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Seismic loss estimates for buildings in Bucharest's historic centre in case of another 1977 Vrancea earthquake

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Abstract

As past seismic events showed, Bucharest (capital of Romania) can be significantly affected by another intermediate depth (or subcrustal) Vrancea earthquake. The 1940 (Mw 7.7) and 1977 (Mw 7.4) earthquakes put the number of casualties in Bucharest over 1600. Although most people and authorities are aware of the exposure, the mitigation actions are still improper and there is actually a very uncertain image of the current damage extent. The paper provides scientifically based answers, through quantitative earthquake loss estimation based on recently developed analytical methods, applied for buildings in the historic centre of Bucharest. The approach offers a relevant picture of the actual possible damage distribution after an earthquake similar to the 1977 event, in an area with heavy traffic and a high number of tourists. The Improved Displacement Coefficient Method used in this study relies on the description of structural behaviour within different limits due to specific ground motion parameters like spectral acceleration. The 358 buildings in the study area are assessed individually and specific vulnerability curves are assigned to each typology, based on height, construction year and material. The same classification as in the Near Real-Time System for Estimating the Seismic Damage in Romania is used. The results are evaluated in order to be further included in the system. In addition, an empirical loss assessment procedure reflecting the economic impact of the previously calculated situation was employed. Relevant maps for mean damage ratio and economic losses are presented and interpreted.

Keywords: *analytical methods, Bucharest historic centre, earthquake loss estimation, physical vulnerability*

Rezumat. Istoric al Bucureștiului, în cazul producerii unui cutremur vrâncean similar celui din 1977

Așa cum au demonstrat-o evenimentele seismice majore anterioare, orașul București poate fi semnificativ afectat de către cutremure de adâncime intermediară (subcrustale) produse în zona Vrancea. Cutremurele din 1940 (Mw 7.7) și 1977 (Mw 7.4) au provocat decesul a peste 1600 de oameni în București. Deși majoritatea oamenilor și autorităților e conștientă de pericol, acțiunile de reducere a riscului sunt încă neconcludente; de asemenea, nu există o imagine completă a pagubelor care ar putea fi înregistrate. Acest articol caută să clarifice acest aspect pentru Centrul Istoric al Bucureștiului, cu ajutorul estimărilor de avariere cantitative bazate pe metode analitice aplicate clădirilor individuale. Această abordare oferă o imagine relevantă a posibilei distribuții a pagubelor după un cutremur similar celui din 1977, pentru o zonă istorică reprezentativă cu trafic pietonal intens. Metoda utilizată pentru analiza clădirilor (IDCM - Improved Displacement Coefficient Method) se bazează pe modelarea simplificată a comportamentului structural în condițiile acțiunii seismice reprezentate prin valori de accelerație spectrală. Cele 358 de clădiri analizate în acest studiu sunt evaluate individual, ținându-se cont de materialul structurii de rezistență, vârstă și înălțime, iar apoi funcții specifice de vulnerabilitate le sunt atribuite. Acestea respectă tipologiile definite în cadrul Sistemului de Estimare în timp real a Pagubelor generate de cutremure în sudul României, operat de către INCDFP. Rezultatele analizei sunt evaluate și din perspectiva includerii în cadrul acestui sistem. Adițional, o metodologie empirică este aplicată pentru calculul impactului economic al avarierii clădirilor. Hărți relevante ilustrând gradul mediu de avariere și vulnerabilitatea economică sunt prezentate și interpretate.

Cuvinte-cheie: *turism pentru menținerea și refacerea sănătății, servicii spa, wellness, România*

Introduction

Cities are more vulnerable to natural hazards than other environments because they consist of a high concentration of people within a relatively small area, in which multiple systems interconnect and lead to vital dependencies. There is also another important aspect - vulnerability increases with complexity, and nowadays big cities are much more complex than they were when past major earthquake occurred. When referring to the effect of earthquakes, urban areas can suffer greatly, both due to direct and indirect damage; the impact can be considerable and on long term. Cities like Mexico City, San Francisco, Tokyo or Bucharest, exposed to seismic hazard, learned to adapt in order to survive, but there is no guarantee that past lessons were learned and also that seismic events will follow the same patterns. Research plays a major role in preparing for the next event and the loss estimates are among the key elements.

