



Influence of site effects on the seismic vulnerability of masonry and reinforced concrete buildings in Tuzla (Bosnia and Herzegovina)

Naida Ademovic¹ · Marijana Hadzima-Nyarko² · Nermina Zagora³

Received: 28 May 2021 / Accepted: 9 January 2022 / Published online: 8 February 2022
© The Author(s), under exclusive licence to Springer Nature B.V. 2022

Abstract

Tuzla is the third most populated city in Bosnia and Herzegovina. In the last 50 years, Tuzla has experienced several minor and moderate earthquakes. On August 30th, 2019, an earthquake of magnitude $m_b = 4.7$ and the intensity from V to VI according to the MCS scale hit an area located 6 km from Mramor a village located 10 km from Tuzla. The city of Tuzla is known for salt and coal exploitation, which has caused the settlement of the city of Tuzla. Assessment of the seismic risk depends on various features, from the availability of data, knowledge regarding the buildings to the selection of vulnerability method that is going to be applied. The outcome risk assessment due to ground motion represents the first step to support the decisions and actions to mitigate potential losses. From the available database, all the structures located in Tuzla were elaborated, leading to a sample of 203 buildings, including reinforced concrete buildings, unreinforced masonry with flexible and rigid floors, and confined masonry buildings. The RISK-UE Building Category Matrix was used for structural and typological characterization of the elaborated buildings. The range of the construction period for the selected sample is from 1961 to 2014. The elaborated structures were residential buildings either for individual or collective housing. This paper aims to provide preliminary information regarding seismic risk in the Tuzla region taking into account the specific site effects on the vulnerability by applying the macroseismic model. The vulnerability index is calculated by applying the macroseismic method being a function of the type of building, behavior modifier factors, and regional vulnerability factors. The seismic risk in the town of Tuzla is in the range from medium to high. Site characteristics have been incorporated in the calculation, leading to amplification of damage and higher vulnerability of structures.

Keywords URM buildings · Reinforced concrete buildings · Vulnerability assessment · Site-effects · Macroseismic method

✉ Naida Ademovic
naidadem@yahoo.com

Extended author information available on the last page of the article

1 Introduction

The recent devastating earthquakes which occurred in Croatia, specifically in Zagreb and Petrinja once again revealed the inadequate seismic behavior of structures in the urban environment. This scenario can be connected to various factors, first of all, the age of the buildings, as most of these structures, are old buildings constructed more than 60 years ago. As well as, inadequate maintenance of buildings during their service life, poor quality of material, and deterioration of material during the time. This all has awakened the research community in Bosnia and Herzegovina (BIH) in the area of seismic assessment of existing structures, due to the similarity of building construction and the same building codes that were enforced for both countries, as before they were part of ex-Yugoslavia.

In order to evaluate the potential losses caused by moderate to high ground motions from the financial point as well as threats regarding the lives of the population, seismic risk assessment became a very powerful tool, which has been utilized not only by government agencies but as well by the owners. The results obtained by such an analysis can be used for mitigation strategies and making priority plans regarding possible strengthening procedures (Blyth et al. 2020, Kohrangi et al. 2021a).

To evaluate the seismic risk, it is necessary to obtain information on hazard, exposure, and vulnerability, all identified as probabilistic components (Kohrangi et al. 2021b). Hazard can be defined as the intensity and reoccurrence of the earthquakes in specific areas which is defined by the seismic hazard maps with a certain return period. Exposure is defined as the spatial distribution of elements at risks exposed to the seismic hazard, and vulnerability is defined as the behavior of the buildings exposed to seismic activities. Knowledge regarding a building's behavior and its vulnerability is a piece of important information for the engineers as it provides information required for decisions regarding their strengthening measures which will lead to the reduction of vulnerability, an increase of building capacity, and as a consequence, the seismic risk will be reduced. The vulnerability of the building stock in the urban center is high as most of the structures are old structures, usually lacking adequate maintenance. Additionally, the exposure of the population is high due to the densely populated areas.

Depending on the available data different approaches can be used in the vulnerability assessment of existing buildings (Arto et al. 2020). In this research, the macroseismic method with the vulnerability index was applied for selected 203 buildings taking into account the site effects which have amplified the seismic impact on the structure's vulnerability.

As far as the authors are aware, very scarce information is available regarding studies dealing with vulnerability assessment of existing buildings in Bosnia and Herzegovina. Most of the studies were done by individual researchers (Ademović 2011; Ademović et al. 2013, 2019, 2020). Vulnerability assessment in this region has not only been underestimated but to a much degree neglected. Until today to the authors' knowledge, no seismic assessment of existing buildings and structures has been done in the Tuzla region.

To obtain the required data about the existing structures, survey forms are required (Vicente et al. 2014; Formisano 2016). In this specific case, the utilized database was the result of the European research project TABULA (IWU 2017) which was implemented from 2014 to 2016. The main goal of this project was to establish a connection between the typology of residential buildings and their energy efficiency (Arnautović-Aksić et al. 2016).

Apart from the usual aspects which are taken into account during the vulnerability assessment (construction time, structural type, number of stories, preservation state, etc.) (Işık 2016; Hadzima-Nyarko et al. 2017, etc.), in the recent studies influence of the geological effects have been taken into consideration for better and more accurate prediction of expected damage (Giovinazzi 2006, 2009; Chieffo and Formisano 2019). Barbat et al. (2010) performed a vulnerability assessment, with the influence of site effects, of the city of Barcelona which is located in low to moderate seismicity. The results showed high seismic vulnerability. The influence of soil was considered by increasing the estimated intensity in the macroseismic intensities and both deterministic and probabilistic scenarios were envisaged. The behavior of the building is dependent upon the local amplification effects, an inherent attribute of the site (Chieffo and Formisano 2019), emphasizing the importance of taking into account the geo-morphological effects. Seismic ground motion is highly dependent on the site effects (geology, geomorphology) which may either amplify or deamplify the seismic motions during their propagation before reaching the surface and affecting the foundation of the structures. It is not only the high-intensity magnitudes that cause a high level of ground shaking, but shaking may be amplified due to specific geological formulations in the low magnitude earthquakes. Cherif et al. (2016) conducted an assessment of 1102 buildings for obtaining the vulnerability factors. The intensity map was produced with soil effect based on the lithological map for both deterministic and probabilistic scenarios. Taibi et al. (2019) evaluated the seismic vulnerability of reinforced concrete structures in Algeria taking into account the site effects as defined in the Algerian codes and produced the fragility curves. A similar investigation was done in 2019 for more than 3000 residential buildings in Imzouren City (Northern Morocco) after the 2004 earthquake ($M_w = 6.4$) (Cherif et al. 2019), obtained results from the deterministic approach were congruent with the observed damage on the site.

Additionally, the duration of the strong ground motion is dependent on the soil conditions and all this has a direct implication of the level of damage of a structure (Giovinazzi, 2009). The local site conditions, besides affecting the frequency content, can have an effect on the duration of the strong ground motion. The 1985 Mexico earthquake showed how extremely soft clay layers amplified the motion of the ground shaking causing a collapse of high-rise buildings at a distance of 200 km from the epicentral location. Significant damage was observed after the 2011 Lorca earthquake, even though it was a fairly small event with $M_w = 5.2$ and a macroseismic intensity of VII (Cabañas 2014). Several factors contributed to such high earthquake actions, effects of a near-source and shallow depth (Cabañas, 2014), together with rupture directivity (López-Comino et al. 2012) The horizontal peak ground acceleration (PGA) reached a high value of 0.37 g, and calculated spectral amplification were up to 4 for frequencies of 7–8 Hz (Alguacil 2014). The level of damage was most probably increased by the soil-building resonances at several sites (Navarro et al., 2013). For specific soil conditions, the ground motion was amplified by the resonant effect and equated with the predominant eigen periods leading to major damages.

This work represents the continuation of work conducted by the authors for the City of Sarajevo and Banja Luka. The main goal of this article is to conduct a vulnerability assessment on 203 buildings taking into account not only the basic modifiers as construction type, construction year, number of floors, but as well putting the center of attention on the geo-hazard effects on the build-up areas. Due to the lack of available geotechnical data on this region, a lithological map was used. The locations were classified into two main categories B and C according to Eurocode 8 (EN 1998-1:2004).

2 Tuzla region

2.1 The historical background

The city of Tuzla is located in northeastern Bosnia and is the third most populated city in Bosnia and Herzegovina (Fig. 1). It represents the scientific, cultural, and economic center of this region. Tuzla is located in the valley of Jala river. Medium–high Mountain Majevisa surrounds the city from the northeast and Spreča valley from the south. The urban area of Tuzla is located between $18^{\circ}56'$ and $18^{\circ}79'$ E and $44^{\circ}48'$ and $44^{\circ}60'$ N, at an altitude from 202 and 480 m.

Starting already from the Neolithic (young stone age) times until today, all the settlements in Tuzla were connected to the salt deposits and their excavation. The very center of the Tuzla city (present) was the location of the first Neolithic settlements. Millions of tons of salt are left behind by the old Pannonian Sea, when, more than 10,000,000 years ago, it withdrew from this area. The name of the city has always, through the time of its existence and in various languages connected with salt. The river Jala, which flows through Tuzla, bears the name derived from the Greek word *Jalos*, which means salt, while the city throughout its history, was called salt in various languages, from Castron de Salenes, Salenes (Greek), Ad Salinas (Latin), Soli (South Slavic), Memlehatejn (Arabic), Memleha-i Zir (Persian), to Tuz (Turkish) (Kožar 1995).

2.2 Seismicity and geological structures of the Tuzla region

The majority of the territory of BIH (83.2%) is identified as a seismic hazard area zone with the PGA up to 0.24 g, which is occupied by almost 90% of the entire population of Bosnia and Herzegovina (BAS 2018).

In recent history, Tuzla was hit by numerous earthquakes of low to moderate magnitude. On August 30th, 2019, an earthquake of magnitude $m_b = 4.7$ and the intensity from V to VI according to the MCS scale hit an area located 6 km from Mramor a village located 10 km from Tuzla. Tuzla belongs to the North Eastern belt known as the Inner Dinaric Alps. This zone is characterized by the most important epicentral areas including Banja Luka, Derveta, Tuzla, and Skelani with reverse faults.

According to the National Annex of Bosnia and Herzegovina (BAS 2018), the peak ground acceleration (PGA) for Tuzla is 0.21 g (Fig. 2), note that $PGA = a_{gR}$.

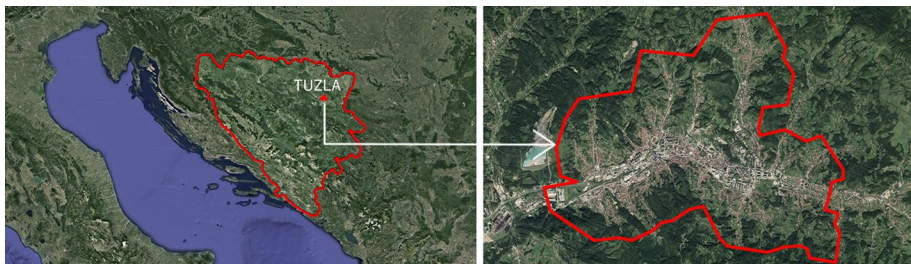


Fig. 1 Location of the city of Tuzla

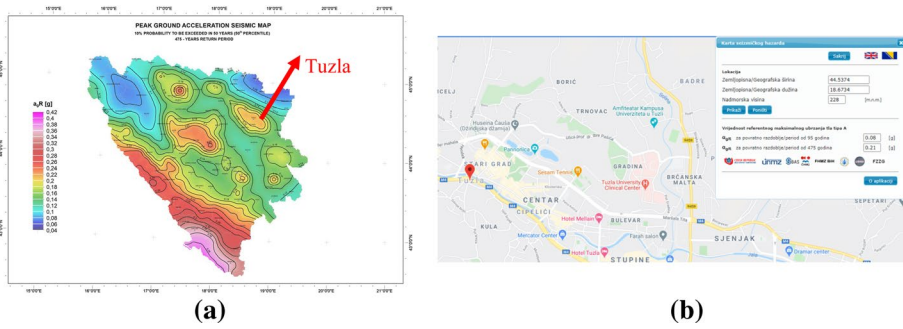


Fig. 2 a Seismic hazard map for Bosnia and Herzegovina (475 years) in the function of PGA (BAS 2018) b Interactive seismic map for the city of Tuzla (<http://eurokodovi.ba/seizmika/>)

The urban area spreads over an area of 98.37 km² and is a residence to a population of 110,797 peoples (CBS 2013).

Dominant tectonic structures for Tuzla are left horizontal faults (NE-SW direction), right horizontal faults (NW–SE direction), and normal faults (Fig. 3). On the right side an extract from the seismotectonic map of BIH is presented showing the deep faults, then the so-called first and second-order faults, as well as labile geological blocks near Tuzla. Green marked circles indicate locations of frequently registered earthquakes: Mramor, Puračić, Gnojnica, Krtova, Dobošnica, and part of the terrain south of Srebrenik. The regional fault south of the Tuzla going above Banja Luka towards Kostajnica, Petrinja, and extends south of Zagreb accumulated a certain amount of seismic energy.

In the last 100 years, 58 earthquakes were selected that influenced the seismicity of the Tuzla region (Threat Assessment 2016). The maximum recorded magnitude by Richter’s scale was 5.1, the intensity was VII by MCS scale, focal depth at 10 km, which occurred on October 29th, 1974 in Dobošnica, around 19 km from Tuzla. During this period, 16 earthquakes with magnitudes between 5 and 7 were registered with intensities between VI and VII degrees on the MCS scale. This region is characterized by shallow earthquakes and the average value of the focal depth (58 earthquakes) is only 8.8 km.

