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Insights from existing earthquake loss assessment research in Croatia

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Abstract. Seismic risk management has two main technical aspects: to recommend the construction of high-performance buildings and other structures using earthquake-resistant designs or evaluate existing ones, and to prepare emergency plans using realistic seismic scenarios. An overview of seismic risk assessment methodologies in Croatia is provided with details regarding the components of the assessment procedures: hazard, vulnerability and exposure. For Croatia, hazard is presented with two maps and it is expressed in terms of the peak horizontal ground acceleration during an earthquake, with the return period of 95 or 475 years. A standard building typology catalogue for Croatia has not been prepared yet, but a database for the fourth largest city in Croatia is currently in its initial stage. Two methods for earthquake vulnerability assessment are applied and compared. The first is a relatively simple and fast analysis of potential seismic vulnerability proposed by Croatian researchers using damage index (DI) as a numerical value indicating the level of structural damage, while the second is the Macroseismic method.

Keywords: seismic risk; seismic hazard; vulnerability assessment; economic and social loss estimation

1. Introduction

There is an increasing need for modern society to be vigilant of the impact of catastrophic natural events due to population growth and its concentration in densely populated areas. The number of disasters in the world is increasing every year which cause more and more damage and deaths. Floods, forest fires and droughts have been causing irreparable damage, often threaten the lives of people, material, cultural resources and the environment and do not choose either the place or time when to occur. There are many areas, including towns and cities that are already at risk, where it is necessary to develop earthquake, tsunami or flood damage scenario by utilizing appropriate vulnerability assessment criteria, building and infrastructure inventories, topographical information, demographical data and other relevant facts. As has been shown in many studies (Isik and Kutanis 2015, Gürsoy *et al.* 2015, Nikoo *et al.* 2016, Makhoul *et al.* 2016) it is necessary to propose an urban planning model to minimize the damages for such areas.

Amongst the strongest and most destructive forces in nature are earthquakes. The seismic phenomenon has always existed but only in the last century have earthquakes been researched leading to knowledge of what earthquakes are and what causes them. There is no possibility to predict where and when the next destructive earthquake will happen, but awareness that the continuous growth of the population is related to a continuous growth of the size and number of towns and cities in seismic areas can lead to a reduction of potential catastrophic consequences. For this reason, the effort in reducing losses due to possible earthquakes is one of the key points in terms of risk evaluation.

When carried out at a national level, disaster risk assessments and risk management can become essential inputs for planning and creating policies in a number of areas of public and private activity. By improving the awareness and understanding of the risks a government faces, decision makers, stakeholders and interested parties are in a better position to agree on the preventive measures to take and to prepare in ways to avoid the most severe consequences of natural and man-made hazards and of other adverse events.

Seismic risk management has two main technical aspects: to recommend the construction of high-performance buildings and other structures using earthquake-resistant designs or evaluate existing ones, and to prepare emergency plans using realistic seismic scenarios.

The territory of Croatia is located in a highly prone earthquake area with the peak ground accelerations with the return periods of 475 years ranging up to 0.38g. More than half of the Croatian territory (56.22%) inhabited by more than one third (1.633.529) of the total current Croatian population is characterized as a zone with a high risk of occurrence of earthquakes. Fortunately, Croatia has not experienced strong ground shaking in the past 20 years. However, considering the map given by the National Protection and Rescue Directorate of Republic Croatia (2013) showing the distribution of past earthquakes that have occurred in the Republic of Croatia and surrounding areas, it can be observed that strong ground motions happens every 20-30 years. Despite this, there exists the need for an analysis of metropolitan areas with highly

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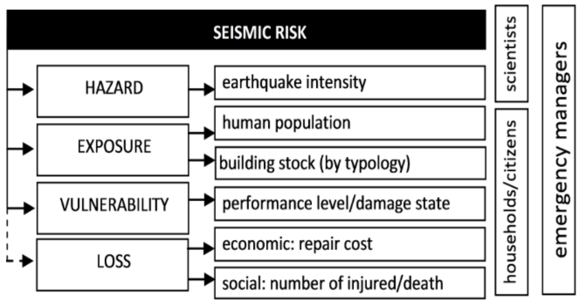


Fig. 1 Earthquake risk components

prominent seismic risk (National Protection and Rescue Directorate of Republic Croatia 2013).

The first and only analysis of earthquake loss assessment in Croatia was conducted for the city of Zagreb 30 years ago (Aničić 1992) with modest resources, and cannot be considered usable today. This is due to changes in the structure of buildings, intensive construction during this time period and new scientific achievements in seismology and earthquake engineering. Also, for earthquake loss assessment, the exposure of people and buildings has to be known, but there is no database of existing buildings for any of the Croatian cities.

Thus, the main objective of this paper is to present the current state of Croatia regarding the earthquake loss estimation procedure comprised by these four main modules: Seismic Hazard, Building Inventory, Structural Vulnerability, and Earthquake Damage Estimations as well as to provide a conceptual framework for earthquake risk assessment and socio-economic loss estimation of buildings in Croatia. Two methods for earthquake vulnerability assessment are compared: the Macroseismic method and a relatively simple and fast analysis of potential seismic vulnerability using damage index (*DI*) as a numerical value indicating the level of structural damage.

2. Elements of earthquake loss estimation

The first step in protecting a city from an earthquake disaster is to form and possess a theoretical prediction of the consequences: structural damage as well as socio-economic losses that may happen after the occurrence of an earthquake. In fact, it is crucial to assess the effects of any potential earthquake in order to prepare an intervention plan for catastrophic situations and to anticipate and take appropriate measures to reduce the vulnerability and expected losses and to guarantee urban resilience.

In literature, there are so many definitions of seismic risk which sometimes can be different, e.g., as per EERI (Earthquake Engineering Research Institute) (1981), WMO (World Meteorological Organization) (2006) or UNISDR (United Nations Office for Disaster Risk Reduction) (2009):

1. EERI: Defined as the probability that social or economic consequences of earthquakes will equal or exceed specified values at a site, at a several sites, or in an area, during a specified exposure time.

