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BUILDING EXPOSURE MODELLING FOR NATIONAL SEISMIC RISK ASSESSMENT IN MONTENEGRO

Nina Serdar [(1)], Jelena Pejović [(2)]

[(1)] *Assistant professor, University of Montengro, Faculty of Civil Engineering, ninas@ucg.ac.me*
[(2)] *Associate professor, University of Montengro, Faculty of Civil Engineering, jelenapej@ucg.ac.me*

Abstract

Seismic risk assessment in Montenegro has been of critical concern since the devastating earthquake of 1979, which spurred initial studies for the country's spatial planning. In response, significant efforts have been made to mitigate seismic risks and regulate the construction of earthquake-resistant structures. Early vulnerability studies were based on damage observations from the 1979 earthquake. However, since then, seismic risk in Montenegro has increased considerably due to rapid urbanization and intense building construction, particularly in coastal zones with high seismic hazard. In 2021, a comprehensive study was conducted as part of a European Commission-funded project to develop a National Risk Assessment (NRA), led by the Department of Civil Protection. This seismic risk assessment was carried out in accordance with EU guidelines ensuring consistency and comparability in terms of prevention, preparedness, and planning. The development of NRA encountered several challenges primarily due to data gaps, especially in the building exposure modelling. In this paper, the methodology applied for seismic risk assessment is presented, with a focus on the main uncertainties in the existing exposure models from literature. A new refined exposure model is proposed tailored for building typologies in northern Montenegro. Ongoing and future research efforts aimed at continually improving the exposure model are also discussed.

Keywords: seismic risk, exposure model, SERA model, buildings.

1. Introduction

The first seismic risk study in Montenegro was conducted in 1984, in response to the devastating 1979 earthquake, to support the development of the national Spatial Plan. This pioneering study [1] assessed the consequences of the earthquake by examining approximately 40,000 facilities across six coastal and two central municipalities. The analyzed structures included residential buildings, as well as cultural, tourism, and educational facilities. Despite significant social efforts at the time to address seismic risks, no subsequent seismic risk studies were carried out until recently. It is widely recognized that seismic risk assessments has to be regularly updated to account for evolving factors such as population growth, building stock changes, and structural vulnerabilities.

In late 2021, a new National Risk Assessment (NRA) [2] was developed by the Department of Civil Protection (DCP) under the Ministry of Interior to fulfil Montenegro's obligations as an EU candidate country. The NRA aligns with the Strategy for Disaster Risk Reduction (2018–2023) and evaluates nine hazard categories: earthquakes, landslides, climate change, floods, forest fires, epidemics, technical accidents, nuclear incidents, and critical infrastructure failures. This effort benefitted from a collaborative approach involving the DCP, the scientific community (notably the Faculty of Civil Engineering at the University of Montenegro), and the National Seismological Institute, which collectively contributed to the development of Montenegro's seismic risk assessment. The seismic risk assessment, as part of the NRA, adheres to EU guidelines [3], ensuring alignment with the risk assessments of EU member states. This consistency fosters a shared understanding of disaster risks, facilitating cooperative prevention and mitigation efforts across borders.

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The implementation of EU methodologies in Montenegro's seismic risk assessment posed several challenges and raised important questions. This paper outlines the adopted methodology, highlights key uncertainties, and addresses open questions, particularly in relation to exposure modelling using existing building exposure data [4], [5]. It introduces a refined exposure model tailored for building typologies in northern Montenegro. The findings aim to contribute to refining risk assessment practices and improving disaster resilience strategies in the region.

2. Seismic Risk Assessment Methodology

This chapter discusses the conceptual framework and methodology for seismic risk calculation, as outlined in the EU guidelines [3]. According to ISO 31010 [6], risk is defined as the combination of the consequences of an event (hazard) and the probability of their occurrence. A hazard refers to a dangerous phenomenon, substance, human activity, or condition that has the potential to cause loss of life, injury, health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage. Consequences describe the negative effects of a disaster, which are quantified through impact indicators. These indicators capture dimensions such as human losses, economic damages, environmental degradation, and political or social disruptions.