The terrains of the Tuzla Canton are classified into 3 categories of MCS seismic intensity. The wider area of Tuzla in the northwest-southeast direction, from Puračići to the line connecting Tupkovići and Tojšići, from Banovići to the south to Gornja Tuzla in the north, belongs to the category of VII accruing to MCS. The terrain of Neogene basins southeast

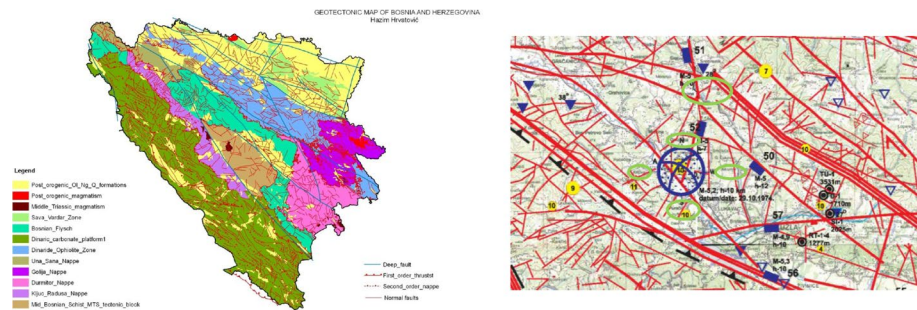


Fig. 3 Geotectonic map of Bosnia and Herzegovina (Hrvatović 2005–2010); Seismotectonic map of Tuzla region (Photo: A. K./Klix.ba)

of Gračanica, between Kakmuž, Donja and Gornja Lohinja and Orahovica, belongs to the same category. Terrains south of the Sava, in a semicircle: Orašje, Žabar, Gornji Rahić, Brusnica, Tobut, Mezgraja, Čengić, and Bijeljina belong to “calmer” terrains of the Intensity V by MCS. They are composed mainly of loose and loosely bound materials and with few tectonic elements. All other terrains of Tuzla Canton belong to the intensity VI according to MCS. The maximum expected earthquake in the city of Tuzla is of VIII intensity by MCS scale, and 6.5 by Richter’s scale. The urban center of Tuzla City belongs mainly to VII intensity by MCS scale, while two regions are identified with a higher intensity (VIII) in the region of Pannonian lakes and Brđani (Fig. 4).

Time variation of the seismic activity based on historical records and instrumental measurement of earthquakes indicates increased seismic activity in the area of Banja Luka, Tuzla, Zenica, and Herzegovina (Threat Assessment 2016). Having in mind the degree of urbanization of Tuzla Canton (TC), the number of floors of buildings, the character of the represented industry (chemical industry and mining), as well as knowledge of non-compliance with “seismic” construction buildings, it can be said that TC is a fairly seismically

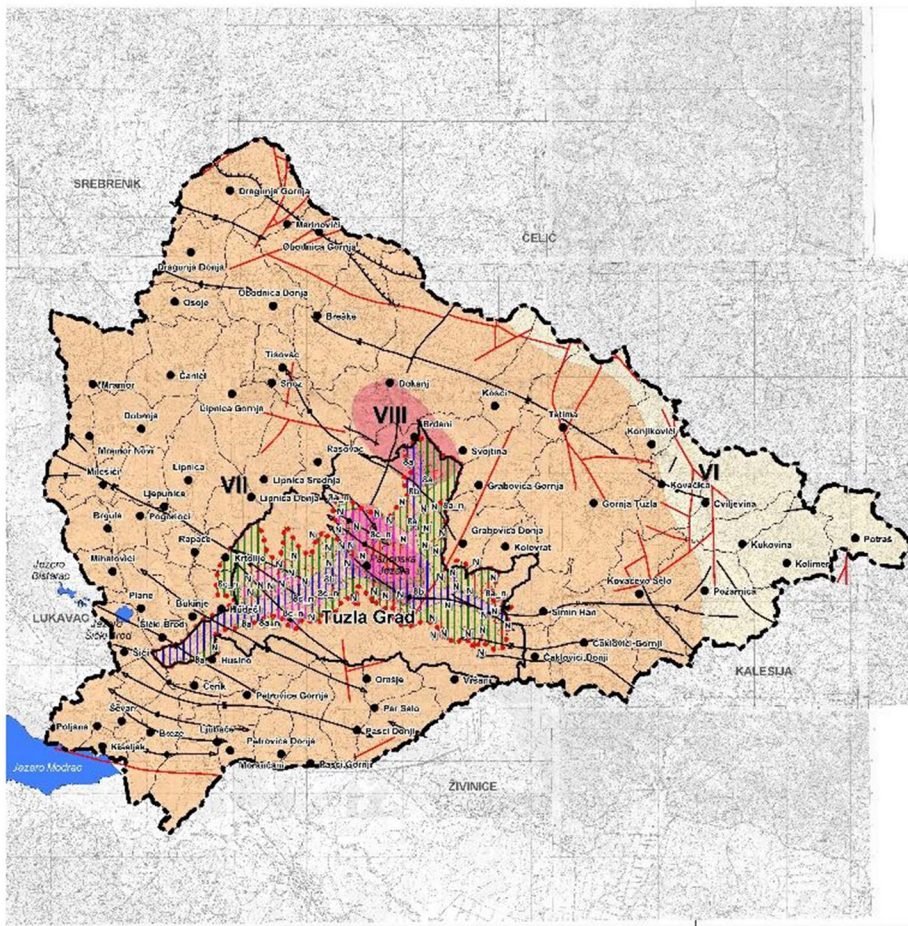


Fig. 4 Seismic map of Tuzla Canton (Department of Urbanism Tuzla Municipality 2011)

endangered area. The problem is complicated by the subsidence of the terrain in the urban part of Tuzla, as a consequence of uncontrolled exploitation of the salt deposit, in a longer period of time, as well as numerous industrial complexes near the most dangerous tectonic fault, in the municipality of Lukavac (Threat Assessment 2016).

The TC area has a complex geological soil structure characterized by weak physical–mechanical soil properties which, in unfavorable hydrological conditions and periods with long-term precipitation, are manifested as soil instability. The area of this Canton is built mostly of marly-clay and sandy sediments of the Neogene age. In the surface part, a layer thickness of 5–6 m is developed. This soil composition as well as the geomorphological properties of the terrain (mild to steep slope), together with intensive mining activity and uncontrolled urbanization, have led to the activation of a large number of landslides. In Tuzla on December 1st, 2014, the number of reported landslides was 2170 (Threat Assessment 2016). This has led to the production of an engineering geological map with marked active landslides which was used in this study and will be presented later in the paper.

The representatives of the oldest geological structures in Tuzla are the formations from Miocene dominated by organogenic limestone (known as “*Slavinovički*” limestones and dolomites) with sporadic marls. Over time clasts have been deposited over them, with specific reddish color (sandstone and conglomerates). The continuation of the sedimentation cycle is made of lithological members dolomite, anhydrite, and tufts where the salt formation is located. All this is known as a “*prugasta*” eng. stripe series (Čerimagić 2019). Among many authors, this is recognized as “*trakasta*” eng. layered series (Čičić 2002; Čerimagić 2019). It should be mentioned that in the lateral parts this is known as “*šarena*” eng. colorful series (Torbarov and Jovanović 1978). The youngest Miocene is characterized by the organogenic limestones, clays, marly clays, sands, and subsidiary conglomerates (Fig. 5) (Čičić et al. 1991). The development of the lower Pliocene is characterized

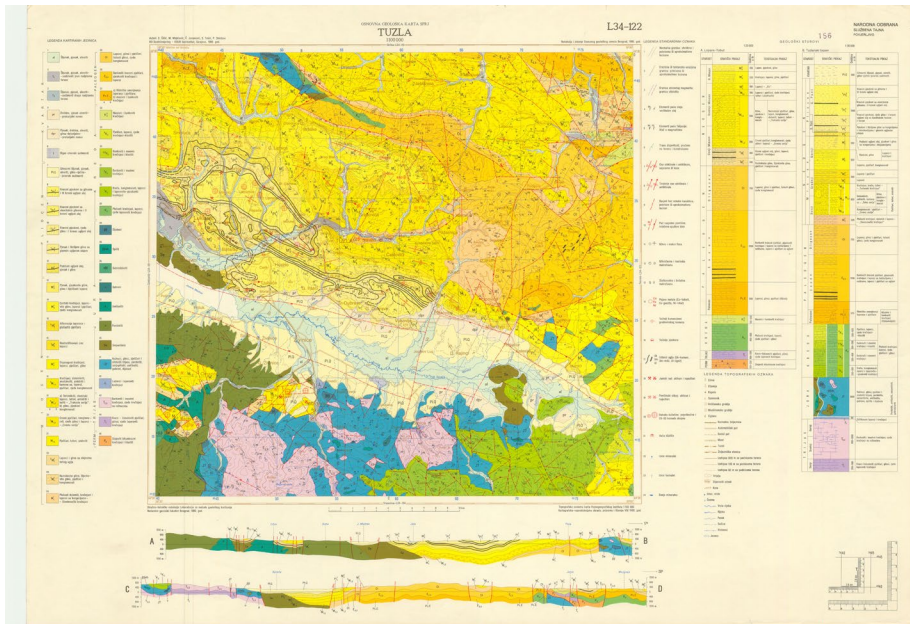


Fig. 5 Geological map of Tuzla (Čičić et al. 1991)

by the deposition of several seams of lignite. The bottom of the Tuzla basin is covered by the youngest Quaternary formations. The bottom surface of the basin is mainly covered by deposits made of semi-bonded and bonded fluvial terraces and alluvial sediments (sand and pebbles) (Lepirica 2013).

Under the surface of Tuzla lies 650 million tons of salt rocks. The exploitation of the salt springs according to the written documents goes back to 1548. It is during the Austrian-Hungarian Empire that massive salt exploitation started in the Tuzla region. The first written documents regarding salt boiling were found in Greek writers Pseudo Aristotle and Strabon (Bakalović and Perić 2011). According to (Mancini et al. 2009a) Tuzla has sunk up to 12 m from 1956 until 2009, which thought the years had a damaging effect on building and infrastructure facilities. Bašić et al. (2012) as a result of their study produced a map indicating the risk induced by the salt extraction from the underground. In their study, they have concluded that the withdrawal of saltwater has triggered new hazards such as fast water table rise after the reduction in the extraction activities. Mancini et al. (2009b) analyzed the building risk assessment exposed to subsidence due to salt excavation identifying five risk zone classes from 1 (the lowest risk) to 5 (the highest risk).

Besides the above-mentioned peculiarity of the Tuzla region, rapid urbanization and identification of landslides in this region have dramatically increased the vulnerability of existing buildings, especially in areas with dense populations. Estimating the capacity of the build-up areas provides information on seismic vulnerability (Chieffo and Formisano 2020).

3 Database of buildings

3.1 Data resource used in the analysis

The study on the residential buildings in the urban area of Tuzla was performed from a database obtained from the project Typology of residential buildings in Bosnia and Herzegovina (Arnautović-Aksić et al. 2016). The typology database contains a collection of architectural and structural properties which was undertaken from 2014 to 2016, as well as energy performance of the surveyed buildings, throughout the entire territory of BIH, according to the predefined criteria and methodology¹ for the purpose of energy assessment of the national building stock. Due to the lack of an official and systematic registry on the residential buildings stock in the country, this project launched the first-of-a-kind survey of a sample of 13,044 residential buildings, from single-family houses to apartment buildings and residential high-rises. The survey consisted of in-situ data collection and their subsequent statistical analysis. Albeit the objective of the research focused on energy consumption, the database itself contains valuable information on existing buildings, which may be used for further research, such as their location, size, form and urban micro-location, construction period, the overall arrangement in horizontal and vertical plans, external finishes, etc. Moreover, the quarter of the entire sample was recorded in more detail, resulting in data compilation on their materialization of the building envelope (roof, external walls), floors and horizontal construction, window types, heating systems, etc.

¹ TABULA project was harmonized with the directives 2002/91/EC and 2006/32/EC and co-financed by the European Commission's IEE program.

The application of the statistical and cluster analysis, as well as the inductive-deductive methodological framework, enabled the projection of the recorded data of the sample on the entire building stock in the country. This examination led to a classification of the recorded buildings into six typological groups according to their urban, architectural, and structural features, as well as into six chronological periods, based on the estimate of their construction period, in a timeframe from 1918 to 2014. The entire building stock was classified into the following six building types, two types of single-family houses (Type 1 and 2) and four types of collective housing (Types 4–6):

- Type 1. Detached single-family houses,
- Type 2. Terraced single-family houses,
- Type 3. Multi-family houses,
- Type 4. Attached apartment building in urban blocks,
- Type 5. Apartment blocks, and
- Type 6. High-rise buildings.

The database of the typology of residential buildings of BIH serves as a basis for different kinds of future analyses on the national level. On the other hand, it may further be utilized to study the topic at the level of particular urban areas, such as cities, towns, or municipalities, such as the city of Tuzla in this case.

