COMPARISON OF SCENARIO-BASED AND TIME-BASED SEISMIC RISK ASSESSMENT: A CASE STUDY IN MONTENEGRO

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Abstract: *This paper presents a comparison of scenario-based and time-based seismic risk assessment approaches for a selected area of moderate seismicity in Montenegro, which is also exposed to other types of natural hazards. The scenario-based risk assessment was developed as part of The National Risk Assessment for all types of hazards affecting Montenegro. However, it is characterized by the use of arbitrary earthquake scenarios, which may result in important scenarios being left out. Moreover, the qualitative description of the risk and using the existing risk matrices can lead to low probability-high consequence events being classified as medium-risk events by definition. On the other hand, the time-based seismic risk assessment, a state-of-the-art approach in contemporary earthquake engineering, has not been implemented in Montenegro but considers all possible earthquakes with relevant source locations and magnitudes without relying on arbitrary scenarios. In this paper, both types of analyses are conducted for one Montenegro pilot area, and the results are compared. The comparison focuses on the impact on people (including the number of fatalities, injured and relocated people) and the direct economic cost resulting from damages to residential buildings. While the scenario-based approach selected two earthquake scenarios, the time-based approach considers six different return periods and shake hazard maps from relevant European models. It was concluded that the deterministic scenario-based approach could provide biased conclusions about seismic risk and is not sufficient for rating the risk compared to other types of risks. The paper emphasizes the importance of selecting the appropriate type of seismic risk assessment to develop solutions for planning the response and prioritizing actions, especially in areas prone to multiple types of risks.*

1 Introduction

Seismic risk assessment (RA) is a convulsion of seismic hazard, asset exposed and vulnerability. Two methodologies are often applied when considering different approaches to estimating seismic risk: the deterministic scenario-based RA and the probabilistic time-based RA.

The deterministic scenario-based approach, present in national seismic risk assessments in many countries (i.e. Montenegro, Serbia, Slovenia, Turkey) (BORIS (2022), relies on defining seismic hazard through earthquakes scenarios. These scenarios are typically based on historical seismic events and are determined to represent the most likely or worst-case consequences. This representation of seismic hazard reflects a will to build the scenarios, which can easily be referred to a certain level of protection/prevention. The scenario-based approach provides a specific picture of potential seismic risk, facilitating targeted mitigation efforts by the relevant stakeholders. Scenarios, like any other simplification of reality, are sometimes made of subjective assumptions that they are based on, and commonly, RA results are strongly affected by those assumptions.

However, the scenario-based approach encounters limitations when comparing seismic risk with other types of risks. Finding historical scenarios of different hazard types that are directly comparable in terms of likelihood can be challenging. Furthermore, as shown in Grünthal et al. (2006), the impact of different hazards can vary significantly across different return periods, i.e., the high probability earthquake event's consequences will most likely be surpassed compared to other natural hazards like floods. This may lead to underestimating prevention and preparedness measures that must be employed, especially in moderate seismic risk-prone areas.

To address these complexities, the probabilistic time-based approach offers a more comprehensive perspective. By evaluating the entire risk curve (also known as an exceedance probability curve), this approach considers the impact associated with different annual frequencies of a hazard: from low to high. Using time-based RA can be especially useful in different risk rankings and comparisons, as presented in Polese et al. (2023) and Tocchi et al. (2023).

In this paper, a case study area is selected in Montenegro, for which the seismic risk analysis will be conducted using both scenario-based and time-based approaches. The selected area is characterized by moderate seismicity, and it is also prone to other natural hazards. In scenario-based risk analysis, scenarios derived for the study will follow the one considered in national RA. However, the time-based analysis will consider shaking hazard maps for six periods from the relevant European model: ESHM20, Danciu et al. (2021). The impact on people and the direct economic losses from residential building damage will be compared and discussed.

2 Seismic risk analysis in Montenegro: state of the art

Accurate seismic risk analysis is essential in Montenegro, given its history of experiencing significant seismic events. Over the years, the region has encountered several moderate to severe earthquakes, with the most devastating on April 15, 1979. The consequences of these earthquakes have highlighted the urgency of developing precise seismic risk assessments.

Historical data, including the IPA Disaster Risk Assessment and Mapping, with support from the UN office, has enabled disaster loss data collection from 2005 to 2018. This survey (Montenegro: Recording disaster losses (2018)) revealed that within this timeframe, 4% of all losses resulting from natural hazards in Montenegro were attributed to earthquakes. This is particularly significant, given that the strongest earthquake registered during that period was the one from 4.01.2018 near the municipality of Plav, with a magnitude of 5.2.