One of the major downsides in taking mitigation actions lies in the fact that the risk is much harder to predict in urban areas, because the processes between different components cannot be easily modelled. A key point to focus initially is the seismic performance of buildings, since they have the highest impact on human lives. The individual assessment of buildings is a very long process, therefore, in order to simulate a quick big picture, different other approaches were developed, showing stakeholders a preliminary estimate of the possible seismic effects they should be aware of (FEMA 2004, Molina et al. 2010, Hancilar et al. 2010).

Due to its position and building stock, Bucharest is supposed to have one of the highest seismic risks among the European capitals. Giving the high probability of occurrence of a major seismic event in the next decade in the Vrancea seismic zone, up-to-date vulnerability and risk analyses at the city level are required.

This paper aims to contribute to this effort, by studying new methodologies involving quantitative earthquake loss estimation based on analytical methods, applied in the historic centre of Bucharest. The focus of analytical methods is on physical factors making certain buildings collapse, and not on previously observed patterns based on intensity or non-invasive evaluations (correspondent to empirical approaches). Analytical methods, such as the capacity-spectrum methods developed since the 90’s, rely on a better description of the structural behaviour due to a well-defined seismic input in earthquake engineering terms (Erduran et al. 2012). The difficulty in applying analytical methods consists in defining accurate-enough models to describe relevant types of buildings' response behaviours in a large area (Vacareanu et al. 2001). Due to knowledge accumulated on site and from different acknowledged projects, we were able to overcome this aspect.

1. METHOD

1.1 Study area

Bucharest began its existence in the 14th century, as a market borough situated near the bridges over the Dambovita River at a junction of existing old roads, in the area between the forest and the steppe (Giurescu, 1979; Harhoiu, 1997; Pippidi, 2002; Mihailescu, 2003). Its growth and evolution towards gaining the status of capital (from 1659 onwards) was mostly politically driven. The city's image has been shaped by the disasters affecting it: earthquakes (1701, 1738, 1802, 1838, 1940, 1977), the Dambovita's floods, great fires (1802, 1804, 1847), and also by foreign troops occupation and influence. After the independence of Romania (in 1877), the diversification of city's functions has been reflected by specific architectural styles, increasingly evident in the 19th century, dominated by the neoclassic and eclectic styles (Curinschi Vorona, 1981; Mucenic, 1997; Celac et al., 2005). Different architectural styles are defined by the function of the building: the residential house, the inn, the shop and the institution.

Within the analysed area of the historical centre (Lipscani core area – Fig. 1) the the dwelling house (usually 2 floors) with a ground floor shop is the predominant type, being specific for the traditional commercial zone. The commercial space is represented by a normal sized room, with an entry straight from the street and with an emphasis on the show-window (the place of merchandise). In the crowded area of the commercial centre, the need to make the most of the existing space determined a narrowing of the facade and the buildings are *I* shaped. These buildings had only the shop on the ground floor, developed in length, from which there was a stair to the upper floor dwelling (Mucenic, 1997).