3.2 Typology of sampled buildings

In this analysis 203 buildings in Tuzla were identified and elaborated. An almost equal percentage of buildings were constructed in the two periods, namely 1983–1991 (26.1%), from 1992 to 2014 (26.6%), however, the highest percentage of buildings were constructed in the period from 1964 to 1982 (42.9%). This period is characterized by the temporary technical standards for construction in earthquake areas that were enforced in 1964 and were effective until 1981. Only four percent of all buildings in the database belong to the period from 1946 to 1963. This is valuable information as the construction age can be indirectly connected with the enforced codes at that time and construction typologies. The vast majority of buildings are low-rise structures having one to two floors (66.5%), while 16.7% of all investigated structures are marked as high-rise buildings having more than 8 stories, and mid-rise buildings make up 16.7% of all built-up area (Fig. 6).

The study is conducted in several regions in the city of Tuzla, where three types of masonry building typologies and one type of reinforced concrete buildings were identified. The structural typologies for masonry buildings are classified according to the RISK-UE

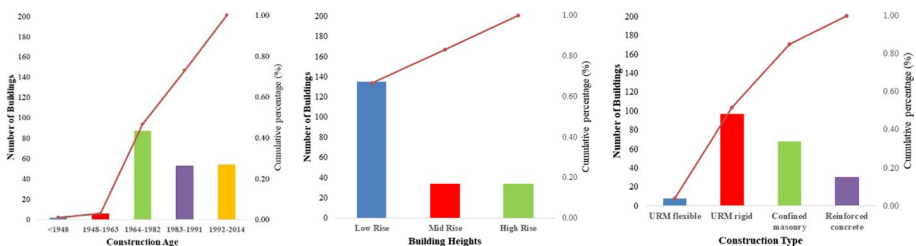


Fig. 6 Characteristics of the examined buildings

Building Category Matrix Milutinovic and Trendafiloski (2003). Masonry buildings with wooden (flexible) floors marked as M3.1, masonry buildings with rigid floors marked as M3.4, and confined masonry buildings marked as M4. The reinforced concrete structures are marked as RC4 representing the dual system according to Milutinovic and Trendafiloski (2003). As for the typology of structures, URM with rigid floors is the most represented type. A little bit less than 50% are URM structures with rigid floors (47.8%), confined masonry makes up 33.5% of all structures, while URM with flexible floors makes up only 3.9%. Thirty reinforced concrete dual system (RC4) structures have been identified in this analysis and all of them are high-rise buildings having ten or more storeys (Fig. 6).

Low-rise single-family masonry buildings with wooden floors (M3.1) are mainly constructed in the period 1946–1960 and from 1961 to 1970. External walls are made of solid brick with thicknesses of 25 cm. Due to the lack of connection between the walls and the flexible wooden floor box behavior of the structure is not possible. Buildings for the collective housing built in the period from 1946 to 1960, had a maximum of three floors, and the slabs were constructed by semi-prefabricated concrete elements, making the structure horizontally rigid (M3.4). The loadbearing structure was made of solid brick with a wall thickness of 38 cm. From the mid-sixties, after the 1963 Skopje earthquake, the construction of confined masonry (M4) structures began and continued up to date mainly for individual houses, but not for all, while for collective housing reinforced concrete moment-resisting frames were used.

It should be mentioned that the first regulations in the Socialist Federal Republic of Yugoslavia (SFRY) limited the seismic share 2–3% of the weight of the building and were enforced in 1948. On the level of SFRY the second temporary seismic code was imposed in 1964 TTPCSR (1964) and was used until 1982. However, on the Republic level, Slovenia imposed their Republic Seismic Design Codes 40 days before the 26 July 1963 Skopje earthquake took place. The Seismic Code of 1981 entitled Technical Regulations for Design and Construction of Buildings in Seismic Regions (TRCBSR 1981), became effective from July 1982, 1 year after their publication, as there was a 1-year postponement due to the lack of accompanying seismic zoning maps. The revision of the seismic codes from 1964 started in 1975 and its completion was accelerated due to the occurrence of the Montenegro earthquake of 1979. A characteristic pattern of this code is that in seismic regions (MCS intensity \geq VII degrees), it limits the minimum base shear to 2% of the seismic weight of the building (Milutinovic et al. 2017).

Besides the various types of masonry typologies in this study reinforced concrete dual system (RC4) structures were assessed, all are high-rise buildings having ten and more floors. The high-rise buildings are of square or rectangular plan and flat accessible roof. The structural system is a reinforced concrete frame with concrete shear walls (a dual system). The infill material is made of either hollow bricks or clay blocks of various dimensions.

As previously specified, the arrangement of the building typologies is presented in Fig. 7.



Fig. 7 Distribution of location of surveyed residential buildings in Tuzla Canton (in total 203 buildings)

4 Macroseismic method

In EMS-98, qualitative descriptions were defined for five damage grades for intensity levels V to XII for six different vulnerability classes (A–F). According to the macroseismic method proposed by Giovinazzi and Lagomarsino (2001, 2004), the EMS-98 scale (Grünthal, 1998) represents the basis for the determination of the damage probability functions.

Table 1 gives a link between acronyms used for the description of the structural types they represent and the nominal EMS-98 vulnerability class.

The advantage of the indirect method is that in addition to the typology of buildings, it uses other characteristics of buildings that affect their vulnerability. In terms of numerical value, the vulnerability index function has an arbitrary value; for simplicity, values from 0 (best-designed buildings) to 1 (most vulnerable buildings) are taken. Figure 8 shows the vulnerability index which defines the affiliation of a building to a particular vulnerability class. In terms of fuzzy set theory, the vulnerability index membership function has a plausible range ($\chi = 1$) and linearly plausible ranges. Table 2 shows the most likely value for each vulnerability class V_0 according to the fuzzy definition. It also shows the limits

Table 1 Link between acronyms used for the description of the structural types they represent and the nominal EMS-98 vulnerability class

Structural Type	Acronym	Description	Nominal EMSC-98 Vulnerability class
URM	M3.1	Masonry buildings with wooden (flexible) floors	(A)–B–(C)
	M3.4	Masonry buildings with RC (rigid) floors	(B)–C–(D)
CM	M4	Confined masonry buildings	(C)–D–(E)
RC	RC4	Dual system (2D moment-resisting frame combined with shear walls)	(C)–D–(E)

(A)–B–(C):B – most likely vulnerability class; (A)–B–(C)—probable range

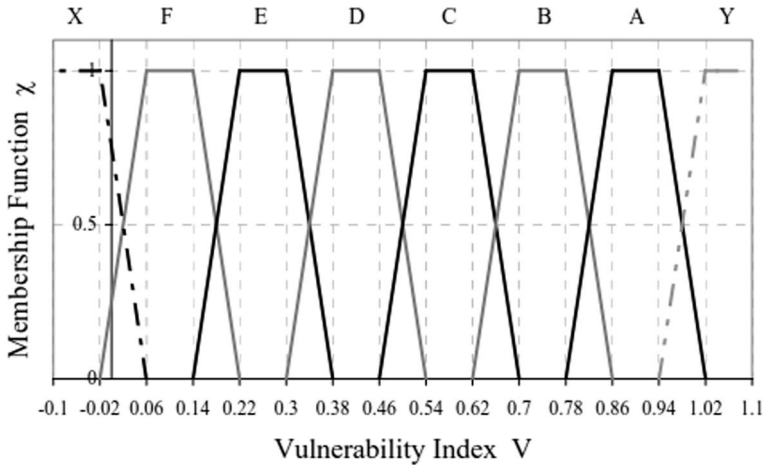


Fig. 8 Membership functions for vulnerability index, V for vulnerability classes A to F according to EMS-98 (Giovinazzi 2005)

Table 2 The values of vulnerability indices for vulnerability classes (Giovinazzi, 2005)

	V_{\min}	V_I^-	V_I^*	V_I^+	V_{\max}		V_{\min}	V_I^-	V_I^*	V_I^+	V_{\max}
A	0.78	0.86	0.90	0.94	1.02	D	0.30	0.38	0.42	0.46	0.54
B	0.62	0.70	0.74	0.78	0.86	E	0.14	0.22	0.26	0.30	0.38
C	0.46	0.54	0.58	0.62	0.70	F	-1.02	0.06	0.10	0.14	0.22

(V^- and V^+) of the possible range ($\chi = 1$) and the upper and lower limits of its possible values (V_{\min} and V_{\max}) (Giovinazzi 2005).

An analytical term is defined for the operational implementation of the methodology; therefore, the mean damage class μ_D is a function of macroseismic intensity I and depends on two parameters, the vulnerability index, V , and the ductility index, Q (Giovinazzi 2005):

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

I —macroseismic intensity, V —vulnerability index, Q —ductility index which describes the ductility of a certain structural type (ranging from 1 to 4).

The seismic behavior depends not only on the behavior of the structure but also on other factors, so an equation for the damage index has been proposed (Giovinazzi 2005):

$$V = V_I^* + \Delta V_R + \Delta V_m \tag{2}$$

where ΔV_R —regional vulnerability factor, ΔV_m —behavior modifier factor.

Since the seismic performance of buildings depends not only on the construction system but also on various factors such as quality, height, horizontal and vertical irregularities, etc., behavior modification factors are defined (shown for masonry and reinforced

Table 3 Values for behavior modifier factors for masonry and RC4 buildings— adopted from Milutinovic and Trendafiloski (2003) and extended with Lantada et al. (2010)

Behavior modifier		Reinforced concrete			
		Earthquake Resistance Design Level (ERDL)			
		Low	Medium	High	
		$V_{m,k}$	$V_{m,k}$	$V_{m,k}$	$V_{m,k}$
State of preservation	Good	-0.04	0	-0.16	-0.16
	Bad	+0.04	+0.02	-	-
Number of floors	Low (1 or 2)	-0.02	-0.04	-0.04	-0.04
	Medium (3–5)	+0.02	0	0	0
Plan irregularity	High (≥ 6)	+0.06	+0.08	+0.06	+0.04
	Geometry	+0.04	+0.04	+0.02	0
Roof type	Weight, pressure, and connections	+0.04			
	Middle	-0.04			
Aggregate building position	Corner	+0.04			
	Head	+0.02			
Aggregate building elevation	Adjacent buildings higher	-0.04			
	Adjacent buildings higher and the others at the same level	-0.02			
	Adjacent buildings at the same level	0			
	Adjacent building lower and the other at the same level	+0.02			
Façade length	Adjacent building lower	+0.04			
	$L \leq 15$	0			
Soil morphology	$L > 15$	+0.04			
	Slope	+0.02	+0.02	+0.02	+0.02
	Cliff	+0.04	+0.04	+0.04	+0.04

concrete structures in Table 3), $V_{m,k}$, for each typology of buildings according to equation (Giovinazzi 2005):

$$\Delta V_m = \sum_k V_{m,k} \quad (3)$$

where $V_{m,k}$ —behavior modifiers.

The behavior modifiers according to Milutinovic and Trendafiloski (2003) and extended by Lantada et al. (2010) for masonry buildings, and reinforced concrete structures of dual systems (RC4) as defined in Milutinovic and Trendafiloski (2003) are presented in Table 3 (only the ones that were taken in the study). Eight behavior modifiers were taken into account for masonry typologies and five for reinforced concrete (RC4) typology. Additionally, for both typologies, the influence of the site effects was taken separately into consideration.

After the devastating effects of the 1979 Montenegro earthquake, moderate code regulations regarding seismic actions were enforced in 1982. Mass implementation of RC frame systems started following the Skopje earthquake. The reinforced concrete buildings built in the period from 1948 to 1961 were considered as low earthquake-resistant structures, the construction period from 1964–1982 was classified as medium earthquake-resistance design level (ERDL), and high ERDL is marked to RC buildings constructed from 1982 onwards.

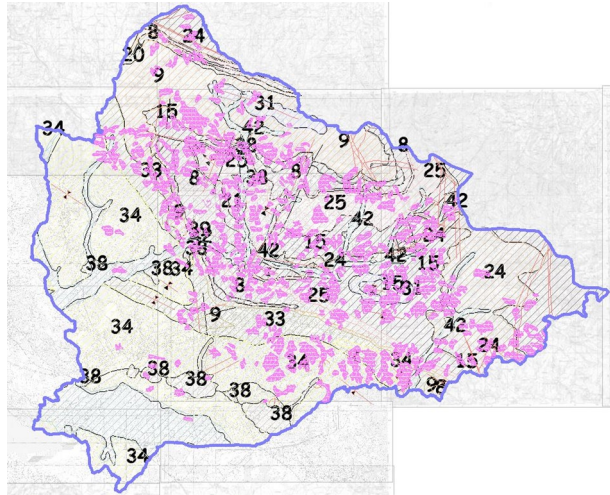
5 Amplification due to site characteristics

In the rapid vulnerability assessment, the damage scenario is obtained on a global scale. The vulnerability is dependent on the properties of the analyzed buildings (the type of construction, number of floors, the position of the structure, type of roof, etc.). However, to obtain more precise information regarding the structure's vulnerability, it is important to take into account as well the geo-hazard effects within the vulnerability index method.

The first necessary data is the geology engineering map of the elaborated terrain. The geology engineering map (lithological map) of the Tuzla territory indicated four major soil classifications in the study area. The division is conducted regarding litho-facial composition and basic characteristics of the soil classification are provided. The area of assessed buildings belongs to one of five engineering geological units which are marked by numbers 8, 9, 15, 33, and 34 (Fig. 9). Table 4 describes individual engineering geological units (EGU) and a correlation with the soil classes as per Eurocode 8 (EN 1998-1:2004) is given.