For natural hazards such as earthquakes, the impacts are often independent of the probability of the hazard occurring. This relationship is mathematically expressed as follows:

$$\text{Risk} = p \times V \times E \tag{1}$$

where p represents the probability of consequences, V denotes vulnerability (expected negative impacts to people and property), and E indicates exposure (assets at risk). Vulnerability refers to the characteristics of assets, properties, or systems that make them susceptible to damage from the hazard. Exposure is defined as the total number of people, properties, systems, and other elements located in hazard-prone areas.

The EU methodology for risk calculation emphasizes the use of quantitative impact indicators wherever possible. However, when the complexity of quantitative calculations does not significantly enhance reliability or robustness, these parameters can be supplemented by qualitative assessments or expert judgment. The EU guidelines categorize impacts into three main types [3]:

- Human Impacts: These include the number of fatalities, severely injured individuals, and permanently displaced persons.
- Economic and Environmental Impacts: These encompass costs related to healthcare, emergency response, restoration of buildings, infrastructure, cultural heritage, and environmental recovery.
- Political and Social Impacts: These consider public anxiety, territorial encroachment, violations of democratic systems, societal psychological effects, disruptions to public order and safety, political repercussions, and damage to cultural assets.

Human impacts are measured numerically, economic and environmental impacts are quantified in monetary terms (Euros), and political and social impacts are expressed semi-quantitatively using categories such as insignificant, minor, moderate, significant, and catastrophic.

Risk is typically visualized using a risk matrix, a two-dimensional chart with the horizontal axis representing the likelihood of impacts and the vertical axis indicating the severity of the impacts. This tool allows for an intuitive comparison of different risks. The seismic risk assessment methodology for Montenegro adopts a scenario-based approach, evaluating risk for specific earthquake events with potentially significant societal consequences. Consequences are categorized from minimal to catastrophic, and when combined with the probability of occurrence, they are depicted in seismic risk matrices. These matrices provide a clear representation of the overall risk level and support decision-making for disaster preparedness and mitigation.

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3. Seismic Risk Assessment Results: Montenegro Overview

The seismic risk assessment from 2021 for Montenegro evaluates two distinct what-if earthquake scenarios:

- Scenario 1: This scenario represents the most likely seismic event, characterized by a return period of 95 years and a magnitude of M=6.
- Scenario 2: This scenario models an event with a return period of 475 years, considered to have the worst possible consequences, with a magnitude of M=7.

Both scenarios assume earthquakes with the same epicenter, located near the municipalities of Bar and Ulcinj, approximately 13 km south of the settlement of Kruce, at a depth of 10 km. The intensity distributions for these scenarios, reflecting the spatial impact and severity, are illustrated in Fig. 1.

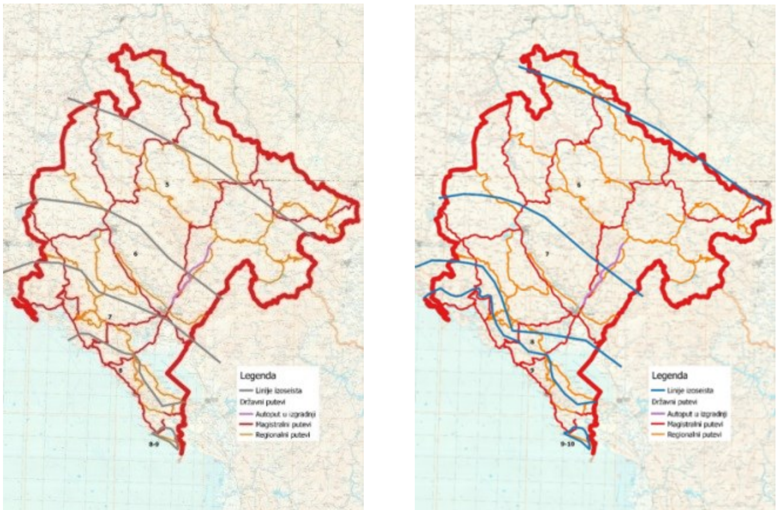

Figure 1. Intensity shaking distribution for a) Scenario 1 and b) Scenario 2 [2].