2. WMO: The expected losses (of lives, persons injured, property damaged and economic activity disrupted) due to a particular hazard for a given area and reference period. Based on mathematical calculations, risk is the product of hazard and vulnerability.

3. UNISDR: The combination of the probability of an event and its negative consequences.

Seismic risk results from the convolution of hazard, vulnerability and exposure (Fig. 1).

Seismic hazard describes earthquakes or the effects of earthquakes (e.g., liquefaction, ground motion, etc.) and their frequency of occurrence. Exposure refers to the inventory of elements in a region where hazardous events may occur and it can be described as the value of the buildings and contents, lives, business interruption, the amount of human activity or other valuables that may lead to a potential loss in a seismic event. It can include a single building with its occupants and contents or all constructed buildings in a given region (with their occupants and contents, lifelines, and utility systems) depending on the aim of the risk assessment study. Vulnerability can simply be defined as the sensitivity of the exposure to seismic hazard(s). The vulnerability of an element is usually expressed as a ratio of the expected loss to the maximum possible loss (on a scale from 0 to 1) for a given hazard severity level (Coburn and Spence 2002). The more vulnerable a building is (due to its type, inadequate design, poor quality materials and construction methods, lack of maintenance), the greater the consequences will be.

In the case of seismic risk assessment of a large region, or even a whole country, seismic hazard is described in terms of a ground-motion parameter, exposure is generally obtained from a building census, while damage of different classes of buildings or other exposed elements is presented through a vulnerability function (Crowley *et al.* 2009).

3. Seismic hazard assessment

Seismic hazard can be assessed at both regional and local scales by using two predominant approaches: deterministic and probabilistic. The deterministic approach focuses on a particular scenario event (usually the maximum credible earthquake in the area), while the probabilistic one studies the entire region's seismicity and seismotectonic characteristics in order to relate its seismic hazard to a certain probability of occurrence (Bulajić *et al.* 2012).

The main difference between these two methods is that the deterministic seismic hazard assessment processes a single or just a few selected sources of earthquakes individually, whereas the probabilistic assessment combines all the essential sources of earthquakes.

Probabilistic Seismic Hazard Assessment (PSHA) commonly uses Cornell's algorithm (Cornell 1968) and his idea of a program for the calculation of seismic hazard which was later improved by others. The definition of the seismic sources can be concluded through the study of the spatial distribution of the seismicity and the geological, geophysical and seismic characteristics of the influence zone of the site. For a given zone, a seismic model is defined for each seismic source which defines the temporal occurrence of earthquakes (e.g., a Poisson model, as well as

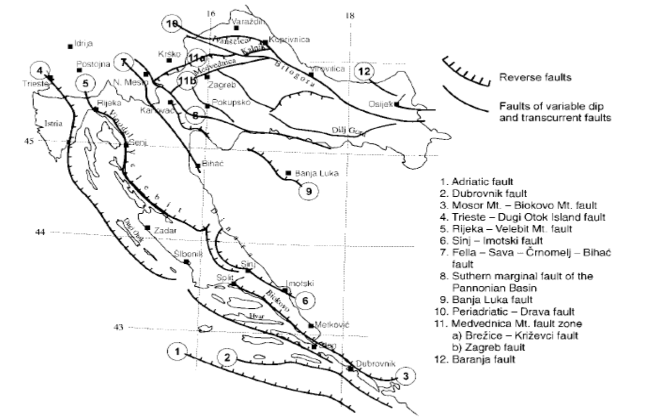


Fig. 2 Map of the most important seismogenic faults (Medak *et al.* 2007)

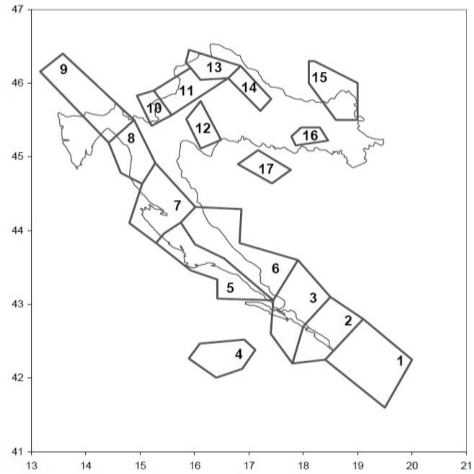


Fig. 3 Seismogenic source zones proposed by Markušić and Herak (1999)

the frequency of occurrence of earthquakes according to its magnitude (e.g., Gutenberg-Richter law)). Once the seismicity of the sources is identified, the distribution of the parameter indicating the seismic hazard at the site has to be collected for each zone using a proper attenuation relationship. Lastly, the seismic hazard for the studied site is described as the annual possibility of exceedance of a certain level of the seismic hazard parameter as a result of the contribution to each one of the sources to the seismic hazard of the site (Bulajić *et al.* 2012).

Both probabilistic and deterministic methods play a role in seismic hazard and risk analyses performed for decision-making purposes. They complement each other to provide additional insights to the seismic hazard or risk problem. One method will have priority over the other depending on: the seismic environment, the scope of the project (single site or a region) or how the decisions to be made are quantitative. According to McGuire (2001), a general rule is that the more quantitative the decision to be made, the more appropriate it is to use the probabilistic approach.

Croatian seismic hazard map was developed based on PSHA method, which will be presented in the next sections.

3.1 Seismicity of Croatia

Croatian territory is a part of the Mediterranean zone of the Alpine-Himalayan seismic belt and comprises several distinct geotectonic units: the Pannonian Basin, the Eastern Alps, the Dinarides, the transition zone between the Dinarides and the Adriatic Platform, and the Adriatic Platform itself. The seismicity is mostly expressed in the coastal part (the Dinarides), because of tectonic processes related to the collision of the Adriatic Platform and the Dinarides (e.g., Prelogović *et al.* 1982, Aljinović *et al.* 1984). The seismogenetic faults there are mostly the reverse ones, and the tectonic movements have predominantly tangential components (Herak *et al.* 1996). The Pannonian Basin is characterized by rare occurrence of large events which is typical of intraplate seismicity (Markušić *et al.* 1998). In this area, tectonic movements are predominantly vertical on steeply dipping faults (e.g., Aljinović *et al.* 1984) (Herak *et al.* 1996). A map of the most important seismogenic faults is presented in Fig. 2.