According to the TC4-ISSMGE manual (1993; revised 1999) relation between the surface geology and the seismic intensity is obtained and the increment is provided by empirical relations if the expected hazard is denoted through the macroseismic intensity. Medvedev (1962) made a correlation between the geology units and the intensity increment ($\Delta I_{M,M,I}$). He grouped different soils into nine groups, and for each group, a range of values indicating the intensity increment were provided, for example, the highest intensity was for moist fill and soil ground which was in the range from 3.3 to 3.9, and the lowest was for limestone, sandstone, and shale in the range from 0.2 to 1.3, using granite as the ethanol (value is equal to 0). On the other hand, Evernden and Thomson (1985) classified the soil units into twelve categories provided with a single value of the

Fig. 9 Lithofacial map of Tuzla Canton (Department of Urbanism Tuzla Municipality 2011)



intensity increment. The lowest value in the amount of 0.4 was for Paleozoic rock, while the highest intensity increment in the value of 1.5 was marked for two classes, Oligocene to middle Pliocene rocks and Alluvium ($100 \text{ ft} < \text{water table}$). Midorikawa (1987) proposed a correlation between surface geology and PGA through the relative amplification factor (f_{ag}). His classification consists of Holocene, Pleistocene, Quaternary volcanic rocks, Miocene and Pre-Tertiary. Pre-Tertiary is taken as an etalon, giving a zero value for the $\Delta I_{M.M.I}$ and the maximum value is 2.3 for Holocene. An increase in the intensity can be done according to the empirical correlation presented by Bard (1997) or according to expert opinions.

Faccioli and Pessina (2003) made a correlation between the soil classification provided in Eurocode 8 and the intensity increment when the EMS scale is considered (ΔI_{EMS}). Ground-type A, represented as rock or other rock-like geological formation, including at most 5 m of weaker material at the surface, with the shear velocity of $V_{s30} > 800 \text{ m/s}$, is taken as the ethanol, together with ground-type B, and the increment ΔI_{EMS} for ground-type C which is classified as deep deposits of dense or medium – dense sand, gravel or stiff clay with thickness from several tens to many hundreds of meters is equal to 0.5, while for ground-type D the increment is equal to 1.0. The limit of this approach was that it is not able to capture the changes in the dynamic amplification linked to the fundamental frequencies of both the soil and the structure (Giovinazzi 2009). Giovinazzi and Lagomarsino (2004) in their work proposed a procedure for obtaining the vulnerability increment ΔV from the EC8 Ground Types and for different building categories. This procedure was applied for all construction types (masonry and reinforced concrete) in this study, taking into account the fundamental period for masonry structures as proposed in Eurocode 8, which is given by an Eq. (4)

$$T_1 = 0.05 \times H^{0.75} \quad (4)$$

and for dual reinforced concrete structures defined in Eq. (5) as proposed by Jalali and Milani (2005)

Table 4 Engineering geological units for the analyzed construction sites

No. of EGU	Description	Soil class as per Eurocode 8
8	Marls, in surface parts decomposed into crumbs and marly clays and in deeper parts terrains of favorable properties, for the foundation and construction of buildings, builds stable rarely conditionally-stable terrains	B
9	Marls and sandy marls, with very variable physical and mechanical properties, are sensitive to the presence of water and climatic influences, in a fresh condition suitable for construction of buildings, builds stable and conditionally stable terrain	B
15	Quartz conglomerates, sandstones, marls, and clays, favorable physical and mechanical properties, suitable for foundations and construction, buildings, build up stable terrains	B
33	Sand, sandy clays, clays, whitish marls; a complex of extremely complex physical–mechanical properties, subject to sliding, yielding (flowing), and creep. builds conditionally stable and unstable terrains	C
34	Quartz sand, gravel, clay, coal, and sand has good compaction and favorable physical and mechanical properties, slopes of cuts and notches they are held vertically, in the presence of clay and coal the complex has unfavorable building properties	C

Table 5 Fundamental period T_1 for masonry and RC4 dual buildings

	No. of floors	Fundamental period (T_1)	
		Masonry buildings	Reinforced concrete dual buildings
Low-rise	1	0.11	
	2	0.19	
Mid-rise	3	0.26	
	4	0.32	
High-rise	5	0.38	
	6	0.44	
	7	0.49	
	8	0.54	
	9	0.59	0.43
	10		0.47
	11		0.51
	12		0.55
	13		0.59
	14		0.62
	15		0.66
	16		0.70
	17		0.74
	19		0.81

$$T_1 = 0.026 \times H^{0.85} \tag{5}$$

where H is the height of the building, in m, from the foundation or the top of a rigid basement.

The values of the fundamental period for masonry and reinforced concrete dual buildings are presented in Table 5.

An example of the calculation for ground-type C is provided. A multiplier factor f_{PGA} for Ground Type C is obtained according to Eq. (6)

$$f_{PGA} = S_a[T_1]_{Soil K} / S_a[T_1]_{Soil A} \tag{6}$$

and presented in Giovinazzi and Lagomarsino (2004). For low and medium-rise masonry buildings $f_{PGA} = 1.15$, while for high-rise $f_{PGA} = 1.265$, and high-rise reinforced concrete dual structures the obtained value is $f_{PGA} = 1.725$.

Guagenti and Petrini (1989) proposed a relation between the Intensity increment ΔI and multiplier factor f_{PGA} given by Eq. (7)

$$\Delta I = \ln(f_{PGA}) / 0.602 \tag{7}$$

This is valid when the connection between intensity and vulnerability is controlled by an analytical expression, providing vulnerability curves as an output (Giovinazzi and Lagomarsino 2004), as defined by Eq. (1).

Table 6 Vulnerability increment ΔV for masonry and RC4 dual buildings

	No. of floors	Vulnerability increment (ΔV)	
		Masonry buildings	Reinforced concrete dual buildings
Low-rise	1–2	0.04	
Mid-rise	3–4	0.04	
High-rise	5–9	0.06	
	9–19	–	0.14

The ductility index Q for masonry is equal to 2.3 (Basaglia et al. 2018; Lagomarsino and Giovinazzi 2006). Reinforced concrete buildings built before 1964 were considered low earthquake-resistant structures with a ductility index of 2.3. The construction period from 1964 to 1982 is classified as the moderate earthquake-resistance design level (ERDL), a value of ductility index of 2.6 was used. The period from 1982 to 1990 regarding the level of development of the seismic codes in ex-Yugoslavia would be considered as high, however as Tuzla according to the seismic maps valid at that time (1982) was identified to have an intensity of 6 by MCS, the structures are classified as low earthquake-resistant structure. The construction period from 1990 to 2005 was classified as medium earthquake-resistance design level (ERDL), a value of ductility index of 2.6, and for RC dual structures constructed from 2006 onwards a value of Q was taken to be equal to 3.1, as per (Giovinazzi 2005).

Once the intensity increment is obtained, vulnerability increment is calculated according to a linear relation given in Eq. (8)

$$\Delta V = \Delta I / 6.25 \quad (8)$$

Vulnerability index soil modifiers for Ground Type C evaluated for masonry typology buildings and reinforced concrete dual typology for various height classifications are shown in Table 6.

The same procedure was done for Class Type B.

6 Results

6.1 Damage probability matrices (DPM) and vulnerability curves

The occurrence probability of a specific damage level for dissimilar typological classes exposed to different seismicity levels according to the EMS-98 scale is expressed by the Damage Probability Matrices (DPM) (Grünthal 1998). Lantada et al. (2009) correlated the mean damage degrees and damage states. The relationship between the relation obtained by Lantada et al. (2009) with the damage level states according to EMS-98 (1998) is presented in Table 7.

The mean damage grades were calculated for the three types of masonry structures and the reinforced concrete dual buildings. The first calculation was done for the case of soil independence and secondly, the site effects were taken into consideration in respect to the build-up area of the selected buildings in this study. The damage grades for the five

Table 7 Damage states for mean damage degrees (Lantada et al. 2009)

Intervals of mean damage degrees	Most likelihood level of damage of certain limit states	Damage level according to EMS-98
0–0.5	No damage	D0
0.5–1.5	Slight	D1 (state 1)
1.5–2.5	Moderate	D2 (state 2)
2.5–3.5	Significant to severe	D3 (state 3)
3.5–4.5	Very severe damage	D4 (state 4)
4.5–5.0	Total collapse	D5 (state 5)

intensity levels are presented indicating various damage from no damage (D0) to total collapse (D5). As anticipated the type of floor had a significant effect on the behavior of the URM structures. Seismic resistance of URM structures with flexible floors (M3.1) is much lower in comparison to the URM with rigid floors (M3.4) and confined masonry (M4). A complete collapse of the M3.1 structures is expected for the intensity XI which is quite realistic. For intensity XI, total collapse may be expected even for reinforced concrete structures, and URM structures regardless of the floor type (Fig. 10). Out of 30 elaborated reinforced concrete dual system structures (RC4), 93.3% belong to moderate seismic code, while 6.67% belong to high ERDL. The second modifier which has the greatest effect on the behavior of RC4 structures is that all of these buildings are high-rise structures, having more than 9 floors.

The site effect has a significant influence on the behavior of all types of structures, confirming that this is something that should be taken into account during the assessment of the existing structure. Disregarding the soil effect may lead to inadequate conclusions regarding the available capacity of the structure and its resistance which may be overestimated. Rather good behavior and lower damage levels are noted for confined masonry. This may be connected to the modifiers taking into account the height of the structure. The earthquake intensity level of VIII would cause slight damage to these types of structures while the same level of damage would be expected for lower intensities (one or two levels) for the other masonry structure typologies. The majority of the structures are low and mid-rise buildings up to 4 floors (83.3%) and the rest 16.7% are high-rise structures. For the case of maximum expected intensity VIII, depending on the typology, damage D1, defined as slight, to D4, defined as very severe can be expected (Table 8).

Damage probability matrices (DPM) with the implementation of the binomial distribution are obtained in the case of not taking into account the soil effects, as indicated in Fig. 10, and the case when the soil effects are taken into account as shown in Fig. 11.

From Fig. 10 it is evident that for different typology classes the binomial distribution has various positions where the highest coefficient is manifested. The highest coefficient is observed for the Damage grade D0 for typology class RC4 and M4 and intensity of earthquake equal to IV. So, for typology class M4 there is a probability of 96.6% that no damage will be observed on these types of structures due to intensity $I_{EMS-98}=IV$. Depending on the typology classes the probability of damage due to the highest intensity $I_{EMS-98}=XII$ results in various percentages of probability damage. The highest damage percentage is observed for URM with flexible floors (86.9%), while the least probability is noted for confined masonry structures (50.2%). In the case of the highest intensity, 26.8% of the thirty RC4 structures would collapse.

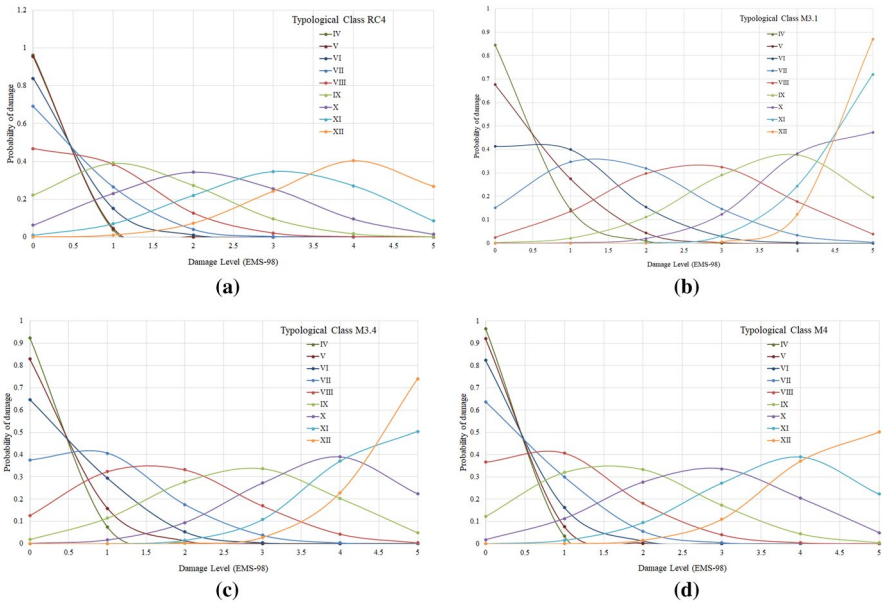


Fig. 10 Damage Probability Matrices for **a** RC4, **b** M3.1, **c** M3.4, and **d** M4 not taking into account soil effects

In the case of VII and VIII earthquake intensity, which are the most probable intensities in this region, 63.7% and 36.7% respectively of confined masonry structures would experience no damage, in contrast to the URM structures with rigid floors (37.6% and 12.6% respectively). For intensity VII 15.1% of all URM with flexible floors would not experience damage, while only 2.5% for VIII intensity earthquake. RC4 structures exposed to VII intensity level would experience no damage for 69.1%, while for a higher intensity level this percentage is reduced by 32.4%.

Figure 11 shows the influence of the soil effects on the damage level and probability of damage for various typological classes and given intensities I_{EMS-98} . For RC4 structures exposed to intensity level VIII and once site effects are considered, the percentage of structures that would be damaged-free decreased by 22.2%, while an increase of 13.2% is noted for structures that would experience moderate damage (damage level D2).