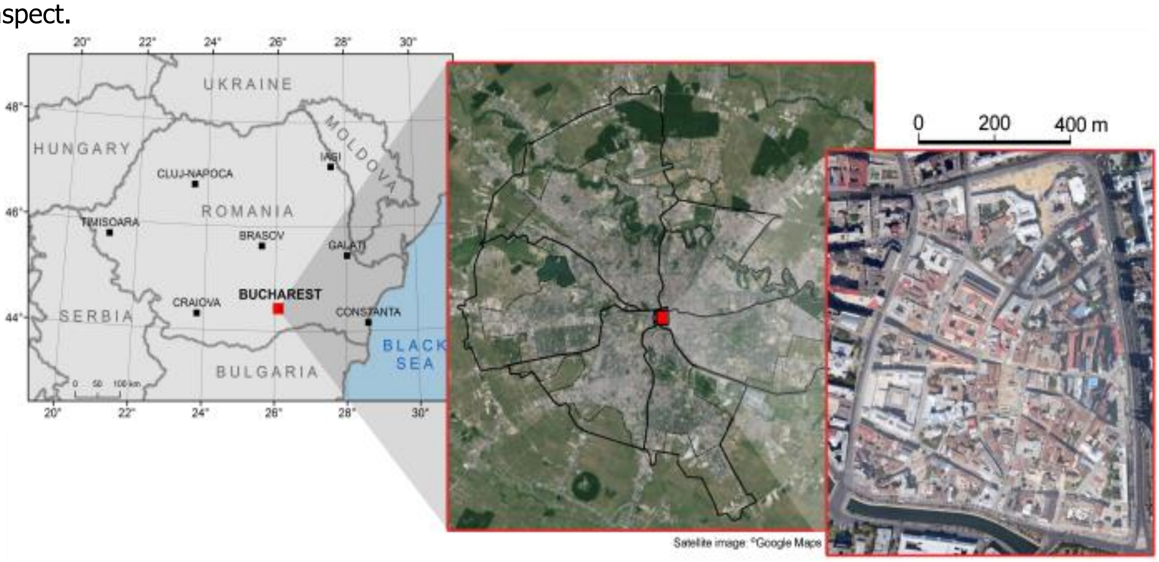

Fig. 1. Location of the study area.

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The "Inn" fulfilled an important function in the commercial development of the city. The Manuc's Inn (Hanul lui Manuc), built in 1808 on the location of the old kingdom court and the Inn with Linden trees (Hanul cu Tei), which was built in 1833 (Potra, 1981, 1985; Oprea, 1986; Mucenic, 2004) are representative for the historic city centre.

The public administration buildings appeared in the beginning of the 19th century; previously, public tasks were performed in the royal palace. From an architectural point of view, the buildings for institutions reflect the mentality of the era, willing to embrace the most modern construction techniques. A relevant example in this respect is the Palace of the National Bank.

A major modification of the central area is noticed after the first systematization of the Dambovita's River course (finalized in a first stage in 1833), when a series of nearby streets were reorganized and some buildings without architectural importance were demolished (Potra, 1990; Predescu, 1990; Pappasoglu, 2000; Olteanu, 2002).

According to the Unitary Zoning Plan (PUZ) for the Historic Centre of Bucharest Municipality and the List of 2004 Historic Monuments, prepared by the National Institute of Historic Monuments in collaboration with the Ministry of Culture and Cults, at the level of the historic core of Lipscani, currently there are 131 monuments, 14 architectural ensembles and 27 areas of archaeological interest. According to the Law no. 422 from 18 July 2001 regarding the protection of historic monuments, the historic monuments are classified into an A Group (64 monuments) and a B Group (44 monuments).

The historic center is very interesting for research, due to its importance and influence still present in today life, since many tourist and nightlife activities take place in the area. The fact that most buildings are old (19th and beginning of the 20th century) and were not constructed according to seismic regulations make the analysis even more needed.

Our attempt is to express the collapse probability of all the buildings in this area using new analytical methods. Also, the proposed methodology is capable of real-time implementation, if actual ground motion parameters recorded at seismic stations can be automatically integrated. Our intention is to test the applicability of the analysis to be used in the future for other areas too, showing what the economic impact might be.