Montenegro's commitment to disaster risk reduction is evident through its participation in the Sendai Framework for Disaster Risk Reduction 2015-2030. In alignment with this framework, the Department of Civil Protection of Montenegro (DCP) undertook the development of a National Disaster Risk Assessment (NRA) at the end of 2021, Tmusic et al. (2021).

The seismic risk assessment conducted within the NRA adopted a scenario-based approach, recognizing the necessity of considering various earthquake scenarios and their potential impact on the country. This method allowed a holistic understanding of Montenegro's seismic risks, enabling policymakers and disaster management authorities to make informed decisions and formulate effective mitigation strategies. The NRA's dedication to seismic risk analysis underscores Montenegro's commitment to enhancing its risk management capabilities and its readiness to respond to Union Civil Protection Mechanism (UCPM) requests. NRA is developed following EU guidelines, EU Risk (2010). The seismic risk assessment findings have been derived at the national level; however, the granular data specific to individual municipalities is absent from the analytical scope. This absence of data on a smaller scale significantly interferes with the efficacy of decision-making and policy-making processes related to risk prevention and preparedness at the local level.

2.1 Scenario-based RA: Overview of the methodology applied in NRA

Starting from the hazard perspective, the methodology for defining seismic hazard in the context of national seismic risk assessment involved the development of two earthquake scenarios with recurrence intervals of 95 and 475 years. The recurrence intervals were selected to be in line with the return periods of the design earthquakes stated in MEST EN 1998-1(2015). These scenarios included the definition of essential parameters: location, magnitude, intensity distribution, soil amplification factors, time of occurrence, and duration of earthquake events. Notably, the scenarios developed for Montenegro were semi-probabilistic, primarily due to the need for a precise definition of the global location and time of occurrence. Figure 1 shows the epicentre location and intensity distribution given in the EMS-98 (European Macro Seismic) scale for the whole territory of Montenegro for considered return periods of 95 and 475 years. In addition, the pilot region taken as the case study analyzed in this paper is marked with a light red. The 95-year return period earthquake is considered the most likely event, and the 475-year return period event is considered the worst-case consequence event. The location of an earthquake epicentre of two considered scenarios is chosen based on historical event from 1979. One compelling reason for selecting this location is the expected magnitude of the earthquake's impact on the economic activities occurring, considering the share of those activities in gross domestic product.