The damage distribution for the two earthquake scenarios is summarized in Fig.2. In Scenario 1, approximately 0.46% of Montenegro's population and 0.53% of all dwellings are expected to experience the most severe damage levels, categorized as D4 (significant damage) and D5 (collapsed buildings). In contrast, Scenario 2 suggests that as much as 2.7% of inhabitants and 3.11% of dwellings across Montenegro would be subjected to high damage levels D4 and D5.

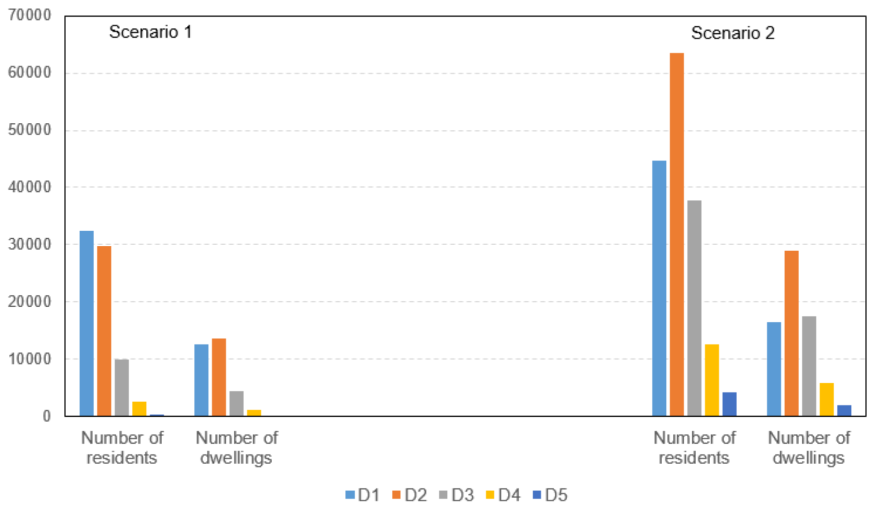

Figure 2. Distribution of damages for Scenario 1 and Scenario 2: number of residents and dwellings for certain damage levels D1-D5.

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Based on the distribution of damages, the impact to people is calculated in terms of fatalities and injuries using two established methodologies: HAZUS [7] and IRMA [8].

- HAZUS Methodology: For Scenario 1, it is estimated that the earthquake will result in 40 fatalities and 169 heavy injuries. In total, 209 residents are projected to be affected, excluding those with minor injuries requiring no to basic medical assistance. For Scenario 2, the estimated impact includes 416 fatalities and 1340 heavy injuries, leading to a total of 1756 affected residents.
- IRMA Methodology: For Scenario 1, the earthquake is projected to cause 65 fatalities and 243 injuries, resulting in a total of 308 affected residents. In Scenario 2, the estimated impact increases significantly, with 543 fatalities and 1,882 injuries, culminating in a total of 2,425 affected residents.

The results highlight small discrepancies between the two methodologies. These findings are illustrated in Fig. 3.

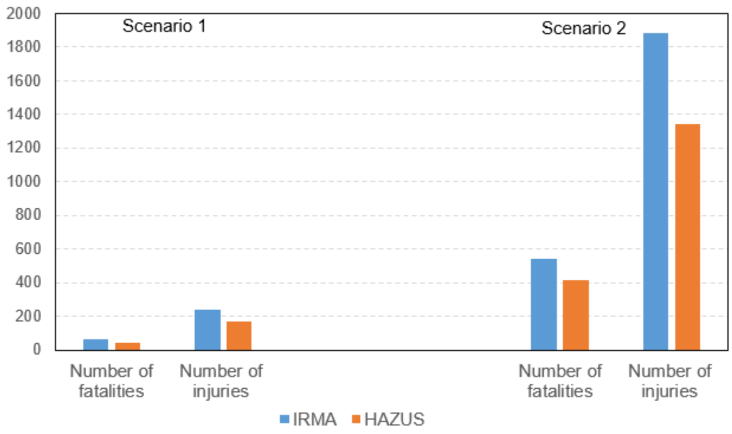

Figure 3. Impact on people according to two methodologies IRMA and HAZUS.