2.2. Seismic hazard

The only seismic source that has the capacity of generating strong earthquakes with destructive effects in Bucharest is the Vrancea Intermediate-Depth Source, located in the curvature of the Carpathians Mountains, at the contact between the East-European Plate, the Moesian and Intra-Alpine Subplates (Fig. 2). Statistically, 2 or 3 earthquakes with moment magnitude greater than 7 occur in this area each century. Previous events, such as the 1940 (Mw 7.7, depth of 150 km) and 1977 (Mw 7.4, depth of 94 km) earthquakes, produced significant casualties in Bucharest – more than 1700 victims in total, more than 8000 injured people and important economic losses (Balan et al., 1982). The main damage was in the centre of the city, due to the old building stock that still poses a threat today; many buildings are now exposed not only because they were built without following a seismic code, but also because they endured several earthquakes (hysteretic factors must be taken into consideration).

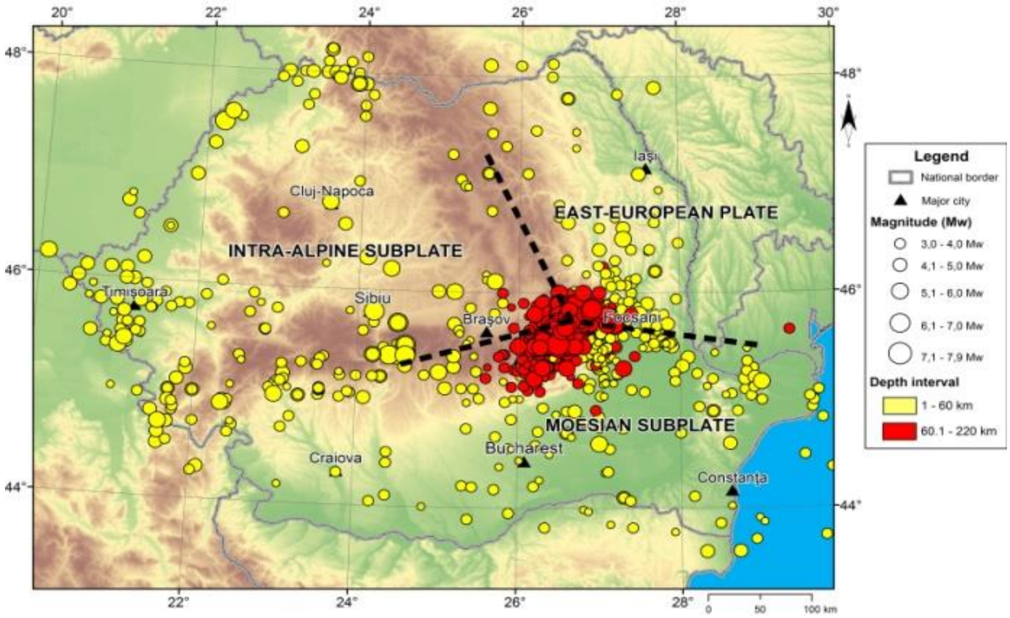

Fig. 2. Map of the earthquake epicentres (ROMPLUS Catalogue, Jan. 2014), for events with moment magnitude ≥ 3.

Although it is a known fact that Vrancea earthquakes can produce significant damage in Bucharest, there are not many studies trying to quantify what the risks are. Because each earthquake, depending on focus, magnitude and rupture plane, shows different local effects for similar areas in Bucharest, there is a great difficulty in defining a ground motion pattern. It is supposed that the non-linear behaviour of clay deposits during strong earthquakes may also be considered as a main disaster cause (Sokolov et al., 2004). Also, due to the soil characteristics (thick quaternary layers up to 250 m depth), the local site amplification is a phenomenon difficult to compute and very variable throughout the city.

Different hazard studies provide for Vrancea intermediate depth earthquakes peak ground acceleration (PGA) approximated intervals for various recurrence periods. The maximum PGA from the official P100 Romanian Seismic Code (2013 version), for a return period of 475 years, is the 0.32 g value for the entire Bucharest area.

Although *g* values are expected to be greater in a maximum possible earthquake scenario, for this study we chose to use the highest PGA value recorded until now at a seismic station in Bucharest: 0.21098 g, for the 1977 earthquake (Mw 7.4, depth 94 km, with the epicentre in the Vrancea area, more than 150 km away) at INCERC station, 5 km away from the study area. By using this value we could compare the results with a real situation.

