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INTEGRATING SEISMIC RISK ASSESSMENT INTO SPATIAL PLANNING: CASE REPUBLIC OF NORTH MACEDONIA

Elena Dumova - Jovanoska (1), Kristina Milkova (2), Sergey Churilov(3) Simona Bogoevska(4)

(1) prof., Chair of Theory of Structures and Computational Analysis, Department of Structural Analysis and Earthquake Engineering, Faculty of Civil Engineering Skopje, N. Macedonia, dumova@gf.ukim.edu.mk
(2) Asst. prof., Chair of Theory of Structures and Computational Analysis, Department of Structural Analysis and Earthquake Engineering, Faculty of Civil Engineering Skopje, N. Macedonia, milkova@gf.ukim.edu.mk,
(3) prof., Chair of Theory of Structures and Computational Analysis, Department of Structural Analysis and Earthquake Engineering, Faculty of Civil Engineering Skopje, N. Macedonia, curilov@gf.ukim.edu.mk
(4) Assoc. prof., Chair of Theory of Structures and Computational Analysis, Department of Structural Analysis and Earthquake Engineering, Faculty of Civil Engineering Skopje, N. Macedonia, simona.bogoevska@gf.ukim.edu.mk

Abstract

Assessing earthquake risk in regions characterized with moderate to high seismic hazard, such as parts of Republic of North Macedonia, is essential for the development of effective risk management and mitigation strategies [1]. Comprehensive risk assessment enables prediction on most likely locations of high-intensity earthquakes and what their potential impacts might be. In the framework of the Study for Natural and technical risks in the Republic of North Macedonia [2], as one of the background documents for the preparation of the Spatial plan of the country for the period 2021-2040, seismic Risk maps have been created.

The process of assessing earthquake risk involves analyzing three critical components: hazard, exposure, and vulnerability of the exposed structures. A detailed seismic hazard assessment for North Macedonia has been conducted using data on historical earthquake activity, earth crust models, and active fault characterization leading to the development of a seismic hazard map [3]. To evaluate the exposure of objects and people in the Republic of North Macedonia, data from the State Statistical Office, including information from the 2021 population census, households, and dwellings, were utilized. Three authentic research studies were selected as key baseline references, providing vulnerability curves and damage matrices for the most common types of structural systems in the country. Consequently, four sets of vulnerability curves (damage matrices) have been selected for the following structural types: structures constructed with unreinforced masonry prior to 1960, reinforced concrete structures built between 1971 and 1981, reinforced concrete structures with a height of up to 10 stories, built from 1981 to the present, reinforced concrete structures exceeding 10 stories in height, built from 1981 to the present.

Using a methodology that integrates hazard maps, vulnerability curves for the selected structural types, and estimated structural damage, seismic risk maps for Republic of North Macedonia have been developed. The proposed methodology connects the region – specific topologies of buildings and their vulnerability on one hand, and region – specific hazard map on the other.

Keywords: spatial plan, risk analysis, hazard, vulnerability, exposure

1. Introduction

The global community is increasingly confronted with a diverse range of risks, including those arising from natural disasters, technological accidents, climate change, overconsumption of natural resources, poor spatial planning and management, risks associated with modern technologies and processes, and risks related to human activities. Analyzing risks is a complex task and is difficult to predict, with consequences that can be vast and severe [4][5].

To address these challenges in a structured and effective manner, ongoing efforts are being made to enhance capacities and capabilities for the integrated management of contemporary risks, both globally and nationally. The primary goal is to reduce these risks to an acceptable level, preventing them from escalating into crises or disasters [6][7].

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The purpose of this paper is to present the findings from the Study on Natural and Technical Risks in the Republic of North Macedonia, which serves as one of the foundational documents for the preparation of the country's Spatial Plan for the period 2021-2040 [2].

2. Seismic risk assessment

Each year, over one million earthquakes are recorded worldwide. Among the catastrophic events that affect urban areas, high-intensity earthquakes stand out as some of the most destructive. Despite being less frequent than other disasters, these events are highly unpredictable and can trigger secondary natural disasters, amplifying their impact. As a result, earthquakes often lead to severe material damage and significant loss of life [8].

In regions with moderate to high seismic hazard, such as parts of North Macedonia, assessing earthquake risk is essential for effective management and mitigation efforts. Comprehensive risk assessments allow for the identification of areas most likely to experience high-intensity earthquakes and help anticipate their consequences. Modern strategies to reduce earthquake risks prioritize identifying and addressing risks through proactive management. The primary goal is to minimize destruction and safeguard lives. While natural hazards like earthquakes cannot be prevented or reduced, engineering solutions can significantly mitigate their impact on buildings and infrastructure [9].