In the work of Markušić and Herak (1999), a detailed research regarding Croatian seismicity is presented. The aforementioned paper also provides an overview of previous research works, dating as far back as 1851, related to Croatian seismicity.

The seismicity of Croatia is characterized by earthquakes of medium-large magnitude spread all over the country. Using data on spatial relations between geological formations and recent tectonic movements, the Croatian territory was divided into five seismotectonic provinces by Skoko and Prelogović (1989)-the uplifted parts of the Dinarides and the Adriaticum, its central part, and the southern and western margins of the Pannonian Basin. Markušić and Herak (1999) provided the first consistent seismogenic zoning and they proposed seventeen zones (Fig. 3), which may serve as sound basis for seismic hazard studies of the investigated region.

Comparison of macroseismic intensities expected for each of the seismogenic zones was investigated by various researchers. Intensities obtained by Markušić and Herak (1999) and by Kuk (1987) for the return period of 1000 years are presented in Table 1. It can be concluded that some larger discrepancies exist. Also presented in the same table are the strongest earthquakes for each of the seismogenic zones according to the article of Markušić and Herak (1999).

The seismicity of Croatia is represented by the catalog compiled from the Croatian Earthquake Catalog (Herak *et al.* 1996), which is regularly updated each year. Croatian earthquake catalogue contains information (focal depth, magnitude, coordinates of the epicenters, intensity, time, etc.) of more than 55,000 earthquakes in Croatia and surrounding areas since the seismic hazard depends on earthquakes whose epicenters are situated several hundred kilometers from the monitored area.

3.1.1 Seismic hazard maps for Croatia

For Croatia, the seismic hazard is presented with two maps, which became a part of the National Annex to EN 1998-1 (HRN EN 1998-1:2011). The maps present the reference peak ground acceleration of soil type A

Table 1 Intensities expected for the return period of 1000 years for each of the seismogenic zones estimated by Markušić and Herak (1999) and by Kuk (1987) and main properties of the proposed seismogenic zones

Seismogenic source zone No.	Name of the seismogenic source zone	I_{1000} °MCS (Markušić and Herak 1999)	I_{1000} °MCS (Kuk 1987)	Strongest earthquakes			
				Year	Area	M_L	I_{max} (°MCS)
1	*Montenegro-NW Albania*	IX	X	1979	Skadar area	6.8	
2	*Dubrovnik*	IX-X	X	1667 1995	Dubrovnik near Dubrovnik	5.1	X
3	*Ston-Metković*	VIII-IX	X	1479 1996	near Metković Ston-Slano		IX VIII
4	*Southern Adriatic*	VII-VIII				up to 5.6	
5	*Dalmatia*	IX	IX	1923–1926 1962	Šibenik area Biokovo Mt.–Hvar	5.3 5.9 and 6.1	VIII and VIII-IX
6	*Dinara*	IX-X	IX	1898 1942 1990	near Sinj near Imotski central part	6.2 5.6 and 5.5	IX VIII-IX
7	*Zadar*	VIII-IX	VIII	1963		4.8	
8	*Vinodol*	VIII	IX	1232 and 1574 1878 1916	vicinity of Vinodol and Senj	5.8	est. IX VIII VIII
9	*Rijeka*	VIII-IX	IX	1926 1511 1721	near Postojna, Slovenia Idrija, Slovenia Rijeka	5.6	VII-VIII IX-X IX-X
10	*Bela Krajina*	VIII-IX	VIII				
11	*Zagreb*	IX	IX	1880 1990	Medvednica Mt.	4.8	VIII VII
12	*Kupa Valley*	VIII-IX	VIII	1909	Near Pokupsko	6.0	VIII
13	*Varaždin*	VIII-IX	VIII	1459 1982	Near Varaždin Ivanščica Mt.	4.7	IX VII
14	*Drava Valley*	VIII-IX	VIII	1757 1778 1938 1993	Virovitica Koprivnica Bilogora Mt. Koprivnica	4.7	IX VIII VIII
15	*Baranja*	-	VIII	1922–1924	North of Osijek		VII– VIII
16	*Dilj Gora*	-	IX	1964	Dilj Gora Mt.	5.7	VIII-IX
17	*Banja Luka* (Bosnia and Herzegovina)	IX	IX	1969 1993		6.4	VIII-IX VII– VIII

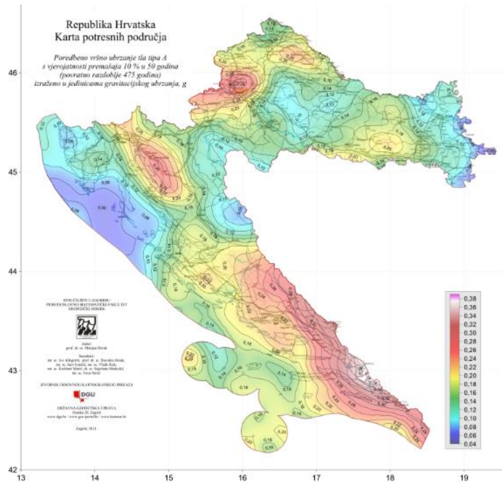


Fig. 4 Seismic hazard map for Croatia (Herak 2012)

(classification according to EN 1998-1), which is exceeded on average once in 95 or 475 years. In Fig. 4 the reference peak ground acceleration for the return period of 475 years, which corresponds to the probability of exceedance of 10% in 50 years, is presented.

4. Exposure

A building inventory is a catalogue of the buildings and facilities in each class of taxonomy, used in loss models to define the exposure to specific hazard, based on insurance exposure (Bevington *et al.* 2012). This underlying building characterization serves as input data for which the losses are calculated, and typically requires building characteristics such as type, age, height, occupancy, building value and location (Erdik *et al.* 2011).