2.3 Analytical loss estimation

The methodology used in this study relies on the Improved Displacement Coefficient Method (I-DCM), which is also currently used within the Near Real-Time System for Estimating the Seismic Damage of Romania. This method was chosen because it was already tested for Romania and a good fit in simulations with the actual damage reported in real earthquakes has been observed (Erduran et al., 2012). This method was recently developed as an enhancement of the capacity-spectrum methods.

I-DCM is based on the idea that any building (defined as a single degree of freedom system - SDOF) is structurally damaged by the spectral displacement (and not by the spectral acceleration itself). For each building, the inter-story drift is a function of the applied lateral force that can be analytically determined and transformed into building capacity curves, based on yield or ultimate points (Erduran et al., 2012). Differently from other capacity-spectrum methods (like CSM or MADRS), through the I-DCM the displacement demand of the equivalent SDOF is modified by multiplying it by a series of coefficients in order to generate an estimate of the maximum displacement demand of the nonlinear oscillator (Molina et al., 2010).

In order to express the probability distributions of the damage, fragility functions (curves) are used, based on observed behaviour of the structures in real situations or after computer-based analysis (like numerically simulated seismic response). Usually, the damage is characterized by specific damage states, like none, slight, moderate, extensive and complete (as in FEMA, 2004). For each building typology, a specific damage probability is obtained by plotting on the fragility functions the spectral displacement coordinates of the target displacement point.

The specific hazard input (in terms of PGA and SA at different periods) is used in generating an elastic response spectrum, which can be obtained through different regulations of codes like Eurocode 8 or IBC2006. In order to use this spectrum with I-DCM, it must be converted into ADRS format.

All the methodology presented above is implemented in the open-source SELENA software (SEismic Loss EstimatioN based on a logic tree Approach, ©NORSAR Institute), which was used in this study. The vulnerability curves, together with the positions of each building, were introduced as .txt input files. The demand spectrum used in SELENA was based on Eurocode8, type 2. There were no considerations of the amplification factors, because the value used was already recorded at surface, and the soil conditions can be considered similar between INCERC station and the study area, when following the Eurocode 8 soil classification (Bala, 2013).

Because the present study refers to the losses probabilities of individual buildings due to a major earthquake, we chose to use as quantitative parameter a specific mean damage ratio (MDR), to translate the probabilities of each damage state into a 0 to 1 form. This MDR is computed as follows:

$$MDR=(0.08*S_D+0.33*M_D+0.85*E_D+1*C_D)/100 \quad (1)$$

where S_D = Slight Damage, M_D = Medium Damage, E_D = Extended Damage and C_D = Complete Damage

The multiplication factors are assigned based on the importance of each damage state; some of the values are specific to formulas expressing the potential economic impact in a specific area of interest, allowing direct comparison with other regions. Giving that within this study, each building has several damage probabilities, we assigned more importance to the potentially fatal probabilities.

2.4 Empirical quantitative economic losses

The equation for quantitative loss assessment was derived from the general risk formula:

Loss= Hazard * Vulnerability * Value of elements-at-risk (i.e. buildings) (2)

In order to calculate the specific loss of the exposed buildings, the above formula was modified as follows:

$$Ls = Pt * Ps * Vn * Vb \quad (3)$$

in which Pt is the annual temporal probability of the major event scenario with the given return period; Ps is the spatial probability of the occurrence of such an event; Vn is the physical vulnerability, specified as the degree of damage to the physical environment due to the occurrence of the hazard scenario; Vb is the value of the building in Euro.