Earthquake risk assessment typically involves analyzing three critical components: hazard, exposure, and vulnerability, as depicted in Figure 1. By thoroughly evaluating these factors, experts can gain valuable insights into seismic risks in a given region and devise targeted strategies to reduce and manage them effectively.

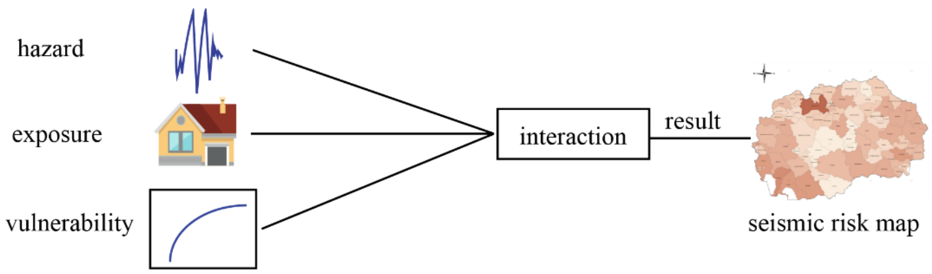

Figure 1. Concept of seismic risk determination

2.1. Seismic hazard assessment

A detailed seismic hazard assessment has been conducted for the territory of Republic of North Macedonia, incorporating data on historical earthquake activity (as shown on Figure 2), crustal models, and the characterization of active faults [10] [11].

The procedure applied based on the application of a complex Poisson-Gamma distribution. This approach allows for the introduction of uncertainties in the time-dependent and variable seismicity. In seismic hazard analyses based on this approach, the parameters of seismic hazard that are assigned to a specific area or local region (which can be referred to as a structural seismic source) are of particular importance. The seismic hazard parameters utilized are: Maximum regional magnitude (the seismic source is a specific structural unit or area with a defined seismic activity), The mean value of the activity coefficient λ within the polygon or seismic source, The coefficient b from the Gutenberg-Richter distribution of earthquake magnitude frequency within the seismic source area [12]. For each surface source, predefined coefficients are introduced to estimate seismic activity, characteristics of acceleration attenuation, and the geographical distribution of epicenters. The final processing of the input data was performed using the R-Crisis software package, where the seismic hazard analysis is based on the full application of the probabilistic approach (PSHA). As a final product, a seismic hazard map (maximum ground acceleration) for a return period of 475 years at national level has been produced [2].

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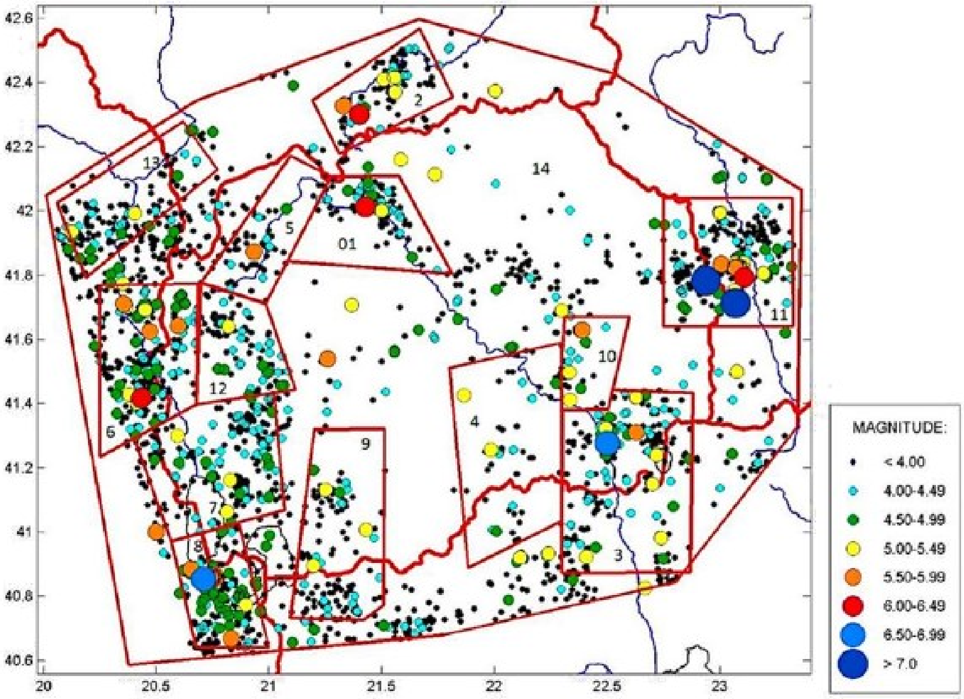