The soil effect for URM with flexible floors for the earthquake intensity of VII caused a decrease in damage grade 0 and 1, in almost the same percentage (4.78%, 5.01%), while an increase was observed in all other damages (2, 3, 4 and even 5) in the amounts of 2.21%, 5.24%, 2.25%, and 0.60% respectively. For intensity VIII, the largest increase is in the damage grade D4 and D5, which increases by 5.72% and 2.54% respectively. Looking at the URM with rigid floors, for intensity level VII, the impact of the site effect was the largest for the damage grade 2. In this case, an additional 8.14% of all buildings would experience moderate damage. In the case of VIII intensity, the highest increase was observed for damage class 3, where now 22.2% of all elaborated structures would experience significant to severe damage. Confined masonry structures exposed to earthquake intensity of VII taking into account site effect would cause an increase in the damage grade 1 and 2, together in the amount of 7.25%, with 61.0% in increase in damage grade 1, and 39.0% increase in damage grade 2. For the same

Table 8 Average values of mean damage grades for six levels of intensity not taking and taking into account soil effects

Intensity	Average μ_D for RC4		Average μ_D for M3.1		Average μ_D for M3.4		Average μ_D for M4	
	without soil amplification	with soil amplification	without soil amplification	with soil amplification	without soil amplification	with soil amplification	without soil amplification	with soil amplification
V	0.047	0.160	0.375	0.461	0.184	0.229	0.082	0.108
VI	0.173	0.331	0.810	0.973	0.417	0.513	0.191	0.249
VII	0.357	0.660	1.575	1.826	0.889	1.067	0.431	0.548
VIII	0.706	1.226	2.612	2.888	1.694	1.955	0.909	1.116
IX	1.298	2.044	3.611	3.824	2.739	3.015	1.712	2.000

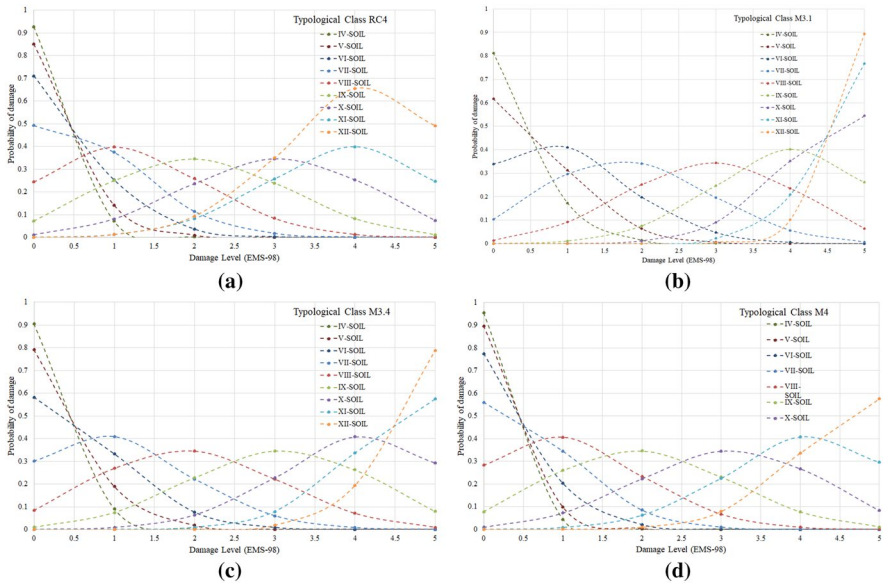


Fig. 11 Damage Probability Matrices for **a** RC4, **b** M3.1, **c** M3.4, and **d** M4 taking into account soil effects

earthquake intensity, for RC4 structures, if soil effects are considered a 19.8% decrease in the number of structures that would be free of damage, is detected. Once site effects are considered, an increase of 10.9%, 7.3%, and 1.4% is observed for damage grades 1, 2, and 3 respectively. Additionally, 0.12% of structures would experience very severe damage once soil effects are considered in the vulnerability assessment (Fig. 12). In the case of VIII intensity, 40.63% of all M4 structures would have slight damage, while 23.35% would be marked with moderate damage (5.2% increase compared to soil effect neglectation). On the other hand, RC4 once exposed to this level of intensity would lead that twenty-five of the thirty RC4 structures would experience slight, and five structures would be damage-free. An additional 6.3% of RC structures once site effects are considered would experience significant to severe damage (D3), resulting in 8.4% of RC structures that would have this level of damage (Fig. 12).

Average mean damage grades for the whole database, three types of masonry structure, and one type of reinforced concrete dual system structure (RC4) are shown in Fig. 13. It is evident that the type of slab has a direct impact on the behavior of structures due to ground motion, so the smallest damage is noted on the confined masonry structures, then on masonry structures with rigid floors, and the URM with flexible slabs would experience the highest damage. The behavior of RC4 buildings is as expected. The RC4 structures would experience the least damage out of all selected structures. This is directly connected to the level of seismic codes as the majority of these structures are constructed according to the medium and high-level seismic codes. The largest site effect impact is detected on these structures due to their location connected to the soil characteristics as opposed to the masonry structure types due to the location of the buildings. As expected, the URM buildings with flexible floors are to experience the heaviest damage in an earthquake event and the least damage would be experienced by confined masonry structures.

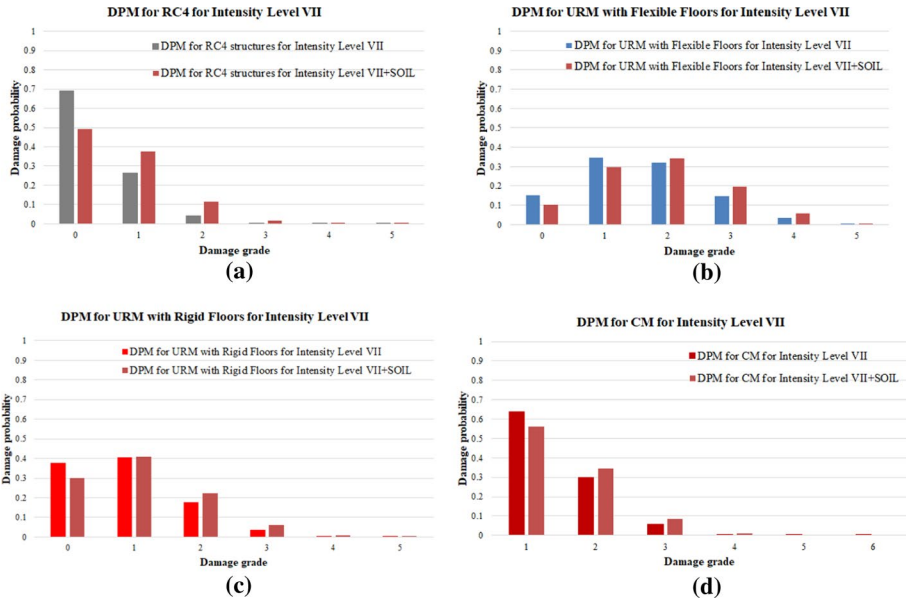


Fig. 12 Damage Probability Matrices for a RC4, b M3.1, c M3.4, and d M4 not taking into account soil effects for Intensity level VII

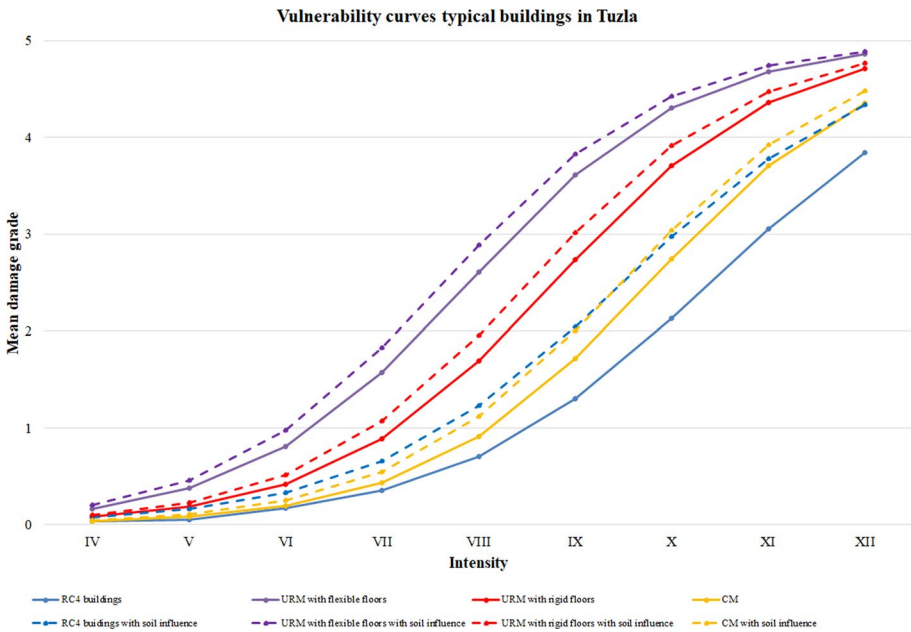


Fig. 13 Average mean damage grades for the whole database

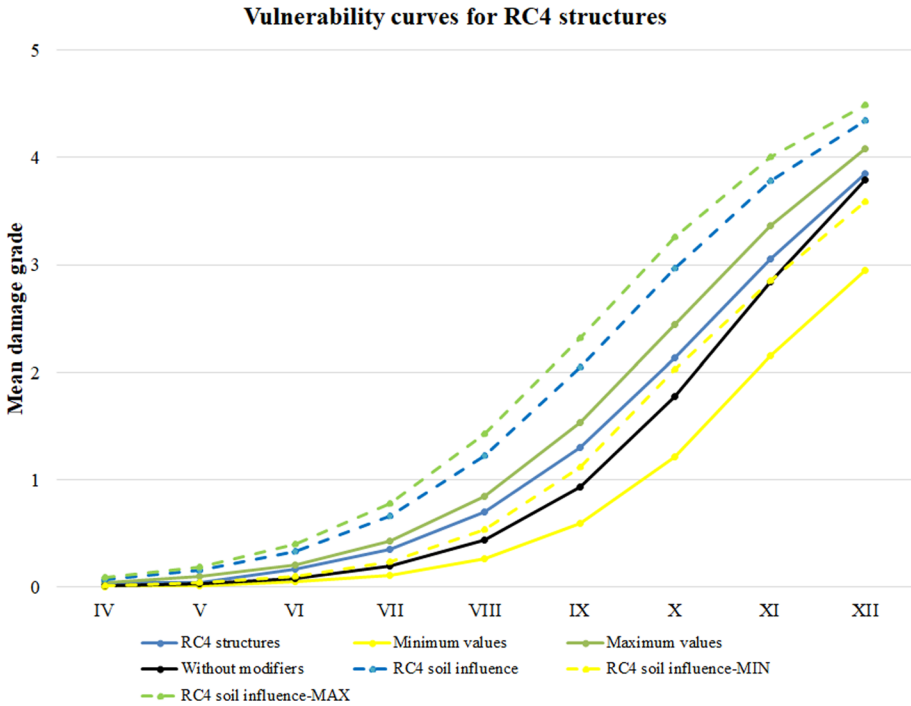


Fig. 14 Vulnerability curves for RC4 structures without and with soil effects

After obtaining the average mean damage grade for every structural type, the influence of all behavior modifiers which were considered is determined (solid lines), and the soil effect modifier is shown separately (dashed lines), as presented in Fig. 14 for RC4 structures. The influence of all modifiers including site effects is more emphasized for the lower intensities, as for intensity VI it reaches a percentage of 51.71, and for intensity VII 45.43 without taking the site effects. In the case of incorporation of the site influence, this difference increases by an additional 23.11% and 25.09% respectively. For the highest intensity, the difference regarding average mean grade value (AMGV) in relation to the smallest intensity is smaller 43.3 times. Using the maximum values for construction of the vulnerability curves would lead to an increase of the mean damage grades in the amount of up to 16.4% for intensity VI and VII earthquake in relation to the AMG. The difference between the vulnerability curves obtained from minimum value and without using the modifiers is 41.51% for VI intensity and 40.96% for VII earthquake intensity, and this amount is increased by 17.74% and 17.84% respectively, once site effects are included.