The repair costs for residential buildings are presented in Fig.4. These costs were calculated based on the average construction cost per square meter of dwellings in 2020 and the total area of dwellings corresponding to each damage level. The percentages of repair or replacement costs (Ct) were determined using the methodologies outlined in references [7], [8]. For Scenario 1, the repair costs exhibit minor variations in results from both methodologies, with the maximum estimated cost reaching 10% of GDP. In contrast, for Scenario 2, which accounts for the most severe earthquake scenario, the repair costs are significantly higher, ranging from 25.9% to 40.2% of GDP, depending on the methodology applied.

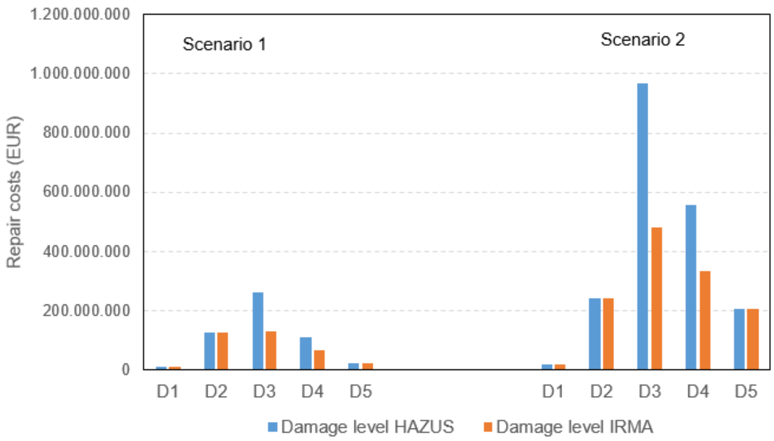

Figure 4. The repair costs for residential buildings for two methodologies IRMA and HAZUS.

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4. Modeling Exposure: Key Challenges

In Montenegro, a systematic database containing essential information about residential and commercial buildings, such as location, structural typology, building materials, and the number of floors, is currently unavailable. These data are critical for accurate seismic risk assessment but are not collected as part of the national census process. The absence of detailed data is a common challenge in many countries and represented a significant obstacle during this research. The only available census information included the number of dwellings categorized by year of construction and population distribution by municipalities.

To address this data gap, the study relied on existing global models, such as the SERA exposure model [4], [5], created based on Montenegro's 2011 census data. The SERA model incorporates assumptions regarding the distribution of common structural systems for residential buildings, categorized by the year of construction. These assumptions were derived from expert opinions and data extrapolated from neighboring countries. In the SERA methodology, the number of dwellings was converted into the number of buildings using assumptions about the average number of dwellings per building typology and the corresponding number of storeys. The distribution of common structural systems by year of construction for urban areas, is illustrated in Fig.5.

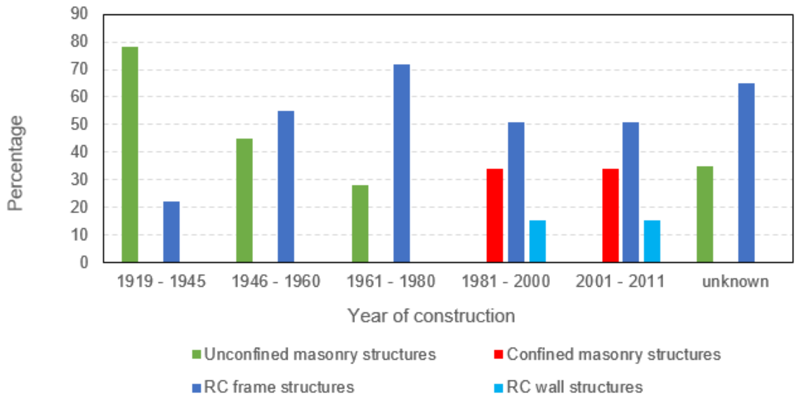

Figure 5. Distribution of common structural systems by year of construction in urban areas.