Figure 2. Map of earthquakes in North Macedonia (538-2020) [2]

2.2. Exposure

To assess the exposure of people and structures in the Republic of North Macedonia, data from the State Statistical Office, including the 2021 population census, household, and dwelling data, were utilized. This dataset encompasses all 80 municipalities in the country and includes information such as:

- **Total population**,
- **Year of construction** (categorized as: before 1919; 1919–1945; 1946–1960; 1961–1970; 1971–1980; 1981–1990; 1991–2000; 2001–2010; 2011–2015; 2016 and later; and unknown),
- **Number of floors** (ground floor, G+1, G+3, G+4, G+5–9, G+10–19, G+20 or more, and unknown),
- **Structural materials of buildings** (concrete and reinforced concrete, concrete blocks, steel, bricks, stone, prefabricated wood panels, adobe, and unknown).

Buildings in each municipality were classified based on attributes such as structural materials, year of construction, and number of floors. The classification was initially determined by the seismic design codes under which the buildings were constructed. This classification was performed for every municipality, and the total built-up area was calculated and distributed according to these attributes. The analysis revealed that Skopje has a substantially larger built-up area and higher population density compared to other regions of the country.

The population distribution within buildings is critical for accurate exposure assessments. This includes not only the total population but also how people are distributed across municipalities and structures, categorized by attributes like year of construction, structural material, and number of floors.

Figures 3 and 4 provide insights into the total area of all structures and population distribution, respectively, based on structural materials and the seismic design codes under which the buildings were constructed. The majority of buildings in North Macedonia are made of concrete and reinforced concrete and were constructed according to current codes.

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The exposure maps highlight that an earthquake near Skopje would likely result in far greater impacts compared to other municipalities, even for earthquakes of similar intensity. However, the resilience of the buildings, particularly their capacity to withstand damage without collapsing, is a critical factor in assessing potential hazards.

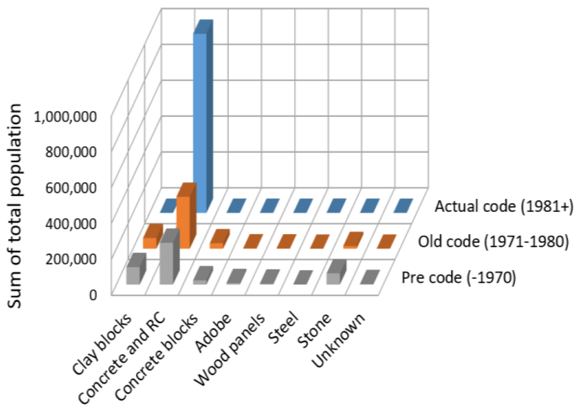

Figure 3. Total population living in buildings from different structural materials and applied codes [2]

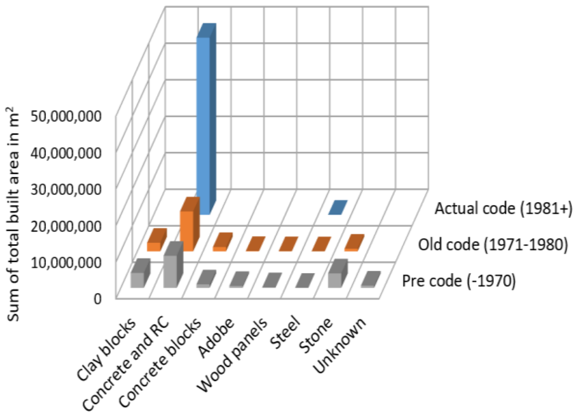

Figure 4. Total built area by structural materials and applied codes [2]

2.3. Vulnerability

The vulnerability of buildings is assessed by analyzing the correlation between earthquake intensity and the likelihood of damage [13]. Different types of buildings, categorized based on predefined attributes, have varying capacities to resist horizontal seismic forces. For example, structures built before 1960 using unreinforced masonry in areas with high seismic hazard are significantly more susceptible to earthquake damage compared to buildings constructed under modern seismic codes.

A detailed analysis of regional research identified three key studies that define vulnerability curves and damage matrices for the most dominant structural systems in the country. Based on these findings and available census exposure data, four sets of vulnerability curves (damage matrices) have been selected for use with the chosen structural types:

- **Unreinforced masonry structures constructed prior to 1960**, Figure 5 [14],
- **Reinforced concrete structures built between 1971 and 1981**, Figure 6[15],
- **Reinforced concrete structures up to 10 stories tall, built from 1981 to the present**, Figure 7 [16],
- **Reinforced concrete structures over 10 stories tall, built from 1981 to the present**, Figure 8 [16].