Various inventory data do exist-HAZUS-MH (FEMA 2006) contains estimated building stocks in the United States by 128 categories; the database for Istanbul, Turkey, created at least in part by contractors examining individual buildings using a modified form of the FEMA rapid visual screening instrument; Geoscience Australia (GA) is developing a national building-exposure database. Models developed by and for the insurance industry are also known to contain estimates of portions of the building stock in various countries, but these are likewise publicly unavailable (Bevington *et al.* 2012).

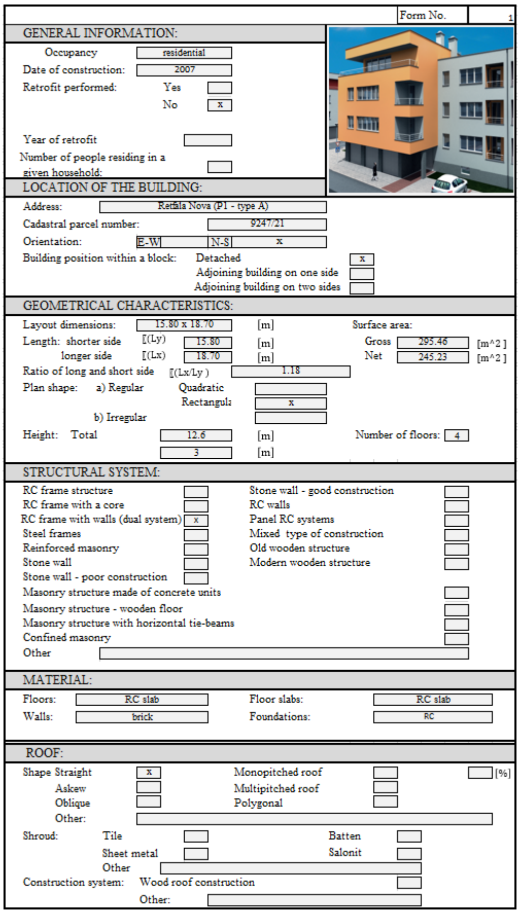
Several building typologies/taxonomies exist. Prominent among these are: EMS-98 (Grünthal *et al.* 1998), ATC-14 (1987), HAZUS-MH (FEMA 2006), RISK-UE (Mouroux *et al.* 2004) or Global Earthquake Model (GEM) (Brzev *et al.* 2013). Any taxonomy is a compromise between simplicity and thoroughness.

A spatial distribution database of buildings at a global scale does not currently exist; only a limited number of countries and cities have well developed building inventories (Erdik *et al.* 2011).

After an inventory of the buildings and other facilities to be considered in the study is collected, the relationships between intensity of ground motion, resulting damage, and associated losses of each inventory category must be established. A step in this direction is the initiative, proposed by Lang and Jaiswal (2011), to collect, compile and publicize available worldwide fragility information on the World Housing Encyclopedia (WHE). WHE, which is an open web-based database on housing construction in earthquake regions around the world, provides architectural, structural and socio-economic information on different building typologies. Unfortunately, analytical vulnerability information that can be directly used for either analytical or empirical computations is not included.

4.1 Building inventory for Croatia

A prerequisite for seismic vulnerability assessment of an area or country is the existence of a catalogue of building typology. This enables one to analyze the vulnerability of each building type, including the influence of the geometric and/or structural modifiers. Unfortunately, a standard building typology catalogue for Croatia has not been generated. This lack of data of current building stock was also pointed out in the project NERA (2011), in which six European countries were identified for such an analysis by Cambridge Architectural Research Ltd. (CAR)-Iceland, Switzerland, Serbia, Bosnia and Herzegovina, Montenegro and Croatia.



Form No. 1

GENERAL INFORMATION:

Occupancy: residential
Date of construction: 2007
Retrofit performed: Yes [ ] No [x]
Year of retrofit: [ ]
Number of people residing in a given household: [ ]

LOCATION OF THE BUILDING:

Address: Retfala Nova (P1 - type A)
Cadastral parcel number: 9247/21
Orientation: E-W [ ] N-S [x]
Building position within a block: Detached [x]; Adjoining building on one side [ ]; Adjoining building on two sides [ ]

GEOMETRICAL CHARACTERISTICS:

Layout dimensions: 15.80 x 18.70 [m]
Length: shorter side [(Ly) 15.80 [m]; longer side [(Lx) 18.70 [m]
Surface area: Gross 295.46 [m^2]; Net 245.23 [m^2]
Ratio of long and short side [(Lx/Ly) 1.18
Plan shape: a) Regular: Quadratic [ ]; Rectangula [x]; b) Irregular [ ]
Height: Total 12.6 [m]; 3 [m]
Number of floors: 4

STRUCTURAL SYSTEM:

RC frame structure [ ]
RC frame with a core [ ]
RC frame with walls (dual system) [x]
Steel frames [ ]
Reinforced masonry [ ]
Stone wall [ ]
Stone wall - poor construction [ ]
Stone wall - good construction [ ]
RC walls [ ]
Panel RC systems [ ]
Mixed type of construction [ ]
Old wooden structure [ ]
Modern wooden structure [ ]
Masonry structure made of concrete units [ ]
Masonry structure - wooden floor [ ]
Masonry structure with horizontal tie-beams [ ]
Confined masonry [ ]
Other [ ]

MATERIAL:

Floors: RC slab
Walls: brick
Floor slabs: RC slab
Foundations: RC

ROOF:

Shape: Straight [x]; Askew [ ]; Oblique [ ]; Other: [ ]
Monopitched roof [ ] [ ] [%]; Multipitched roof [ ]; Polygonal [ ]
Shroud: Tile [ ]; Sheet metal [ ]; Other [ ]; Batten [ ]; Salonit [ ]
Construction system: Wood roof construction [ ]; Other: [ ]

Fig. 5 Proposed form for collecting building data (Galista and Hadzima-Nyarko 2015)

So, the first step is to provide data about the buildings and population in a typical urban area in Croatia. This has been started for the city of Osijek, the fourth largest city in Croatia (with a population of 107 784 as of 2011) and the economic, cultural, governmental and industrial centre of the eastern Croatian region Slavonia.