The behavior of masonry typologies is quite different in respect to the reinforced concrete dual system structures (RC4). Separate calculations were done for all masonry types, and vulnerability curves (without and with soil effects) are presented in Figs. 15, 16, 17. A similar pattern of the average mean damage grade regardless of the floor type was obtained, while confined masonry had some characteristic features. As most probably earthquake intensity shaking in the Tuzla region has been identified for VII and VIII intensity, M4 structures experienced an increase of the AMG due to soil effects is 27.35% and 22.76% respectively. In the case of masonry structures with rigid floors, this increase was

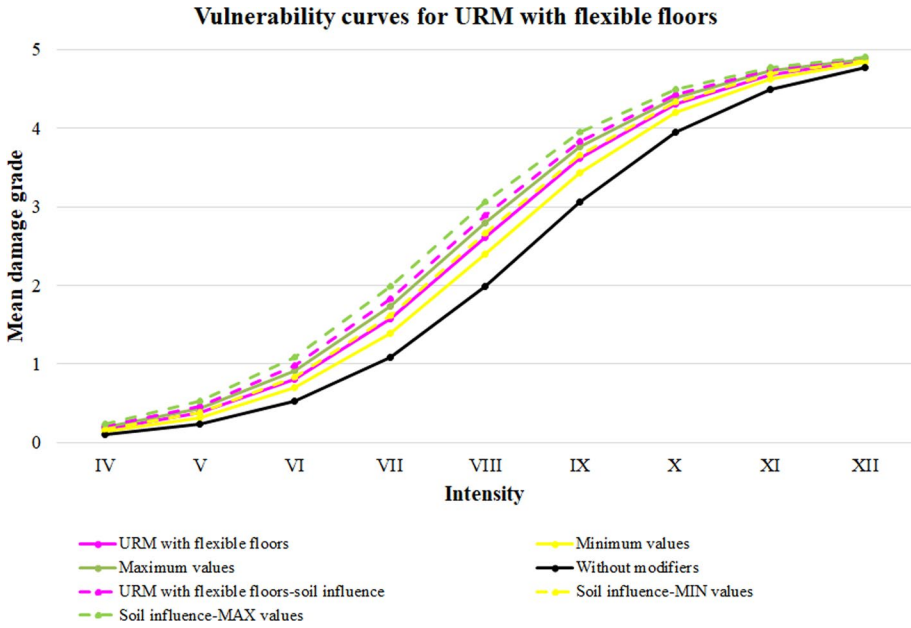


Fig. 15 Vulnerability curves for URM with flexible floors without and with soil effects

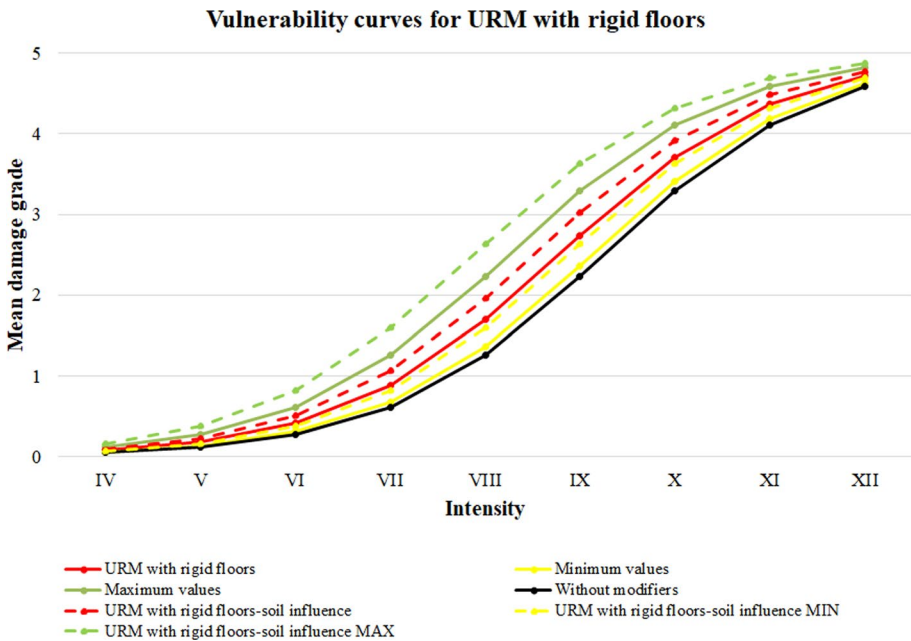


Fig. 16 Vulnerability curves for URM with rigid floors without and with soil effects

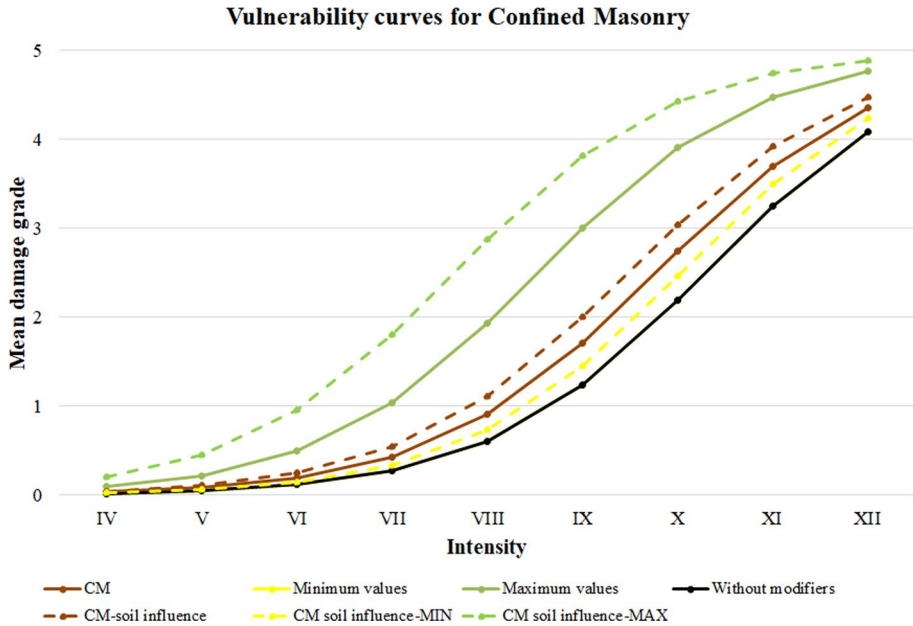


Fig. 17 Vulnerability curves for Confined masonry without and with soil effects

smaller and amounted to 20.04% and 15.46%. The reasoning for this lies in the fact that these buildings are low to medium-rise buildings in which case the soil effects were the smallest. Masonry structures with flexible floors had an increase of 15.88% and 10.57% respectably which can be connected to the fact that all eight buildings are low-rise buildings so the effect of soil even though they are located in the ground-type C is the smallest. The highest effect was noted on RC4 where the increase was 80.53% and 59.64% respectably. An increment of 66% was detected for local effects in the study conducted by Chieffo and Formisano (2019). The reasoning lies in the fact that two-thirds of all the RC4 structures are located in ground-type C and all are high-rise structures, all have ten or more floors. It has been confirmed that the local site effects and soil-structure interaction (SSI) are more noticeable in the case of soft soil formations and high-rise structures as found in Stewart et al. (1999).

6.2 Vulnerability classes

Taking into account all the aforementioned, behavior modifiers for reinforced concrete dual system and three types of masonry structures obtained as a result of the visual inspection of each building and by applying the formulas (1), (6), and (8), the vulnerability index was calculated and the intermediate degree of vulnerability for each building, while the soil effects are separately calculated and shown. The average values of the vulnerability index and the behavior modifiers are shown in Table 9.

Table 9 Average values of the vulnerability index

Building type	Typological value V_I^*	The average value of the modifiers $\sum \Delta V_m$	The average value of the modifiers	The average value of the vulnerability index V_I	The average value of the vulnerability index V_{I-soil}
RC4	0.386	0.046	0.132	0.432	0.576
M3.1	0.740	0.093	0.041	0.833	0.874
M3.4	0.616	0.076	0.042	0.692	0.734
M4	0.451	0.083	0.046	0.534	0.580

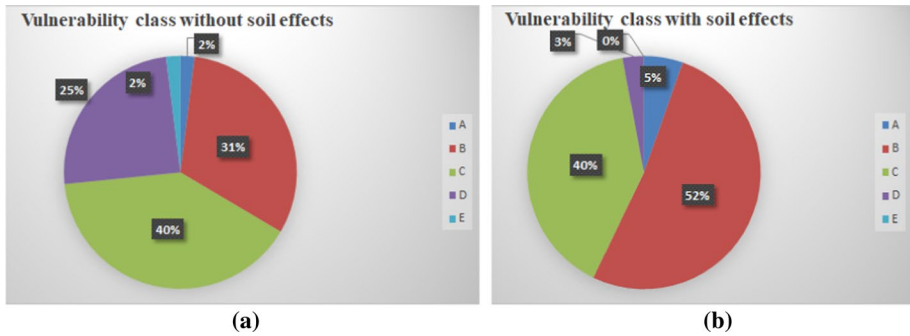


Fig. 18 Vulnerability class: **a** for the structural type not taking into account site effects, **b** after the influence of soil effects on all structures

The vulnerability index values are affected by the influence of various modifiers. This means that in some cases structures of lower vulnerability class will pass to higher vulnerability class. Looking specifically to the influence of the site effects, from 30 RC4 structures twenty-three were classified as D, and seven as E. After the implementation of the site effects, 26 were identified as C, and four as D. All URM buildings with flexible floors, once soil effects are taken into account became class A (50% were B classes). For masonry buildings with rigid floors before soil effects are incorporated in the calculation, 60% of all structures are classified as in B class, and 40% as C class. The soil effects influence the behavior of structure so after their incorporation in the calculation 2% of all structures became class A and the rest is classified in class B. Regarding confined masonry structures once soil effects were taken into account 22 buildings passed from class D to C, while nine moved from C to B, and one was identified as class A. So, once soil effects are taken into account 80.9% of buildings are in class C, 14.7% class B, 2.9% class D, and 1.5% class A.

The result for the whole database consisting of 203 buildings is presented in Fig. 18. After taking into account the impact of site effects on the vulnerability classes, it is seen that the percentage of vulnerability class A increased by 3.4%, while the same percentage of buildings was kept in vulnerability type C. After taking into account site effect the vulnerability class B has additional forty-one building. Forty-four buildings left class D, while after taking into account the soil effect no buildings of vulnerability class E remained.

The influence of the site effects on various types of structures in relation to different seismic intensity levels for summary purposes is given in Tables 10, 11, 12, 13. Table 14 presents how soil influences the EMS-98 vulnerability class and a modified vulnerability class is obtained.

Table 10 Percentage of buildings with different damage grades for vulnerability classes (not) taking into account soil effects for various earthquake intensities for URM with flexible floors

Type	Vulnerability class (EMS98)	% of buildings	
		without soil amplification	with soil amplification
M3.1	A	50	100
	B	50	0

Type	Intensity	VII		VIII		IX	
		% of buildings		% of buildings		% of buildings	
		without soil amplification	with soil amplification	without soil amplification	with soil amplification	without soil amplification	with soil amplification
M3.1	0	15.08	10.32	2.49	1.35	0.17	0.07
	1	34.67	29.66	13.59	9.20	2.14	1.17
	2	31.90	34.11	29.74	25.15	11.18	7.61
	3	14.67	19.62	32.51	34.38	29.07	24.75
	4	3.37	5.64	17.78	23.50	37.79	40.23
	5	0.31	0.65	3.89	6.42	19.65	26.16

Table 11 Percentage of buildings with different damage grades for vulnerability classes (not) taking into account soil effects for various earthquake intensities URM with rigid floors

Type	Vulnerability class (EMS98)	% of buildings	
		Without soil amplification	With soil amplification
	A	0	2.06
	B	59.79	97.94
	C	40.21	0

Type	Intensity	VII		VIII		IX	
		% of buildings		% of buildings		% of buildings	
		Without soil amplification	With soil amplification	Without soil amplification	With soil amplification	Without soil amplification	With soil amplification
M3.4	0	37.57	30.10	12.64	8.38	1.90	0.98
	1	40.63	40.85	32.38	26.88	11.46	7.49
	2	17.57	22.17	33.18	34.53	27.75	22.76
	3	3.80	6.02	17.00	22.18	33.61	34.56
	4	0.41	0.82	4.35	7.12	20.35	26.24
	5	0.02	0.04	0.45	0.91	4.93	7.97

Table 12 Percentage of buildings with different damage grades for vulnerability classes (not) taking into account soil effects for various earthquake intensities for Confined Masonry

Type	Vulnerability class (EMS98)	% of buildings					
		Without soil amplification	With soil amplification				
M4	A	0	1.47				
	B	2.94	14.71				
	C	61.76	80.88				
	D	35.29	2.94				
Type	Intensity	VII		VIII		IX	
		% of buildings		% of buildings		% of buildings	
M4	0	Without soil amplification	With soil amplification	Without soil amplification	With soil amplification	Without soil amplification	With soil amplification
		63.74	55.94	36.67	28.28	12.29	7.78
M4	1	Without soil amplification	With soil amplification	Without soil amplification	With soil amplification	Without soil amplification	With soil amplification
		30.04	34.46	40.74	40.64	32.01	25.93
M4	2	Without soil amplification	With soil amplification	Without soil amplification	With soil amplification	Without soil amplification	With soil amplification
		5.66	8.49	18.10	23.35	33.34	34.56
M4	3	Without soil amplification	With soil amplification	Without soil amplification	With soil amplification	Without soil amplification	With soil amplification
		0.53	1.05	4.02	6.71	17.37	23.03
M4	4	Without soil amplification	With soil amplification	Without soil amplification	With soil amplification	Without soil amplification	With soil amplification
		0.03	0.06	0.45	0.96	4.52	7.68
M4	5	Without soil amplification	With soil amplification	Without soil amplification	With soil amplification	Without soil amplification	With soil amplification
		0.00	0.00	0.02	0.06	0.47	1.02

Table 13 Percentage of buildings with different damage grades for vulnerability classes (not) taking into account soil effects for various earthquake intensities for reinforced concrete dual systems

Type	Vulnerability class (EMS98)	% of buildings	
		Without soil amplification	With soil amplification
RC4	A	0	0
	B	0	0
	C	10.00	10.00
	D	76.67	86.67
	E	23.33	13.33

Type	Intensity	VII		VIII		IX	
		% of buildings		% of buildings		% of buildings	
		Without soil amplification	With soil amplification	Without soil amplification	With soil amplification	Without soil amplification	With soil amplification
RC4	0	69.08	49.27	46.71	24.49	22.25	7.23
	1	26.52	37.47	38.40	39.79	39.01	24.98
	2	4.07	11.40	12.63	25.86	27.35	34.53
	3	0.31	1.73	2.08	8.40	9.59	23.87
	4	0.02	0.13	0.12	1.37	1.68	8.25
	5	0.00	0.00	0.06	0.09	0.12	1.14

Table 14 Distribution of buildings per structural type and effect of soil on the vulnerability class

Structural type	Nominal, EMS-98 vulnerability class					Total	Modified Vulnerability class					Total
	A	B	C	D	E		A	B	C	D	E	
	M3.1	4	4	–	–		–	8	8	0	–	
M3.4	0	58	39	–	–	97	2	95	0	–	–	97
M4	2	42	24	–	–	68	1	10	55	2	–	68
RC4	0	0	0	23	7	30	0	0	26	4	–	30
Total	6	104	63	23	7	203	11	105	81	6	0	203

The values of bold are representing sub-total numbers and total numbers

6.3 Simulation of the results on the selected urban block in Tuzla

According to the provided data from the TABULA database, a block with all typologies was identified as shown in Fig. 19. The ground type identified according to Eurocode 8 was C and according to the lithofacial map of Tuzla Canton (Fig. 9), and the number of EGU was 33 according to Table 3. This area has been recorded by unmanned aircraft systems (UAS) (Fig. 19b), commonly known as drones. So, the obtained data in



Fig. 19 Selected urban block in Tuzla **b** Aerial photo of the site (DRONE)

TABULA was additionally verified together with the information kindly provided by the Service for Physical Planning and Environmental Protection of Tuzla Municipality.