Based on the authors' expertise and analysis of relevant documents, such as the Protect and Rescue Plans [9]–[12] developed by local civil protection units for specific municipalities, several deficiencies in the SERA exposure model were identified. One significant issue is the model's tendency to overestimate the number of reinforced concrete (RC) buildings as well as the number of dwellings and residents in RC buildings, particularly in the northern part of Montenegro. The distribution of residents by region and structural typology, as represented in the SERA model, is illustrated in Fig.6, highlighting these discrepancies.

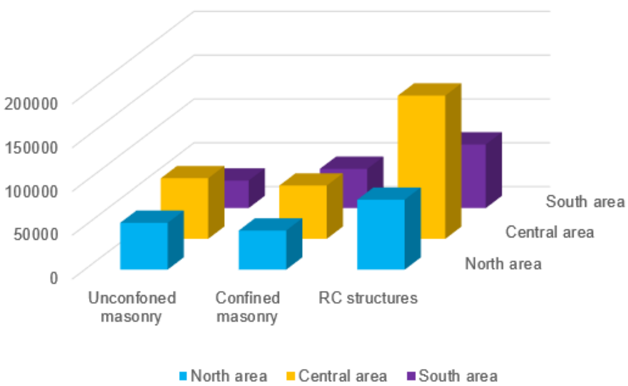

Figure 6. Regional distribution of residents by building typology.

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Earthquake protection and rescue strategies have been specifically tailored for urban areas in the northern municipalities of Montenegro, including Berane, Bijelo Polje, Mojkovac, Pljevlja, Plužine, and Rožaje. Unfortunately, comparable data for municipalities in the southern and central regions were not available. As a result, adjustments to the SERA exposure model were limited to the urban areas of the northern region.

5. Refined SERA exposure model tailored for Montenegro

This chapter provides an in-depth analysis of the refinements made to the SERA exposure model, with a primary focus on the northern municipalities of Montenegro. These adaptations were driven by the lack of comparable data for the southern and central regions, limiting model adjustments to urban areas in the northern region. From the available documents used to refine the SERA model, the existing data from Berane, Bijelo Polje, Mojkovac, and Rožaje proved particularly valuable. These municipalities provided detailed information, including the number of buildings or apartments, construction year, number of floors, and in some cases, even the structural system. This chapter systematically analyzes the available data for each municipality, detailing the adjustments made to the SERA model and their implications.

5.1. Rožaje Municipality

Data analysis for the urban areas of Rožaje were based on the information from 33 collective housing units, predominantly featuring reinforced concrete (RC) structures and reflecting recent construction trends. Individual housing units in this area, by contrast, primarily consist of masonry, adhering to traditional building practices in northern Montenegro. Data collected by local authorities included the number of floors, year of construction, and the number of dwellings. The adjustments were conducted as follows:

- RC Buildings: These were categorized according to the SERA taxonomy, based on the floor count, structural system, and seismic design level (quality of construction). The seismic design levels for buildings were classified as:
  - CDN (no seismic design): built before 1964.
  - CDL (low seismic design): built between 1964 and 1981.
  - CDM (moderate seismic design): built after 1981.
- Masonry Buildings: The relative percentage distribution from the SERA model was maintained, including the assumptions on the number of dwellings per floor (1 dwelling for 1 and 2-storey buildings and 4 dwellings per floor for 3 to 5-storey buildings).

Based on these assumptions, the number of masonry buildings was calculated according to the SERA taxonomy. The final distribution of buildings in specific typologies was derived and expressed in percentages.

5.2. Berane and Bijelo Polje Municipalities

Combined data from 170 collective housing buildings in Berane and Bijelo Polje revealed a prevalence of RC structures in newer constructions and masonry buildings in older ones. The available data included the number of stories and dwellings but lacked construction year details. This missing information was supplemented using data from the 2011 census track. Once the dataset was completed, it was processed in the same manner as for Rožaje municipality.

