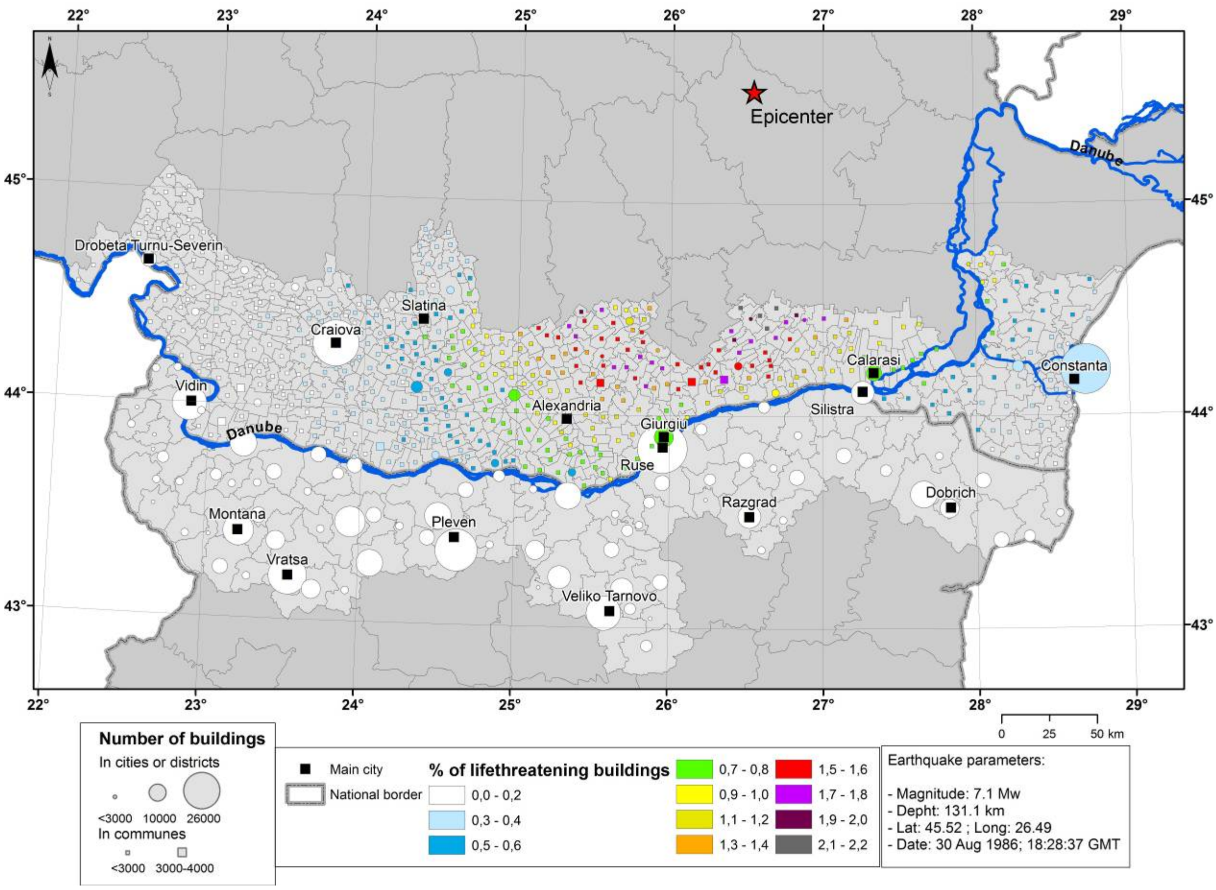


Figure 8. Final presentation of results of the damage assessment.

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