The damage grades for this block were calculated for earthquake most probable earthquake intensity VII, maximum possible intensity VIII, and in the case of IX earthquake intensity. In all the cases the first calculation did not take into account the site effects, while in the second case, the impact of specific site effect (in this case Type C) was incorporated. For earthquake intensity VII, most of the structures would experience slight damage, while six confined masonry buildings would experience no damage at all. These buildings are all mid-rise structures, two of them were constructed in the period from 1982 to 1991, and the remaining four were reconstructed in the period from 2000 to 2010.

In the case of the highest expected earthquake intensity (VIII) in the city of Tuzla, the damage state of the building increases. With the inclusion of the site effects, the URM building with flexible floors would experience significant to severe damage, and only one URM building with rigid floors (Fig. 20). All the rest of the URM buildings with rigid floors would experience moderate damage with and without site effects, with exception of one building that would have significant to severe damage with the inclusion of the site effects. Rather good behavior is observed for confined masonry structures in which case out of 13 buildings, 92.3% would have slight damage and only one building would experience moderate damage in the case site effects were neglected. Once site effects are taken into account the situation dramatically changes, where 53.9% would experience moderate damage, while 46.1% would experience slight damage. The RC4 building inside of the block has fourteen storeys, and once site effects are incorporated in the analysis, it would experience from slight (for intensity VII) to moderate

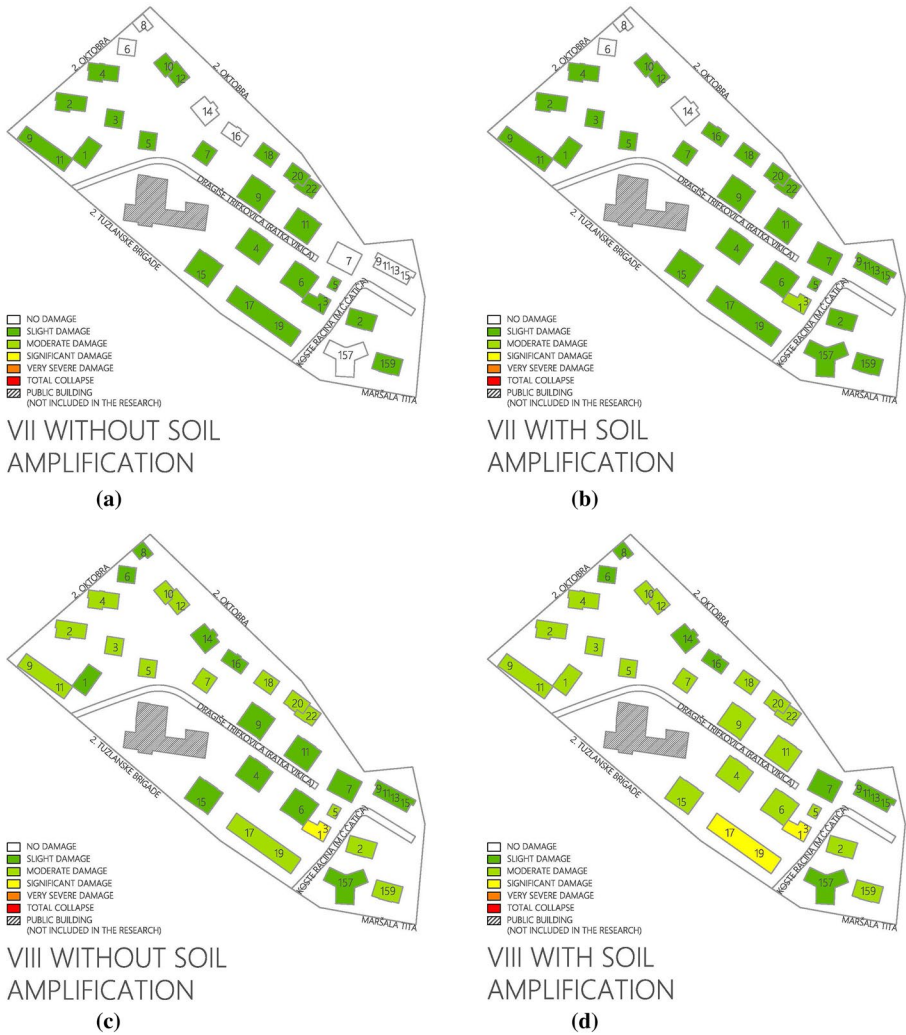


Fig. 20 Damage grades of the selected urban block **a** VII without soil effects, **b** VII with soil effects; **c** VIII without soil effects, **d** VIII with soil effects; **e** IX without soil effects, **f** IX with soil effects

damage (intensity IX) in comparison to the case when site effects are not considered where the largest level of damage would be sight (for intensity IX). It should be noted that in all cases the values are close to the upper limit of the damage interval.

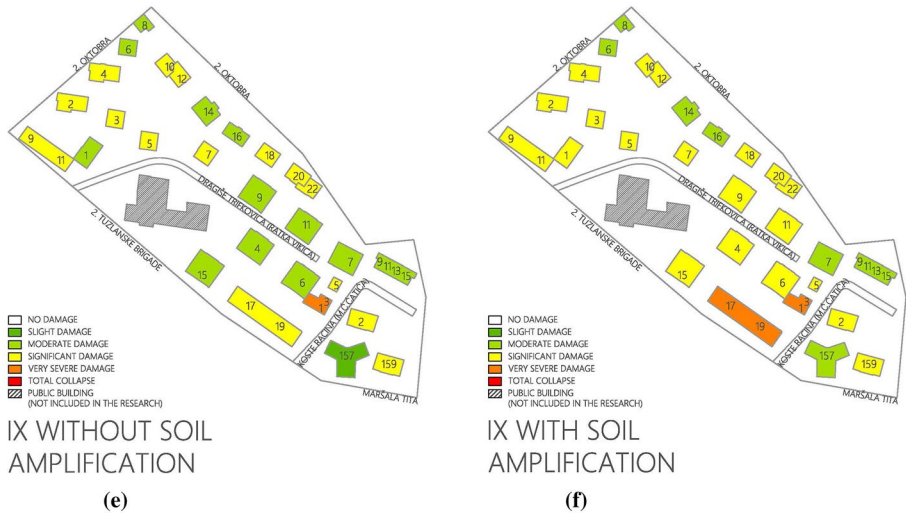


Fig. 20 (continued)

7 Conclusion

Tuzla, as the third-largest and populated city in Bosnia and Herzegovina, was chosen to be analyzed in this study. Tuzla with the PGA of 0.21 g is considered to be in the medium to high seismicity range.

The analyzed structures belong to various construction periods leading to structural heterogeneity. The data-based used in this analysis was taken from the typology of residential buildings of the BIH project which was used to establish a connection between the typology of residential buildings and energy efficiency. Thermal radiography enabled the identification of the type of vertical and horizontal construction systems which was used for the classification of the buildings in certain typologies. The identified typologies were masonry buildings with various types of floorings, flexible floors (M3.1), rigid floors (M3.4), confined masonry (M4), and reinforced concrete dual systems (RC4), according to the acronyms in the EMS-98 scale.

The macroseismic method with the vulnerability index was used for the creation of vulnerability curves and assessment of damage for various intensity scales according to the EMS-98. This simple method has confirmed its applicability in the case of scarce information as a powerful tool for vulnerability assessment of existing buildings.

The analysis was concentrated on the most probable intensities VII and VIII. In the case of the lower intensity, the best behavior was noted for RC4 structures. In the case of an intensity increase to VIII, 38.40% of structures would experience slight damage, while 12.62% of structures would have moderate damage if no soil effects are considered, and if local effects are to be taken into account an increase of structure that would experience significant to severe damage increases by 6.32%. The highest increase in the soil effect impact was observed in RC4 structures due to the type of soil where the buildings were located and the height of the buildings, all classified as high-rise structures. For the intensity VIII, 32.51% of all URM floors with flexible floors would experience significant to severe damage and 17.78% would have very severe damage if no site effects are considered. In the case of inclusion of site effects this percentage

increases by 1.87% and 5.72% respectively. In the case of M3.1 after considering the soil impact all structures pass to vulnerability class A. In the case of earthquake intensity VII, 17.57% of the URM with rigid floors would experience moderate damage if no local soil characteristics are considered, while this percentage increases by 4.60% if the ground type is taken into account. The behavior of confined masonry was rather good because most of the structures were of low-rise buildings. Slight damage would be manifested in 34.46% if the site effects are considered, while 30.04% if not. Thus, it has been detected that the local site effects provide the largest impact on the seismic intensity in the case of RC4 structures.

In the case of VII and VIII earthquake intensity, which are the most probable intensities in this region, taking into account soil effects, confined masonry structures would experience no damage for a large number of structures (55.94% and 28.29% respectively), in contrast to the URM structures with rigid floors (30.11% and 8.37% respectively). For intensity VII only 10.32% of all URM with flexible floors would not experience damage, while an insignificant number of 1.35% of these buildings would have no damage for VIII intensity earthquake (site effects considered). 49.3% of the built area of RC4 structures exposed to VII intensity level would experience no damage (taking into account soil effects), while for a higher intensity level this percentage is reduced by 50.3%. In this specific case, the behavior of confined masonry showed better performance in relation to the RC4 structures due to the location of the buildings, specific site effects at that location, and the fact that all RC4 buildings are high-rise structures having more than nine floors.

One selected block was analyzed due to its heterogeneity and various damages have been observed for different structures and the influence of the site effects have been presented.

From this study and obtained results, it may be concluded that the site effects play a dominant role in the assessment of the vulnerability of existing structures in the urban area of Tuzla city under moderate to high-intensity ground motion. Disregarding the site effects would lead to inaccurate results leading to underestimation of damages and overestimation of the capacity of existing buildings.

This is a pioneer work in this field in the Tuzla region, BIH, and can be the starting point for further and more extensive analysis in this urban center, as well as in other urban areas in the country. It is believed that this approach with slight modifications can be applied to other cities in BIH and the entire Western-Balkan countries due to the same building class typologies.

Acknowledgements We gratefully acknowledge the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH for giving their approval to use the data obtained through the project „Typology of residential buildings in Bosnia and Herzegovina”. We gratefully acknowledge the Department of Urbanism of Tuzla City for the city *urban plan* which was used in the mapping process, and the Service for Physical Planning and Environmental Protection of Tuzla Municipality for their validation of the data for the selected urban block.

Funding No funding for this research was provided.

Availability of data and material (data transparency) The data is available as indicated in the text.