5.3. Mojkovac Municipality

The dataset for Mojkovac consisted of 38 collective housing buildings but lacked information on the number of floors. To address this issue, floor counts were estimated based on the distribution of apartment numbers and expert opinion. The subsequent data processing followed the same methodology applied to the other municipalities.

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5.4. Aggregate Adjustments

At the end, cumulative adjustments were made to the combined data from the four municipalities. These adjustments were used to recalibrate the SERA model's assumptions on building types and their distribution, aligning the model with the observed construction practices in the northern region. The recalibration also accounted for variations in the seismic design across different construction periods. Table 1 presents the refined distributions of buildings based on the SERA taxonomy. Representations of building types in percentage within the urban areas and for specific time periods were calculated according to the following equation:

$$p_{ti}(\%) = \frac{\sum_{j=1}^{4} p_{ti,j} \cdot d_j}{d_{tot}} \tag{1}$$

p_{ti} corrected percentage of building typology i with taxonomy t

$p_{ti,j}$ corrected percentage of building typology i with taxonomy t for the municipality $j=(1-4)$

d_j number of dwellings in municipality j

d_{tot} total number of dwellings in analysed municipalities

Table 1. The SERA model refined for Northern Montenegro

Taxonomy	1919-1945	1946-1960	1961-1980	1981-2000	2001-2011
CR/LFINF+CDM/HBET:6-/2.5	0.0	0.0	0.0	1.5	1.2
CR/LFINF+CDN/HBET:6-	0.0	0.0	0.0	0.0	0.0
CR/LFINF+CDN/HBET:3-5	0.0	3.8	0.7	0.0	0.0
CR/LFINF+CDN/H:2	3.3	3.6	0.1	0.0	0.0
CR/LFINF+CDM/HBET:3-5/2.5	0.0	0.0	0.0	5.8	6.8
CR/LFINF+CDM/H:2/2.5	0.0	0.0	0.0	1.9	1.2
CR/LFINF+CDL/HBET:6-/0.0	0.0	0.0	0.2	0.0	0.0
CR/LFINF+CDL/HBET:3-5/0.0	0.0	0.0	0.9	0.0	0.0
CR/LFINF+CDL/H:2/0.0	0.0	0.0	0.3	0.0	0.0
CR/LDUAL+CDM/HBET:6-/2.5	0.0	0.0	0.0	3.2	5.8
MUR/LWAL+CDN/HBET:3-5	5.8	11.1	0.0	0.0	0.0
MUR/LWAL+CDN/H:2	43.5	30.5	35.2	0.0	0.0
MUR/LWAL+CDN/H:1	47.4	51.0	62.6	0.0	0.0
MCF/LWAL+CDN/HBET:3-5	0.0	0.0	0.0	25.8	25.1
MCF/LWAL+CDN/H:2	0.0	0.0	0.0	25.8	25.1
MCF/LWAL+CDN/H:1	0.0	0.0	0.0	36.0	34.8

The detailed comparison between the original and revised SERA models highlights significant differences in estimations and categorizations. A key conclusion is that the original SERA model tends to overestimate the number of RC frame buildings, particularly those designed with moderate seismic design. One of the most notable adjustments pertains to the category of RC frame buildings with infill walls (CR/LFINF+CDM/HBET:3-5). In the original SERA model, these buildings were estimated to constitute approximately 28% of the total number of structures during the period 1981–2000. However, the refined model significantly reduces this figure to about 5.8%, reflecting a more accurate assessment