Fragility curves represent the probability of exceeding specific damage levels for a given earthquake intensity. Defining these curves requires definition of damage indicators and thresholds. The damage levels are generally derived from the computed capacity curve for each construction type and encompass several thresholds, ranging from no damage to total collapse. Due to a lack of information for some damage thresholds, an interpolation process was applied to generate fragility curves for reinforced concrete structures built between 1971 and 1981. These curves were then converted into damage matrices to obtain discrete values, which can be utilized in subsequent steps to define the risk level.

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Table 1. Damage probability matrix for RC frame structures lower than 10 stories [16]

	Damage probability matrix						
	Damage states	Damage index	VII	VIII	IX	X	XI
1	None	<0.05	100.0	99.09	44.37	8.57	1.56
2	Minor	0.05–0.1	**0.00**	0.91	51.65	13.77	2.03
3	Moderate	0.1–0.25	**0.00**	**0.00**	3.97	48.53	8.56
4	Severe	0.25–0.5	**0.00**	**0.00**	**0.00**	28.79	25.32
5	Collapse	>0.5	**0.00**	**0.00**	**0.00**	0.34	62.53

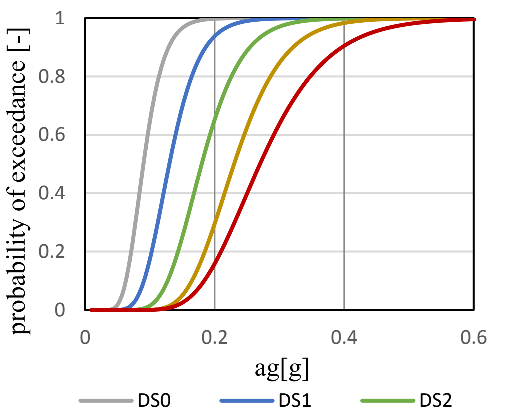

Figure 5. Vulnerability curves for unreinforced masonry structures [15]

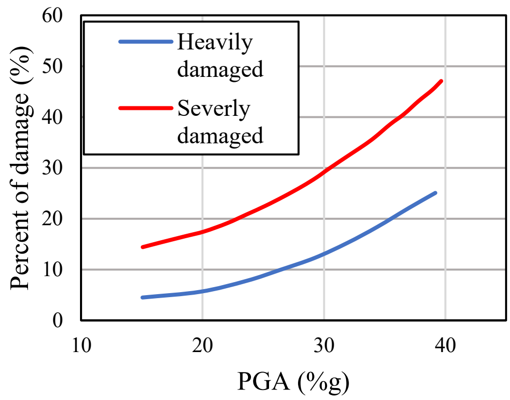

Figure 6. Vulnerability curves for reinforced concrete structures constructed between 1971 and 1981 [14]

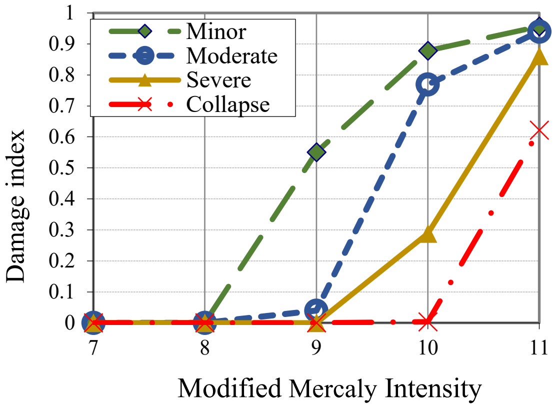

Figure 7. Vulnerability curves for reinforced concrete structures with a height of up to 10 stories [16]

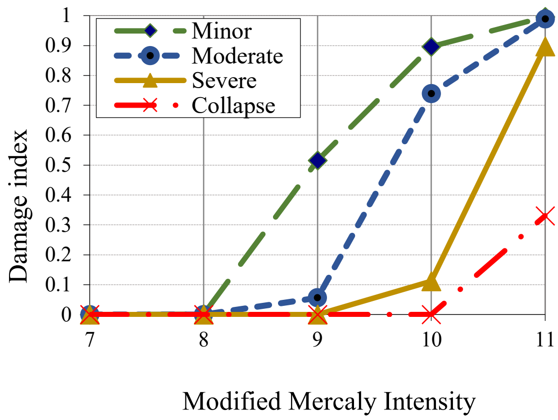

Figure 8. Vulnerability curves for reinforced concrete structures exceeding 10 stories in height [16]

2.4. Methodology for calculation of risk map

The seismic risk calculation, based on the expected damage built area, was conducted at the municipal level. Census data, including population and building area categorized by type, were processed for each municipality. Hazard maps were transformed into municipality-specific maps, allowing for the determination of the maximum expected earthquake intensity for each municipality. This approach enabled the creation of an earthquake scenario for maximum ground acceleration for a return period of 475 years.