The amount of loss can be quantified in different ways (Armas et al., 2014, Bostenaru Dan, 2004). In this paper, the loss was limited to the physical vulnerability of the built environment, determined by the PGA of the earthquake event scenario and the value of the buildings in the centre of the city. The physical vulnerability was specified as the degree of damages to a building in case of an earthquake scenario similar to the 1977 event. The loss was quantified according to the value of the building estimated in Euros. This aspect was calculated as the annual probability of a major earthquake to occur multiplied by the mean damage ratio (MDR) and the value of each building. The spatial probability of the hazard event was considered as 1, because only one significant event was simulated. The value of each building was computed from the value of a square meter in the central area, multiplied by the height and the total floor space of each building. The loss analysis was spatially assessed using the Ilwis software (ITC, 2001; Westen, 2009) and the different correlational approaches were made in SPSS software.

2.5 Buildings database characteristics

For the 358 buildings in the core Lipscani, the most common structural types are:

- buildings of brick masonry structure with small bricks arch flooring M3.2 (33% of the total number of buildings)
- buildings of brick masonry structure with timber flooring M3.1 (22%)
- reinforced concrete frame with an irregular configuration RC3.2 (23%)

These three types represent over 77% of the total buildings. Table 1 presents the types of structures by height range. The investigation of buildings from the historical centre was carried out by the UTCB (Technical University of Constructions Bucharest) team led by Senior Lecturer Al. Aldea in frame of the PNII 31005/2007 project – HERA Project (website: www.hera.ase.ro), coordinated by prof. Armaş (Lungu et al., 2004; Văcăreanu et al., 2001; Armaş et al. 2010).

The buildings from M3.1 category - Masonry structures with timber flooring are unreinforced load bearing masonry constructions with wooden flooring. The flooring between levels and roof flooring are made of wooden planks supported by timber beams. In general, the seismic vulnerability of these structures is controlled by the number, dimensions and positions of cavities. Large cavities, the small shutters between cavities and corners, the small number of interior dividing walls because the rooms are spacious contribute to a higher vulnerability of the buildings.

The buildings from M3.2 category **-** Structures with masonry load bearing walls made of unreinforced bricks with small bricks arch flooring are made of unreinforced bricks with masonry arches. The masonry arches download the pressure directly on the masonry load bearing walls or indirectly through other masonry arches. In the majority of cases this structural type is used for churches or other buildings for religious purposes. In general, the vulnerability is influenced by the number, dimension and position of cavities.

The masonry structures have a medium height (56% from the total number of buildings). All old buildings were planned and constructed without taking into account the seismic activity and are classified as 'no-code'. The buildings classified as H class (high-code, advanced code) are new buildings, or retrofitted buildings in compliance with current requirements.

The RC3.2 Typology **-** Frames with an irregular configuration - have irregular structure, irregular fillings, flexible ground floor/floor (Reinforced concrete structure with reinforced concrete structural walls**)** became widespread in the 1930s, when Bucharest has seen an explosion of multi-stories reinforced concrete building. This type satisfyingly answered the various requirements of partitioning and space use. These buildings were not designed to bear the lateral stress and in addition the quality of materials and workmanship was in many cases lower. Most of these high rise buildings suffered major damage or were even destroyed during the earthquakes of 1940 and 1977.

In order to perform analysis at building level, a specific database was created based on terrain survey and statistical or land register data, with detailed information to meet the requirements of the methods used. The year of the database is 2006. The 358 buildings were defined in GIS format, with description of the height, age, construction material, address or qualitative aspects. This data were useful in determining a specific vulnerability curve correspondent (capacity and fragility curves), as defined in the list of recommended curves for Romania, developed within the DACEA Project (DAnube Cross-border system for Earthquake Alert) by the UTCB and NORSAR Institute and represented in Table 1.