The way of construction in Croatia is similar to other Balkan countries. Traditional art of construction in Croatia are mostly masonry buildings, similar as in Bosnia and Herzegovina, as it was stated in the works of Ademović *et al.* (2013) and Ademović and Hrasnica (2015). Traditional art of construction were unreinforced masonry (URM) buildings with wooden floors, which were built until the mid 1930s, when first half-prefabricated RC floors started to apply. First seismic codes were published after the earthquake in Skopje in 1963 and vertical confining RC elements were introduced in masonry building practice (Ademović *et al.* 2013). Presently, confining masonry is the common art of masonry structures in both of mentioned countries.

Before creating a building inventory for Osijek, the pertinent data for these buildings had to be defined. The data collection form for these buildings considered the attributes given by the GEM building typology (Brzev *et al.* 2013). The GEM typology describes the building using 13 properties which might affect seismic performance: direction, material of the lateral load-resisting system, lateral load-resisting system, height, date of construction or retrofit, occupation, building position within a block, shape of the building plan, structural irregularities, exterior walls, roof, floor, and foundation system. Fig. 5 illustrates the proposed building classification for the existing building stock in Osijek, defining 15 structural types.

The current database contains buildings which have an important role in the educational process, e.g., the primary schools and kindergartens, in Osijek (Ivandić *et al.* 2015, Antičević *et al.* 2015). As it is stated in Ivandić *et al.* (2015), there are 16 primary schools in the city of Osijek and most of them were built in the 1970s. Due to irregularity of layouts, because of the need to upgrade the school since the population of the city increased, it was observed that most of the schools are divided into several separate structures separated by dilatation joints. Most of the buildings consist of a ground floor, and one or more floors. Depending on the number of floors, building height is between 6.50 m to 14 m, measured from the ground level. The classification of structural system of all independent buildings can be divided into four categories: RC frames, unreinforced masonry (URM) with wooden floors (which represent flexible floors) or with RC or clay block floors (which represent rigid floors) and confined masonry.

The kindergarten buildings in Osijek were built between 1900 and 1980. Most of them, about 71%, were built in the 70-s of the last century (Antičević *et al.* 2015). Almost all kindergarten buildings suffered war damage, and apart from necessary repairs after the war there were no serious construction interventions until 2005 when reconstruction of most kindergartens began. Kindergarten buildings mostly consist of only a base floor appropriate to activities that are performed within them, only some of them include a second floor as well. Approximately 62% of the buildings consist of only a base floor, while the remaining also include a second floor. The majority of kindergarten buildings are built of reinforced concrete (RC) as RC frame with URM infill walls, while a minority are built as URM structures. The foundation mainly consist of a system of RC footings and foundation beams with RC supporting slabs, and the floor structures are constructed as RC slabs or as semi-prefabricated systems.

The oldest part of the city, Tvrdja, an eighteenth-century complex containing 106 buildings, is also included in the database (Hadzima-Nyarko *et al.* 2015). All buildings of Tvrdja were constructed in the 18th and 19th century as URM made of full brick and wooden slabs.

The database also contains more than 300 private houses located in 147 different streets in the city. All the considered houses are masonry buildings. Statistical analysis shows that 12% of the houses are URM with flexible floors, 12% are URM with rigid floors (RC or semi-prefabricated floor systems) and most of the houses, 76%, are confined masonry. These three types of masonry buildings are the representative structures in the city. However, since statistical analysis was performed on a relatively small number of houses, it can be expected that the inter-building relationship might be slightly different.

The database is further extended with the residential buildings typical for every suburb in Osijek (Hadzima-Nyarko *et al.* 2017). All the considered buildings are

Table 2 Representative building types in the database (Hadzima-Nyarko *et al.* 2017)

Number of storeys	Number of buildings	Structural type
2	3	Confined masonry
3	18	Confined masonry
4	1	Confined masonry
5	57	Shear walls (9) Confined masonry (48)
6	3	Confined masonry
7	10	Confined masonry
10	4	Dual (1) Confined masonry (3)
11	1	Shear walls
12	3	Dual
ALL	100	

constructed in the second part of the 20th century, within the period from 1962 to 1987. Out of 100 buildings included in the database, 85% of the buildings are confined masonry, 11% are reinforced concrete shear wall (RC SW) dominant buildings, constructed using a special tunnel form technique, while 4 % are classified as dual systems (RC prestressed frames with RC shear walls-dual systems). With respect to the number of stories, all buildings have 2 to 12 stories (Table 2), with a greater percentage of buildings having up to five stories.

Naturally, these percentages will change when the whole database for the city of Osijek will be completed, which is presumed to be in two years. This database is used for the building typology catalogue for Croatia and for the assessment of the seismic vulnerability and earthquake risk for the city of Osijek.

5. Vulnerability assessments

Vulnerability can simply be defined as the degree of loss to a given element at risk resulting from a given level of hazard. The vulnerability of an element is usually expressed as a percentage loss (or as a value between 0 and 1) for a given hazard severity level (Coburn and Spence 2002). In a large number of elements, like building stocks, vulnerability may be defined in terms of the damage potential to a class of similar structures subjected to a given seismic hazard.

Preciado *et al*. (2015) stated that there is enormous variety of methodologies to assess the seismic vulnerability of buildings ranging from simple (e.g. empirical or qualitative) to more complex quantitative approaches (e.g. analytical-experimental). They classified the vulnerability assessment methods into two main categories: qualitative and quantitative. Analytical methods are used when a single building is evaluated in a detailed way and in numerical terms (displacement capacity, ultimate force etc.) (Hak *et al.* 2014, Muratović and Ademović 2015, Apostolska *et al.* 2016, Remki *et al.* 2016). The reliability of these results depends on the modelling capabilities and the number of assumptions that are necessary to model a real structure as a computational model. Types of analytical methods are: Analytically-Derived Fragility Curves (Farsangi *et al.* 2015), Capacity Spectrum-Based Methods (Galista and Hadzima-Nyarko 2015), Collapse Mechanism-Based Methods (Bernardini *et al.* 1990) and Fully Displacement-Based Methods (Calvi 1999). Empirical or qualitative methods are used to evaluate the seismic vulnerability of a large group of buildings in a quite general manner and allow obtaining a vulnerability qualification in terms of seismic vulnerability that could range from low to high. Empirical (or observed) assessment methods are based on the observation of damage suffered during past seismic events. Traditionally, earthquake loss studies exclusively relied on empirical observations based on a macroseismic intensity scale. The main types of empirical methods (with the works implemented method) are: Damage probability matrices (DPM) (Eleftheriadou and Karabinis, 2013), Vulnerability Index Method (Hadzima-Nyarko *et al.* 2016, Hadzima-Nyarko *et al.* 2017) and Screening Methods (Isik 2016).