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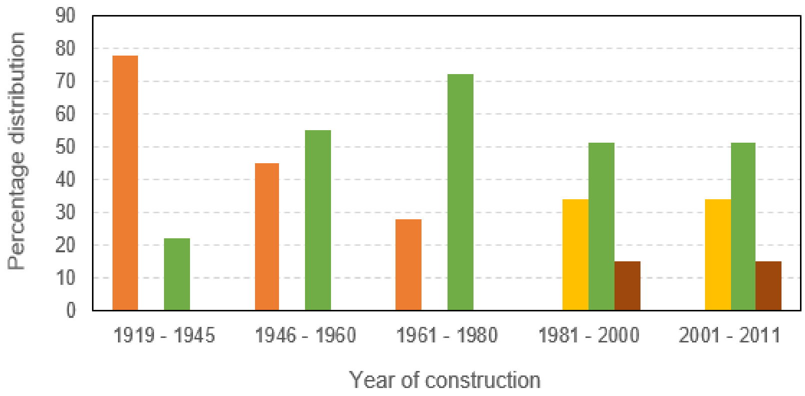
of the construction practices in the region. Additionally, the refined model introduces a new category for buildings with a dual structural? system with moderate seismic design (CR/LDUAL+CDM/HBET:6), accounting for 3.2% of structures from the same period. This addition represents an enhancement in the current understanding of the building technologies and structural systems likely underrepresented or overlooked in the original SERA assessment.

These revisions underscore the importance of local data and expert input in refining exposure models, ensuring that they better reflect the reality of construction practices and structural diversity in Montenegro's urban areas. The adjusted distribution is illustrated in Fig. 7.

a)



b)

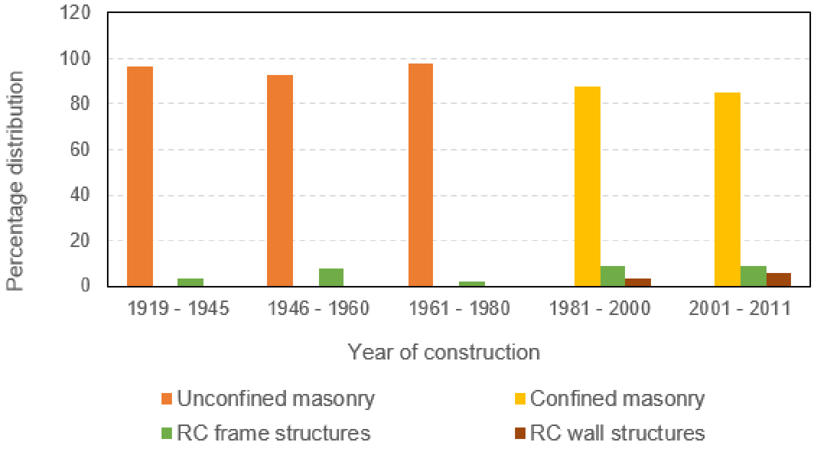


Figure 7. a) Existing SERA model and b) Refined SERA model

6. Conclusions

There were no seismic risk assessment studies conducted in Montenegro since 1979. In 2021, as a part of the European Commission-funded project led by the Department of Civil Protection (DCP) and in collaboration with researchers from the University of Montenegro and the Institute of Seismology, a new National Seismic Risk Assessment (NRA) was developed. The development process faced

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numerous challenges, primarily due to data deficiency, particularly in the building exposure model. This paper discusses the main uncertainties associated with the SERA building exposure data and presents a refined SERA exposure model tailored specifically to the building typologies of northern Montenegro.

An analysis of the SERA model, deemed the most suitable option at the time, concluded that it did not adequately reflect local construction practices. Using the existing rescue and protection plans, a refined model was developed to address these limitations. This refined model, relevant to the northern region of Montenegro, integrates updated data from local assessments, resulting in significant adjustments to the distribution of building types. For instance, the proportion of RC buildings with moderate seismic design was revised to better reflect compliance with updated seismic standards, which were underrepresented in the original model. Moreover, the refined model not only updates previous estimates but also enhances the classification granularity by introducing new building typologies into the existing framework. These revisions underscore the importance of local data and expert input in refining exposure models, ensuring that they better reflect the reality of construction practices and structural diversity in Montenegro's urban areas.

Future research should prioritize systematic data collection in the central and coastal municipalities, addressing the gaps that currently hinder comprehensive national seismic risk assessment. Additionally, advancements in artificial intelligence, image processing, machine learning, digital map analysis, and elevation modeling should be integrated into the analysis of exposure models. These technologies hold the potential to improve data accuracy and achieve more reliable and detailed seismic risk assessment outcomes.

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