Table 1: Structure of the DACEA Project buildings database and associated vulnerability curves (48 in total)

	Construction material	Material Code	Height class	Construction code
MAW	Adobe	M2	L	PC, LC, MC, HC
MAW	Unreinforced masonry bearing walls with flexible floors	M3_1	L	PC, LC, MC
MAW	Unreinforced masonry bearing walls with flexible floors	M3_1	M, H	PC, LC, MC
MAW	Unreinforced masonry bearing walls with rigid floors	M3_2	L	PC, LC, MC
MAW	Unreinforced masonry bearing walls with rigid floors	M3_2	M, H	PC, LC, MC
MAW	Reinforced or confined masonry bearing walls or retrofitted (overall strengthened) masonry buildings	M4	L, M, H	HC
MAW	Wood structures	W	L	PC, LC, MC, HC
RC	Concrete shear walls	RC2	L, M, H	PC, LC, MC, HC
RC	Concrete frame with unreinforced masonry infill walls	RC3	L, M, H	PC, LC, MC, HC
RC	Precast concrete walls	RC5	L, M, H	PC, LC, MC, HC

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

Code abbreviations *PC = PreCode - older than 1963; LC = LowCode - 1963-1977; MC = Moderate Code - 1978 – 1991; HC = High Code - 1991 - 1999*

Although these vulnerability curves involve a generalization of many building types and not all of them are designed based on local construction practices, we think that for the analyzed area – which comprises mostly very old buildings which doesn't respect many seismic regulations (many are in the PreCode class), the universal difference is not at all significant with buildings in other parts of the world (especially the Balkan area). The same vulnerability curves are also used within the Near Real-Time System for Estimating the Seismic Damage of Romania, operated by the National Institute for Earth Physics (NIEP), and it is believed they provide a good fit with the possible losses (Erduran et al., 2012).

Figure 3 and table 2 show the particular classification of the buildings within the analyzed area.

Fig.3. Building classification, according to the Material and Construction Code in Table 1

Table 2. Height range of the typologies M and RC in the historic centre

Typology	LR	MR	HR	Total
MAW	27	198	27	252
RC	8	50	41	99
Total	35	248	68	351

2. RESULTS AND DISCUSSIONS

The medium probability of a building typology (based on construction material) to belong to a specific damage class due to its structure is presented in Figure 4.

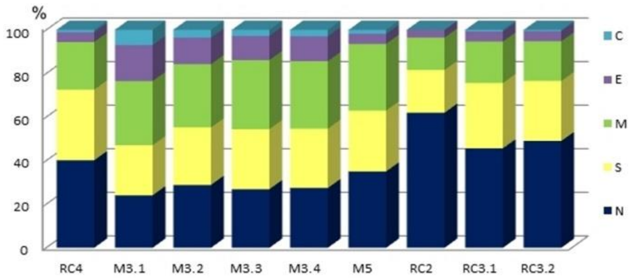

Fig- 4. Probability of damage by buildings type (where N=none, S= Slight, M = Medium, E = Extensive and C = Complete. Cumulative values = 100%)

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The analysis shows that the brick buildings are the most vulnerable in the case of a seismic scenario similar to the one from 1977. Over 85% of the M3.1 category is expected to encounter damage, with a 22.7% probability to be into the S damage class, 28.3% probability into the M damage class, with 16% probability into the E damage class and 7.7% probability into the C damage class. Over 82% of the M3.2 building structures will fit in a percentage of 25.9% to damage class S, 28% to damage class M, 12.6% to damage class E and 3.9% to damage class C. These buildings have a Mean Damage (MDR) ratio of 32%, being followed by the buildings from M3.2 category and M3.3 with a MDR of 25%. The lowest MDR of 9% is attributed to the RC2 buildings. The application of ANOVA multifactor test indicates a close relationship between typology and building vulnerability, at a significance level of 0.001 (R^2=87%).

Figure 5 presents the distribution of the classified MDR index. The classes were established based on the histogram of the medium and variation in MDR distribution on the typologies from the historic centre, as follows: 0-0.1 = very low; 0.1-0.15 = low; 0.15-2 = medium and over 0.2 = high.

Figure 6 shows the classified image of physical loss to the selected earthquake hazard scenario. The loss classes were established based on the histogram and the interpretation of specific indicators of building values (in Euros) distribution.