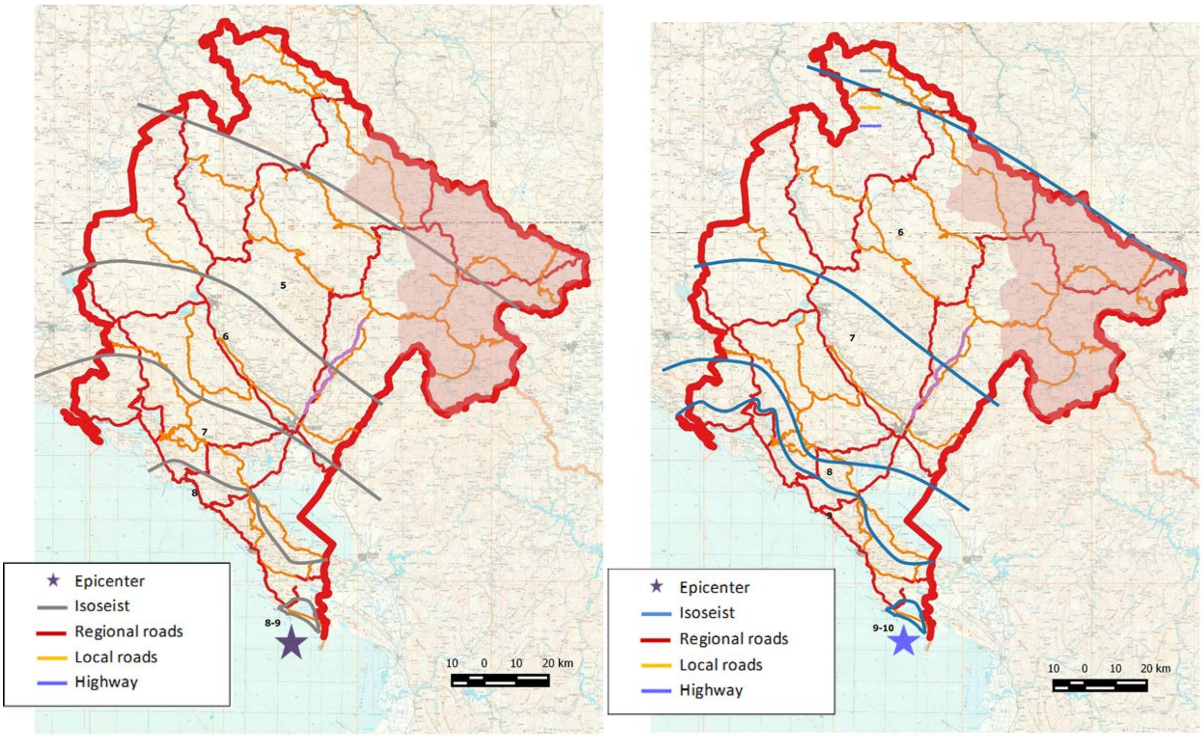

Figure 1. Scenario earthquake intensity distribution in Montenegro NRA for 95 and 475 years return periods, respectively (Tmusic et al., 2021).

Regarding the exposed assets, for the residential buildings, the SERA exposure model (SERA (2020), ESRM20, Crowley et al. (2020)) is employed, utilizing data from the 2011 census. Given the absence of more precise data, utilizing the SERA model becomes necessary to fill this information gap and enhance the accuracy of seismic risk assessment. This model offers insights into the distribution of typical structural systems in residential buildings across Montenegro concerning its construction period. Figure 2 shows the distribution of people over dominant typologies of building and tree regions in Montenegro.

The vulnerability assessment of the exposed assets in Montenegro was carried out using the EMS-98 methodology. According to this methodology, buildings are classified into four material-based structure types and six vulnerability classes (ranging from A to F) depending on the material, load-bearing system and seismic design level. However, it is worth noting that the E and F classes were not applied in this classification because the model is based on data from the 2011 census and provisions ensuring a high seismic design level were not established in Montenegro until 2021. Vulnerability assessment in NRA utilized damage probability matrices, where quantitative parameters for the categories "few," "many," and "most" were determined through expert judgment. Damages are classified into five damage classes from D1 to D5. Damage to specific building vulnerability class is determined depending on the seismic intensity by appointing the numerical values to descriptive terms of few, many and most.

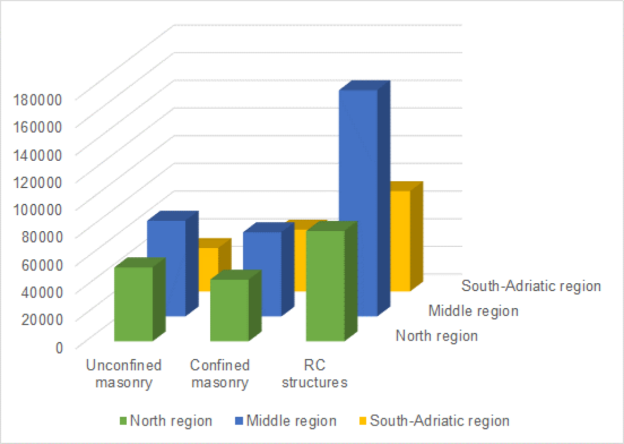

Figure 2. Distribution of people over dominant building typologies in Montenegro (SERA 2020, ESRM20), Crowley et al. (2020).

In the context of assessing consequences, the NRA includes estimations for the following parameters: the expected number of victims, the expected number of injured people, the expected number of collapsed and unusable buildings, as well as the direct economic losses—computed as the cumulative expenses covering residential building repairs, healthcare costs, and the repair of road infrastructure. Furthermore, the actual economic losses in residential buildings are calculated using the cost ratios assigned to each damage state. The respective cost ratios are taken as follows: 0.02, 0.1, 0.35, 0.6, and 1, corresponding to damage states from D1 to D5. According to the Montenegro Institute for Statistics, cost ratios are applied to the official construction cost of square meters of residential buildings (on average 720 €/m^2). It is important to note that all these consequences are reported and computed at the state level.

Lastly, risk matrices were employed to describe the probability of a hazard on one axis and its potential impact on the other axis, categorizing the level of risk into predefined categories, including extreme, high, medium, and low.

2.2 Time-based assessment for Montenegro

Time-based seismic RA is still not employed for the whole territory of Montenegro. To test the exportability of a methodology developed within EU project BORIS (BORIS 2022a, BORIS 2022b), time-based RA was used on one pilot region in Montenegro in a multi-layer, multi-risk analysis. Here, the methodology used for the selected pilot will be briefly explained.