Using a methodology that integrates hazard maps, fragility curves for selected structural types, and estimates of structural damage based on damage factors and states (as outlined by Whitman et al. [17]), presented in Table 2, seismic risk maps in terms of expected damaged area for North Macedonia have

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been developed. These maps illustrate the expected extent of damage for the most severe earthquake scenario in each municipality (Figure 9).

Table 2. Correlation - damage level and states Whitman et al. [17]

Damage level	Threshold values (%)
Minor	3.5-7.5
Moderate	7.5-20
Severe	20-65
Collapse	65-100

3. Conclusion

The proper selection and authenticity of all data utilized in the methodology is critical point for ensuring reliable results in seismic risk assessments. This includes the use of accurate data from the census, which provides essential information about the distribution and characteristics of the population and infrastructure. Local hazard calculations, based on historical earthquake activity, earth crust models, and active fault characterization for the country, are critical in determining the seismic risks specific to each region. The use of accurate vulnerability curves, created for specific construction types in North Macedonia, is also a key aspect in defining the seismic risk map. Only by ensuring the authenticity and precision of these data sources a robust and accurate seismic risk map that truly reflects the potential risks and informs effective risk management strategies can be developed at a national level. The presented map is a valuable tool for local governments in preparing strategic documents to define seismic risk mitigation policies.

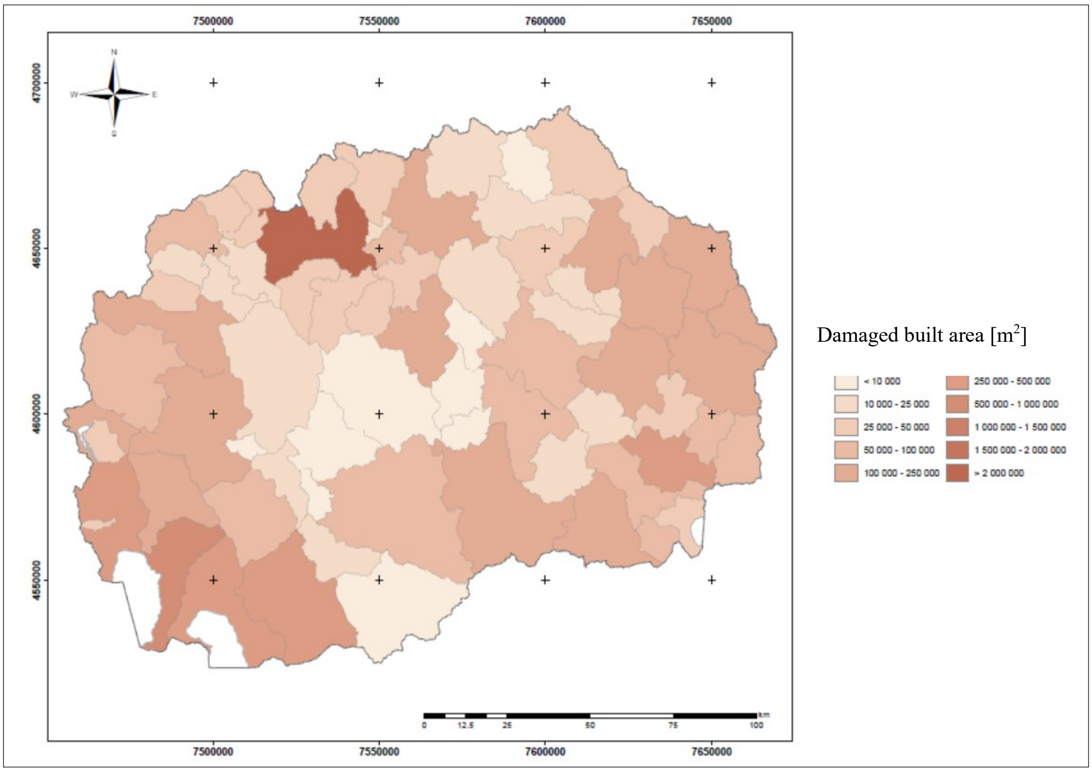

Figure 9. Earthquake risk map for seismic return period of 475 years by municipalities and the city of Skopje (damaged built area) [2]

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