Fig.5. Distribution of the building damage probability, using the I-DCM method and the MDR classification

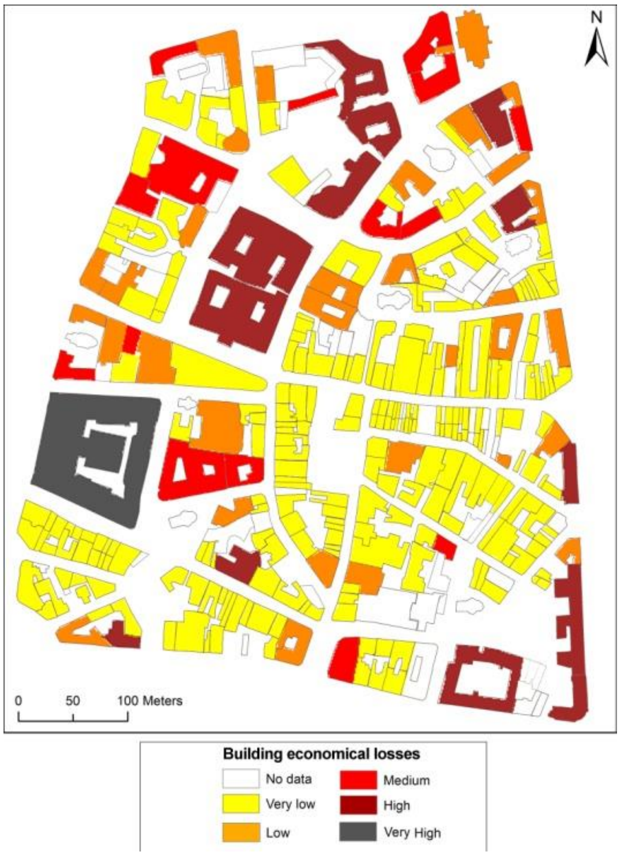

Fig. 6. Empirical economic losses (Ls), based on the estimated value of each building

The modality of loss evaluation in monetary terms (Euros) offers a simplified and incorrect image of reality, because the calculations did not take into account the effective value of the building and its content, but only the value of its 'occupied' space. Thus, the small low height buildings have a low calculated loss, even though they have high vulnerability and can be largely affected by an earthquake. Therewith, the chosen calculation method does not capture if those small buildings are architectural works of great value. On the other hand, renovated buildings of great value but with low vulnerability are represented on the annual loss map as a high risk category. That is due to the fact that if it were damaged, it would involve high costs, despite the fact that their vulnerability is low and the probability of damage is reduced. Unfortunately, the method omits these differences and requires additional adjustments with other methods in a complex risk evaluation study. Furthermore, a significant improvement in outcome would involve a punctual expertise of the monetary value of all buildings in the area analyzed. Besides, we are aware that due to its dynamics, the 2014 historic centre reality no longer corresponds to that of the year 2006, these kinds of analysis requiring regular updates and involving high costs for the continuous update of the database.

3. CONCLUSIONS

Through the methods we used and the results, we showed that seismic loss assessment at building scale can be performed, with adequate data; however the uncertainties must be always taken into account. By definition, risk is a measure of probability, not of reality. Therefore beneficiaries of the analysis (authorities, emergency units, insurers) must understand this aspect accordingly. Analytical methods are believed to offer more scientifically based assumptions, still they are relatively recent development has not allowed yet a proper validation with the actual large scale seismic damage.

The study area can be, as expected, severely damaged due to a major earthquake; there are certain buildings that will most probably not collapse and their inhabitants will be able to offer support right after the earthquake. However, the area is far from being considered safe (and it is not only the consideration of this study), and giving that a lot of activities take place here (both diurnal and nocturnal), mitigation actions need to be considered quickly. One of the key issues is persuading and efficiently helping the building owners to retrofit their buildings (since most of them cannot be demolished due to the historic and architectural importance).

All this leads us to consider these quantitative methods as potentially reliable in the loss and risk analysis only combined with other types of analysis and a continuous field-validation of results. The methodology presented is however adequate for the preliminary judgment of spatial evidence and for the identification of hot spots to be further investigated.

4. ACKNOWLEDGEMENTS

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