Each vulnerability assessment method models the damage on a discrete damage scale. Some scales use categories that are defined and based on visual observation of cracks, with or without structural meaning, deterioration of concrete elements and masonry walls, spalling of concrete cover and buckling of reinforced rods and many others. The damage scale is used in inspection efforts to produce post-earthquake damage statistics (in empirical vulnerability procedures) or is related to limit-state mechanical properties of the buildings, for example interstorey drift capacity (in analytical procedures).

Classification of damage quantity is a very difficult task and very few recommendations are currently available, some of which are those proposed by Anagostopolus *et al*. (1989) or Bracci *et al.* (1989).

The distributions of building damage, reported in surveys after an earthquake, serve as the statistical basis of empirical curves. On the other hand, analytical vulnerability curves use damage distributions obtained from analytical simulations of structural models under increasing earthquake loads.

The damage scale limit states need to be unambiguous with respect to the damage expected in the structural and non-structural elements of buildings with different lateral load resisting systems.

Intensity (damage) scales, e.g., EMS-98 (Grünthal *et al.* 1998) and the US HAZUS method/damage scale (FEMA 2003) and ATC-13 (1987) have been widely used in loss estimation studies in Europe in recent times.

In Morić *et al*. (2003), the limit states were defined in terms of a damage index (*DI*) with values assigned to five damage grades in EMS-98.

For physical damage to the building, the EMS-98 damage grades were also considered in macroseismic method (Giovinazzi 2005).

5.1 Vulnerability assessment for Croatia

The first method implemented in this paper is a relatively simple and fast analysis of potential seismic vulnerability proposed by Croatian researchers Morić *et al.* (2001, 2002). The research provides a detailed analysis of the concept on which seismic vulnerability analysis of structures is based, especially the notion of damage index (*DI*) as a numerical value indicating the level of structural damage (Morić 2002).

Damage models are intended to quantify the structural damage as a result of earthquake action. They are based on the state variables, i.e., variables which should be able to describe the degradation/the state of the structure during the loading. Examples of these variables are interstory displacements, the deformations at member or section level, the ductility demand, the stiffness, the dissipated energy etc. Alternatively, damage index (*DI*) is a variable capable to quantify the amount of damage, which means it's a direct measure of structural damage. *DI* can involve one or more variables.

Damage indices can be determined either based on the response of the structure to a particular loading pattern or based on the dynamic response of a structure (Sadeghi and Nouban, 2016). The overall seismic response indicators distil the complexity of structural response in a single value (Nanos and Elenas 2016). Therefore, *DI* is a mathematical model for the quantitative description of the damage state of the structures and in most cases it is in correlation with the actual damage in earthquakes.

Complexity of numerical methods must correspond to the level of what it seeks to achieve. Even if the structure is modelled in detail, the exact seismic response would not be achieved since the dynamic characteristics of a future earthquake are unknown. Fast assessment must direct and brief which means that the building is interpreted by standard parameters: number of storeys, ground plan disposition, structural system, regularity of the ground plan and section, floor structure, and everything that can be determined quickly. In damage assessment algorithm, apart from knowledge of the seismicity of the location, it is sufficient to view the structure as a dynamic system; a system which is described with enough essential characteristics of seismic response with which it is possible to classify all buildings, that are according to EC8 regular in height and in the ground plan.

Therefore, Morić *et al.* (2001) proposed that the seismic response analysis of regular structures is acceptable if it is done as a simplified non-linear dynamic analysis with the time history function of ground motion as input load, and an SDOF model with known weight, elastic stiffness, damping, elastic base shear capacity and post-elastic stiffness representing the structure.

A deterministic formula of the *DI* was presented in the aforementioned article, where the *DI* is defined as a linear combination of plastic deformations, stiffness degradation and energy dissipation of a structure during an earthquake

$$DI = \frac{1}{30}\left[D + \Delta K + \sqrt[3]{\left(N_{\mathrm{Y}} E_{\mathrm{H}} / W\right)}\right] \tag{1}$$

where:

$D = u_{max}/u_y$ - the displacement ductility demand;

u_{max} - the maximum top displacement;

u_y - the yield displacement;

$\Delta K = K_e/K'$ - the relative degradation of stiffness at the end of the earthquake;

$K_e = BS_y/u_y$ - the initial structure stiffness;

$K' = BS_{max}/u_{max}$ - the residual secant stiffness of a structure after an earthquake;

BS_y - the elasticity limit base shear;

BS_{max} - the maximum base shear force;

N_y - the number of yield excursions reached during the earthquake;

E_H/W - the hysteresis energy per unit of structure mass, dissipated during an earthquake.

Table 3 Physical interpretation of damage index (*DI*) (Hadzima-Nyarko *et al.* 2011a)

Damage Index (*DI*)	Structural damage description	Possibilities of technical and economic reparation	Damage grade (EMS-98) (1° to 5°)
$0 \le DI \le 0.3$	insignificant	repairable	1°
$0.3 < DI \le 0.5$	moderate	repairable	2°
$0.5 < DI \le 0.8$	severe	repairable	3°
$0.8 < DI \le 1.0$	heavy	repairable	4
$1.0 < DI$	extremely high level or collapse	non-repairable	5°

The proposed methodology has been carefully valorized on a set of available experiments (Morić *et al.* 2001, 2002).

Spectral vulnerability functions and a database of damage indices have been generated for regular buildings classified using relevant parameters for seismic response (e.g., fundamental period, yield base shear, damping and post elastic stiffness). This was done by applying formula (1) using 20 earthquake accelerograms (Hadzima-Nyarko *et al.* 2011a). Such a dynamic system will, for a given potential seismic activity, find in the database an already determined spectral function and the corresponding *DI* in the interval from 0 to 1.