Code availability NA.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

References

- Ademović N (2011) Structural and seismic behavior of typical masonry buildings from Bosnia and Herzegovina. Master Thesis, Advanced Masters in Structural Analysis of Monuments and Historical Constructions, University of Minho, Portugal
- Ademović N, Hrasnica M, Oliveira DV (2013) Pushover Analysis and Damage Assessment of a Typical Masonry Residential Building in Bosnia and Herzegovina. *Eng Struct* 50:13–29. <https://doi.org/10.1016/j.engstruct.2012.11.031>
- Ademović N, Oliveira DV, Lourenco PB (2019) Seismic Evaluation and Strengthening of an Existing Masonry Building in Sarajevo B&H. *Buildings* 9(30):1–15. <https://doi.org/10.3390/buildings9020030>
- Ademović N, Hadzima-Nyarko M, Zagora N (2020) Seismic vulnerability assessment of masonry buildings in Banja Luka and Sarajevo (Bosnia and Herzegovina) using the macroseismic model. *Bull Earthq Eng* 18(8):3897–3933. <https://doi.org/10.1007/s10518-020-00846-8>
- Alguacil G, Vidal F, Navarro F, García-Jerez A, Pérez-Muelas J (2014) Characterization of earthquake shaking severity in the town of Lorca during the May 11, 2011 event. *Bull Earthq Eng* 12:1889–1908. <https://doi.org/10.1007/s10518-013-9475-y>
- Arnautović-Aksić D et al (2016) Typology of residential buildings in Bosnia and Herzegovina. Faculty of Architecture, University of Sarajevo, Sarajevo. German Agency for International Cooperation. Eds: Arnautović-Aksić D, and N Zagora
- Arto I, Garrido J, Gutiérrez-Carrillo ML (2020) Seismic vulnerability analysis of medieval rammed earth fortifications in Southeastern Spain. *Bull Earthq Eng* 18:5827–5858. <https://doi.org/10.1007/s10518-020-00912-1>
- Bakalović M, and Perić N (2011) Industrial heritage of the Tuzla city, PI Museum of East Bosnia Tuzla Bosnia and Herzegovina, condition of the cultural and natural heritage in the Balkan region, pp 15–21. Accessed December 23, 2020. <https://icom-see.mini.icom.museum/wp-content/uploads/sites/58/2018/12/CONDITION-OF-THE-CULTURAL-AND-NATURAL-HERITAGE-...-Volume-2-optimized.pdf>
- Barbat AH, Carreño ML, Pujades LG, Lantada N, Cardona OD, Marulanda MC (2010) Seismic vulnerability and risk evaluation methods for urban areas. A review with application to a pilot area. *Struct Infra Eng* 6:17–38
- Bard PY (1997) Local effects on strong motion ground motion: basic physical phenomena and estimation methods for microzoning studies. In SERINA: seismic risk and integrated seismological, geotechnical and structural approaches. ITSAK, European Commission, Directorate General for Science and Development
- Basaglia A, Aprile A, Spacone E, Pilla F (2018) Performancebased seismic risk assessment of urban systems. *Int J Archit Heritage* 12(7–8):1131–1149. <https://doi.org/10.1080/15583058.2018.1503371>
- Bašić A, Čeliković R, Husejnjagić E, Šišić R (2012) Comprehensive value assessment of surfaces affected by underground mining. Proceedings of the 16th international research/expert conference "trends in the development of machinery and associated technology" TMT 2012. pp 10–12. Dubai, UAE
- Blyth B, Di Napoli F, Parisse Z, Namourah EA, Giatreli A-M, Rodrigues H, Ferreira TM (2020) Assessment and mitigation of seismic risk at the urban scale: an application to the historic city center of Leiria, Portugal. *Bull Earthq Eng* 18:2607–2634. <https://doi.org/10.1007/s10518-020-00795-2>
- Bureau of Statistics [CBS] (2013) National population and housing census 2013 (national report). Agency for Statistics of Bosnia and Herzegovina
- Cabañas L, Alcalde JM, Carreño E, Bravo JB (2014) Characteristics of observed strong motion accelerograms from the 2011 Lorca (Spain) Earthquake. *Bull Earthq Eng* 12:1909–1932
- Čerimagić Đ (2019) Primjenjena geologija u građevinarstvu, Univerzitet u Sarajevu, Građevinski fakultet, pp 167, ISBN 978-9958-638-58-9
- Cherif S, Chourak M, Abed M, Pujades L (2016) Seismic risk in the city of Al Hoceima (North of Morocco) using the vulnerability index method, applied in Risk-UE project. *Nat Hazards* 85(1):329–347. <https://doi.org/10.1007/s11069-016-2566-8>
- Cherif S-E, Chourak M, Abed M, Douiri A (2019) Potential seismic damage assessment of residential buildings in Imzouren City (Northern Morocco). *Buildings* 8:179. <https://doi.org/10.3390/buildings8120179>

- Chieffo N, Formisano A (2019) The influence of geo-hazard effects on the physical vulnerability assessment of the built heritage: an application in a district of Naples. *Buildings* 9(1):26. <https://doi.org/10.3390/buildings9010026>
- Chieffo N, Formisano A (2020) Induced seismic-site effects on the vulnerability assessment of a historical centre in the molise region of Italy: analysis method and real behaviour calibration based on 2002 earthquake. *Geosciences* 10:21. <https://doi.org/10.3390/geosciences10010021>
- Čičić S (2002) Geološki sastav i tektonika Bosne i Hercegovine, Earth Science Institute Sarajevo, pp 350, ISBN 9958-9352-0-4
- Čičić S, Jovanović C, Mojičević S, Tokić S, Dimitrov P (1991) Osnovna geološka karta SFRJ, list Tuzla, 1: 100 000, OOUR Geoinstitut Sarajevo, in Bosnian language
- Department of Urbanism Tuzla Municipality. (2011) Seismology
- EN 1998-1:2004. (2004) Eurocode 8: design of structures for earthquake resistance. Part 1: general rules, seismic actions, and rules for buildings. European Committee for Standardization, Bruxelles
- Evernden J, Thomson JM (1985) Predicting seismic intensities. U.S. Geol. Survey. Paper 1360
- Faccioli, E., and V. Pessina. 2003. WP2-Basis of a handbook of earthquake ground motion scenarios. RiskUE Project An advanced approach to earthquake risk scenarios with applications.
- Formisano A (2016) Theoretical and Numerical seismic analysis of masonry building aggregates: case studies in San Pio Delle Camere (L'Aquila, Italy). *J Earthq Eng* 21(2):1–19. <https://doi.org/10.1080/13632469.2016.1172376>
- Giovinazzi S (2005) The vulnerability assessment and the damage scenario in seismic risk analysis. Ph.D. Thesis
- Giovinazzi S (2006) Geotechnical Hazard representation for damage scenario and seismic risk analysis. Christchurch, New Zealand: Earthquake Geotechnical Engineering Workshop, Canterbury, November 2006
- Giovinazzi S (2009) Geotechnical hazard representation for seismic risk analysis. *Bull N Z Soc Earthq Eng* 42(3):221–234. <https://doi.org/10.5459/bnzsee.42.3.221-234>
- Giovinazzi S, Lagomarsino S (2001) A methodology for the seismic vulnerability analysis of buildings. Proceedings of the 10th Italian conference on earthquake engineering. Potenza, Italy (in Italian)
- Giovinazzi S, Lagomarsino S (2004) A Macro seismic Model for the vulnerability assessment of buildings. Proceedings of the 13th World Conference on Earthquake Engineering, Vancouver, Canada, paper 896.
- Grünthal G (1998) European macroseismic scale. European Seismological Commission (ESC), Working Group Macro seismic Scales, Luxembourg. ISBN 2879770084.
- Guagenti E, Petrini V (1989) The case of ancient constructions: toward a new damage-intensity law. Proceedings of the 4th national conference of seismic engineering. vol. I, pp 145–153. Milan, Italy.
- Hadzima-Nyarko M, Mišetić V, Morić D (2017) Seismic vulnerability assessment of an old historical masonry building in Osijek, Croatia, using Damage Index. *J Cult Herit* 28:140–150. <https://doi.org/10.1016/j.culher.2017.05.012>
- Hrvatović H (2005–2010) Identifikacija i procjena geoloških hazarda-zemljotresa, pp 25, <http://www.msb.gov.ba/dokumenti/AB38725.pdf>.
- BAS (2018), Institute for Standardization of Bosnia and Herzegovina, National Annex BAS EN 1998-1:2018—design of structures for earthquake resistance—part 1: General rules. seismic actions and rules for buildings.
- Interactive seismic map for the city of Tuzla (<http://eurokodovi.ba/seizmika/>), Accessed January 16, 2021. <http://eurokodovi.ba/seizmika/>
- Işık E (2016) Consistency of the rapid assessment method for reinforced concrete buildings. *Earthq Struct* 11(5):873–885. <https://doi.org/10.12989/eas.2016.11.5.000>
- IWU, I.W. TABULA (2017) Typology approach for building stock energy assessment. Accessed September 12, 2020. <http://episcopo.eu/ice-project/tabula/>
- Jalali A, Salem Milani A (2005) Fundamental periods of buildings measured from ambient vibration measurements. Proceedings of the 2005 world sustainable building conference. Tokyo, pp 27–29 September 2005 (SB05Tokyo).
- Kohrangi M, Bazzurro P, Vamvatsikos D (2021) Seismic risk and loss estimation for the building stock in Isfahan. Part I: exposure and vulnerability. *Bull Earthq Eng* 19:1709–1737. <https://doi.org/10.1007/s10518-020-01036-2>
- Kohrangi M, Bazzurro P, Vamvatsikos D (2021) Seismic risk and loss estimation for the building stock in Isfahan: part II—hazard analysis and risk assessment. *Bull Earthq Eng* 19:1739–1763. <https://doi.org/10.1007/s10518-020-01037-1>
- Kožar A (1995) Regionalni istorijski arhiv Tuzla 1954–1994, Tuzla, Arhiv, pp 108.

- Lagomarsino S, Giovinazzi S (2006) Macroseismic and mechanical models for the 680 vulnerability and damage assessment of current buildings. *Bull Earthq Eng* 681(4):415–443. <https://doi.org/10.1007/s10518-006-9024-z>
- Lantada N, Pujades LG, Barbat AH (2009) Vulnerability index and capacity spectrum based methods for urban seismic risk evaluation. A comparison. *Nat Hazards* 51:501. <https://doi.org/10.1007/s11069-007-9212-4>
- Lantada N, Irizarry J, Barbat AH, Goula X, Roca A, Susagna T, Pujades LG (2010) Seismic hazard and risk scenarios for Barcelona, Spain, using the risk-UE vulnerability index method. *Bull Earthq Eng* 8:201–229. <https://doi.org/10.1007/s10518-009-9148-z>
- Lepirica A (2013) Geomorphological characteristics of Tuzla's basin and its local influence on ground-level air pollution. pp 1–9. In: *Geomorfologija Bosne i Hercegovine*, Sarajevo Publishing.
- López-Comino JA, Mancilla FL, Morales J, Stich D (2012) Rupture directivity of the 2011, Mw 5.2 Lorca earthquake (Spain). *Geophys Res Lett* 39(3):1–5. <https://doi.org/10.1029/2011GL050498>
- Mancini F, Stecchi F, Zanni M, Gabbianelli G (2009a) Monitoring ground subsidence induced by salt mining in the city of Tuzla (Bosnia and Herzegovina). *Environ Geol* 58(2):381–389. <https://doi.org/10.1007/s00254-008-1597-1>
- Mancini F, Stecchi F, Gabbianelli G (2009b) GIS-based assessment of risk due to salt mining activities at Tuzla (Bosnia and Herzegovina). *Eng Geol* 109(3–4):170–182. <https://doi.org/10.1016/j.enggeo.2009.06.018>
- Medvedev J (1962) *Engineering seismology*. Academia Nauk Press, Moscow
- Midorikawa S (1987) Prediction of Isoleismal map in the Kanto Plain due to hypothetical earthquake. *J Struct Eng* 33B. (in Japanese).
- Milutinovic ZV, Trendafiloski GS (2003) RISK-UE, an advanced approach to earthquake risk scenarios with applications to different European towns. Report to WP4: vulnerability of current buildings.
- Milutinovic Z, Salic R, Tomic D (2017) An overview on earthquake hazard and seismic risk management policies of Macedonia. Proceedings of the 16th World Conference on Earthquake Engineering. Santiago, Chile. paper 3726.
- Navarro M, García-Jerez A, Alcalá FJ, Vidal F, Enomoto T (2013) Local site effect microzonation of Lorca town (SE Spain). *Bull Earthq Eng* 12(5):1933–1959. <https://doi.org/10.1007/s10518-013-9491-y>
- Seismotectonic map of Tuzla region;(Photo: A. K./Klix.ba), <https://www.klix.ba/vijesti/bih/miralem-mulac-tlo-u-mramoru-je-veoma-osjetljivo-zbog-dubokih-rasjeda/190911087> (2020)
- Stewart JP, Fenves GL, Seed RB (1999) Seismic soil-structure interaction in buildings. I: analytical methods. *J Geotech Geoenviron Eng* 125(1):26–37
- Taibi H, AitYoucef M, Khellafi M (2019) Seismic vulnerability assessment using the macroseismic method proposed in the framework of Risk-UE project based on the recommendations of the Algerian seismic code RPA99/Version 2003. *Asian J Civil Eng* 21:59–66. <https://doi.org/10.1007/s42107-019-00190-6>
- TC4-ISSMGE 1993; revised (1999) Manual for zonation on seismic geotechnical hazards. Technical Committee for Earthquake Geotechnical Engineering.
- Threat Assessment to natural and other disasters in the Tuzla Canton, Cantonal Administration of Civil Protection Tuzla Canton, Federation of Bosnia and Herzegovina, Bosna and Hercegovina, March 2016, pp 140, in the Bosnian language
- Torbarov K, Jovanović R (1978) *Inžinjerskogeološke karakteristike geološke građe Bosne i Hercegovine*. pp 470, Knjiga 1, in the Bosnian language
- TRCBSR. (1981) Technical regulations for construction of buildings in seismic regions (1981), Official Gazette of SFRY No. 31/81, Amendments 49/82, 29/83, 21/88 and 52/90
- TTPCSR. (1964) Temporary technical provisions for construction in seismic regions (1964), Official Gazette of SFRY No. 39/64
- Vicente R, Ferreira T, Maio R (2014) Seismic risk at the urban scale: assessment, mapping and planning. *Proced Econ Finance* 18:71–80

Authors and Affiliations

Naida Ademovic¹  · Marijana Hadzima-Nyarko²  · Nermina Zagora³ 

Marijana Hadzima-Nyarko
mhadzima@gfos.hr

Nermina Zagora
nermina.zagora@af.unsa.ba

¹ University of Sarajevo-Faculty of Civil Engineering, Patriotske lige 30, Sarajevo, Bosnia and Herzegovina

² Faculty of Civil Engineering and Architecture, J. J. Strossmayer University of Osijek, Vladimira Preloga 3, Osijek, Croatia

³ University of Sarajevo-Faculty of Architecture, Patriotske lige 30, Sarajevo, Bosnia and Herzegovina