Sensitivity analysis using neural networks was then applied in order to obtain the impact of structural response parameters (fundamental period, yield base shear, damping and post elastic stiffness) on the damage level (e.g., *DI* values). In this way, the information about the importance of the individual parameters (e.g., fundamental period, yield base shear, damping and post elastic stiffness) on the value of *DI* was determined (Hadzima-Nyarko *et al.* 2011b).

In order to relate the parameters of real buildings, seismic loads and *DI*, a detailed analysis of the dynamic properties and post elastic parameters of vertical and horizontal structural RC elements (columns and walls) was also performed by Hadzima-Nyarko *et al.* (2011a). It was done by using available databases of experiments carried out using standard cyclical loading-one database containing the results of tests of 265 RC columns with rectangular cross-section and the second database containing the results obtained on RC walls. All results were displayed in the form of load-displacement curves, which were used to define post-elastic stiffness and yield base shear. Finally, using the results and database obtained during these researches, a software (Earthquake Damage Analysis of Building Structures (EDABS)) that relates structural dimensions with the dynamic properties of structures and global *DI* for various earthquakes was created for RC frame and wall structures (Hadzima-Nyarko *et al.* 2012). Seismic damage spectrum functions constructed for RC frames were presented and proposed in Hadzima-Nyarko *et al.* (2014).

Hadzima-Nyarko *et al.* (2011a) implemented the *DI* values in pre- and post-earthquake damage analysis by relating the *DI* values with the values of damage level identification according to the EMS-98 (Table 3).

Preliminary results are obtained for assessment of seismic vulnerability of structures using *DI* based on the collected building data described in the previous section (Antičević *et al.* 2015, Ivandić *et al.* 2015, Hadzima-Nyarko *et al.* 2015).

For each of the 16 primary school buildings in the city of Osijek, the seismic vulnerability was determined using the software for Earthquake Damage Analysis of Building Structures (EDABS) which is based on the calculation of *DI* coefficient and a database of damage ratio spectral functions. According to the results of the analysis provided, the buildings will suffer insignificant damage only in the case of the earthquake with a peak ground acceleration (*PGA*) of 0.1 g for both RC frames and masonry buildings. In the cases of earthquakes having *PGA* 0.2 g or higher, it is likely that the masonry buildings will collapse. RC frames show lower values of damage grades, indicating much better seismic performance, as it was expected (Ivandić *et al.* 2015).

A relatively fast seismic analysis of all kindergarten buildings in Osijek was also performed using EDABS. According to the results of the analysis provided using the software EDABS, the buildings will suffer insignificant damage only in the case of the earthquake with a *PGA* of 0.1 g for both RC frames and masonry buildings. RC frames show lower values of damage grades, indicating much better seismic performance. In the cases of earthquake having *PGA* 0.2 g or higher, it is likely that the masonry buildings will collapse. The reason of such insufficient seismic resistance is due to year of construction, material properties and the absence of rigid floors (Antičević *et al.* 2015).

The seismic vulnerability of a historical building (unreinforced masonry building with wooden floors) located in Osijek, Croatia by the damage index method is assessed by Hadzima-Nyarko *et al.* (2015). The seismic input is included by seven earthquake records based on structures represented by a SDOF system and spectral functions. Several parameters are used to represent the main characteristics of unreinforced masonry buildings without rigid floors as a simplified system and to obtain the seismic response based on the spectral functions (Hadzima-Nyarko *et al.* 2015).

The second method implemented in the articles considering building stock in Osijek is Macroseismic method (Hadzima-Nyarko *et al.* 2016). This method uses the collected information and parameters which influence the building vulnerability (plan, type of foundation, structural and non-structural elements, type and quality of materials). The method is called 'indirect' because through the vulnerability index, which was acquired by combining data from different building typologies in a specific area collected by observation in situ, the relation between seismic action and the response is obtained. While the seismic action is defined in terms of macroseismic intensity, the building's seismic quality has to be described by means of a vulnerability index V_I.

The vulnerability index of every building depends on the behavior of its structural system and it involves other modifiers as follows (Giovinazzi 2005)

$$V_I = V_I^* + V_r + V_m \tag{2}$$

where:

V_I^* - the typological vulnerability index;

V_r - the regional vulnerability modifier;

V_m, - the behavior modifier.

For each typology, a vulnerability index (V_I) is defined by a most likely value V_I^* (e.g., the typological vulnerability index), the most plausible value for the specific building type, which is computed as the centroid of the membership function. These values were adopted according to the proposals from Milutinovic and Trendafiloski (2003).

The behavior modifier, V_m, which modifies building vulnerability, is associated to geometrical features of the building (number of stories, roof loads, plan irregularities, irregularities in vertical planes, length of facade), the state of conservation and to its position in relation to the adjacent buildings.

A regional vulnerability factor, V_r, takes into account building typologies at a regional level which affects vulnerability due to traditional construction techniques in different regions.

An analytic expression is defined for the operational implementation of the methodology; accordingly the mean damage grade, μ_D, is defined as a function of the macroseismic intensity *I* and depends on two parameters: the vulnerability index V_I and the ductility index *Q* (Giovinazzi 2005)

$$\mu_D = 2.5\left[1 + \tanh\left(\frac{I + 6.25 \times V_I - 13.1}{Q}\right)\right]. \tag{3}$$

In this study, the macroseismic approach was used as it was proposed by Milutinovic and Trendafiloski (2003) and Giovinazzi (2005) in order to provide the vulnerability evaluation for each of the 111 buildings within Osijek's area. The EMS-98 vulnerability approach was also used to help with the interpretation of results. It is convenient to translate the obtained estimates V_I into the vulnerability classes defined in the EMS-98.

This impact of the behavior and regional modifiers on the V_I values, e.g., on the mean damage grade, μ_D, is presented in Fig. 6. Four separate estimates are provided, resulting from the different approaches used to estimate the V_I values: The first one considers mean damage grade calculated using only the typological V_I^* value (blue) for the M4 building typology (confined masonry-according to Milutinovic and Trendafiloski (2003)), the second one considers the typological V_I^* value (red) for the corresponding building class according to EMS-98 (most probable vulnerability class D), while the last two values consider all behavior modifiers-first (green) calculated for M4 typology and second one (violet) for the corresponding class according to EMS-98. 42% of confined masonry buildings will belong to vulnerability class C, and even 64 buildings (58%) will belong to vulnerability class B (Hadzima-Nyarko *et al.* 2016).

The mean damage grades expected in confined masonry and RC buildings for three levels of intensity (VII, VIII and

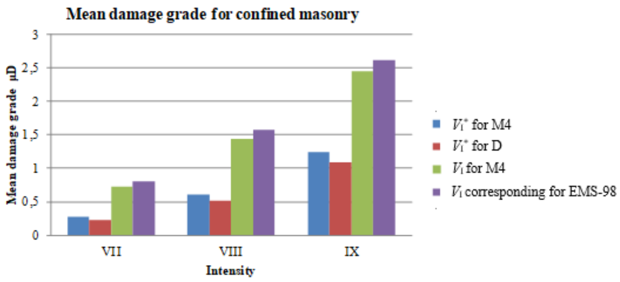


Fig. 6 Mean damage grade calculated for confined masonry buildings (Hadzima-Nyarko *et al.* 2016)

Table 4 Average values of mean damage grades and most probable damage state for three levels of intensity (Hadzima-Nyarko *et al.* 2016)

Intensity	Average μ_D for confined masonry	Most probable damage state
VII	0.722	Slight damage
VIII	1.436	Slight damage
IX	2.450	Moderate damage

IX) are calculated and the results are presented in Table 4.

Table 4 shows the most probable damage grade as a function of average damage index that allows expressing seismic damage scenarios by using a single parameter.

Using the calculated mean damage grades, the damage probability matrices are obtained for VII, VIII and IX degrees of earthquake intensity.

It can be noticed that confined masonry has a lower seismic resistance when the mean damage grade is related to the probable damage grade. For earthquake intensity VIII, it can be seen that minor to moderate damage can be expected to be observed in these buildings. Likewise, for intensity IX moderate damage may be expected.

6. Social and economic loss estimation

The measure of loss depends on the element at risk. Thus, it may be be measured as the ratio of people killed or injured to the total population, as the repair cost ratio or as the degree of physical damage defined on a suitable scale (Coburn and Spence 2002). Generally speaking, losses can be classified as direct losses (observed for a specific site as a direct result of the physical damage) and indirect losses.

Direct losses are expressed as the cost of repair or replacement, that is to say they represent the losses caused by an earthquake arising from the repair effort needed to return a damaged building to its undamaged state.

Direct economic losses for buildings include costs of repair and replacement of damage to the structural systems, non-structural components, and building contents. Replacement costs of individual buildings can simply be estimated as the product of average replacement costs of a building per unit area and total floor area of a building for each combination of model building type and occupancy class. The repair costs and contents value for different vulnerabilities are expressed as a percentage of structural and non-structural replacement cost for each occupancy class. Replacement cost is the amount needed to rebuild a building in the same location and with the same features and quality.

Strictly speaking, human casualties represent a direct loss, generally related to the collapse of the structure. Nevertheless they are in general considered separately from economic impacts, since equating or converting human lives to a monetary value is considered problematic or involving social equality issues.

We suggest that, for the expected number of deaths and injured people the casualty model by Coburn and Spence (2002) should be used. The occupancy rate of each building will be evaluated from the number of inhabitants for each census area, so the number of inhabitants for each type of building will be estimated.

7. Conclusions

This paper presents an overview of the main components of seismic risk with details regarding the components of the assessment procedures: hazard, vulnerability and exposure. An overview of the current state of seismic risk assessment in Croatia is also provided in this paper.

A review of the works considering seismic hazard is presented, as well as two basic methodologies that are used: the “deterministic” (DSHA) and the “probabilistic” seismic hazard analysis (PSHA) approaches. It is pointed out that these two methods complement one another in order to provide additional insights to the seismic hazard or risk problem. One method will have priority over the other, depending on how quantitative the decisions are to be made, depending on the seismic environment, and depending on the scope of the project (single site or a region). For Croatia, the hazard, presented with two maps, is expressed in terms of the peak horizontal ground acceleration, which is exceeded on average once in 95 or 475 years.

Exposure is related to the building stock and the amount of human activity located in zones of seismic hazard. Therefore, recent studies considering building inventory have been highlighted (Mouroux *et al.* 2004, Brzev *et al.* 2013, Lang and Jaiswal 2011). The classification of buildings, existing building typologies/taxonomies as well as a building identification procedure was presented also. A standard building typology catalogue for Croatia has not been prepared yet and the lack of data of current building stock was also pointed out in the project NERA. A database for the fourth largest city in Croatia is currently in its initial stage, but this database generation and identification of predominant building typologies of this continental city will be of great interest for other Croatian cities because of similarity in construction.

Vulnerability or the sensitivity of the exposure to seismic hazard, is usually expressed as a percentage loss (or as a value between 0 and 1) for a given hazard severity level. An overview of the various vulnerability methodologies, as well as commonly used classifications, according to different authors and countries is presented with emphasis on the initial works. An important conclusion that can be made is that any methodology, which is based on the effects of an earthquake that actually occurred, is different for each country because it is based on the proposed research methods by researchers in those countries. Simple methods for the seismic vulnerability assessment of building stocks are of principal importance for the development of earthquake loss models. As far as seismic risk is concerned, these models are essential to support the decision process in disaster prevention and emergency management.

Therefore, a relatively simple and fast analysis of potential seismic vulnerability using damage index (*DI*) as a numerical value indicating the level of structural damage is proposed, while the Macroseismic method for earthquake vulnerability assessment was also applied for residential confined masonry buildings built between 1962 and 1987.

Direct economic losses include costs of repair and replacement of damage to the structural systems, non-structural components, and building contents. In order to estimate the possible loss, the database of buildings needs to be created. This procedure is in its initial stage for the city of Osijek.

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