Regarding hazard assessment, the ESHM20 model is applied in the time-based Risk Assessment (RA). The maximum Peak Ground Acceleration (PGA) values on rock or rock-equivalent sites are considered as the earthquake intensities. PGA serves as the primary intensity measure, while the impact of local soil conditions is factored in using a supplementary model developed by Worden and Heath (2019). The utilization of the global hazard model is motivated by the wish to produce results comparable to neighbouring regions.

Modelling of exposure is done in the same manner as in the scenario-based approach considering SERA (2020) and ESRM20 model and Crowley et al. (2020) model of residential buildings as representative.

The vulnerability model used in this analysis is based on expert vulnerability curves. In seismic vulnerability modelling, the preliminary classification is based on the material of vertical structures, as in EMS98, and then more detailed classification is done considering additional vulnerability factors (Lagomarsino and Giovinazzi (2006), Babic et al. (2021)). Curves were derived by combining expert judgment, qualitative damage EMS98 scale and available data on damages caused by the 1979 Montenegro earthquake. Damages are classified into five damage classes: D1 to D5. The motivation for assessing vulnerability using vulnerability curves is rooted in their capacity to offer a detailed and continuous description of the relationship between ground-shaking intensity and anticipated damage. This heightened level of detail contributes to greater precision and transparency in risk assessment. Figure 3 shows the vulnerability curves for low-rise masonry buildings built before 1965 and medium-rise RC buildings built after 1981.

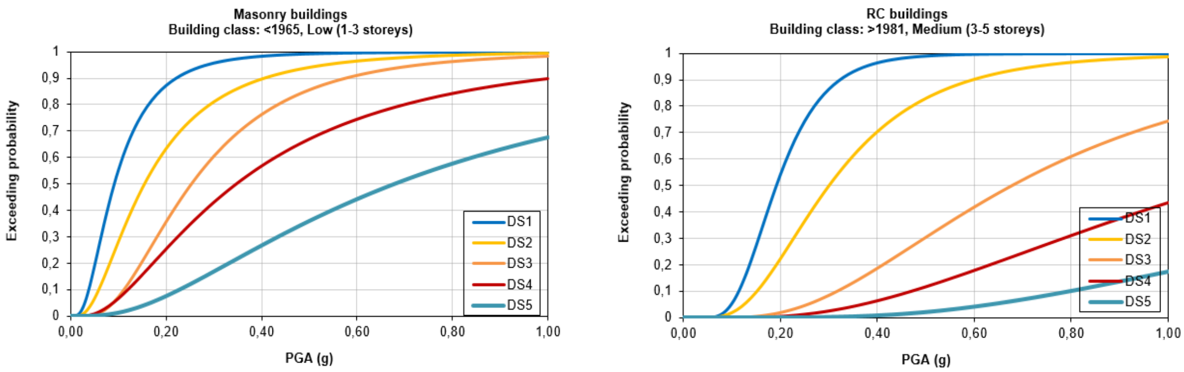

Figure 3. The vulnerability curves for low-rise masonry buildings built before 1965 and medium-rise RC buildings built after 1981.

In terms of consequences, impact on people (number of victims, injured and relocated people) and direct economic losses on residential buildings are calculated, as well as unusable dwellings in the short and long term. Impact on people regarding the number of victims and injured is estimated as a percentage of occupants in buildings experiencing damage states D4 and D5. Furthermore, the direct economic losses linked to the physical damage of structures are determined by calculating the ratio of the reconstruction cost for each damage state. The exact ratios are used as they were taken in NRA.

Risk can finally represented by deriving risk curves for each municipality in the considered pilot region, giving the losses on one axis and the annual probability of exceeding for another.

3 Seismic risk analyses for the selected pilot region in Montenegro: comparison and discussion

3.1 Description of the pilot region

As the case study to compare two methodologies of RA, one pilot region in Montenegro is selected. The Montenegro municipalities defined in the area are Andrijevica, Berane, Bijelo Polje, Plav and Rozaje. The region is characterized by moderate seismicity, where, according to ESHM20, expected values for maximum PGA on rock or rock-equivalent sites range from 0.1 g to 0.14 g for an event with a return period of 475 years. As previously mentioned, the most recent documented earthquake in the region occurred on January 4, 2018, near the municipality of Plav, registering a magnitude of 5.2. Local authorities reported damage to approximately 50 buildings and the temporary displacement of 10 families due to this event. The region is situated at a cross-border location and is recognized also as a flood-prone area. Hence, conducting a more comprehensive analysis of all potential risks holds significant advantages for the local community. Figure 4 shows the selected pilot region.

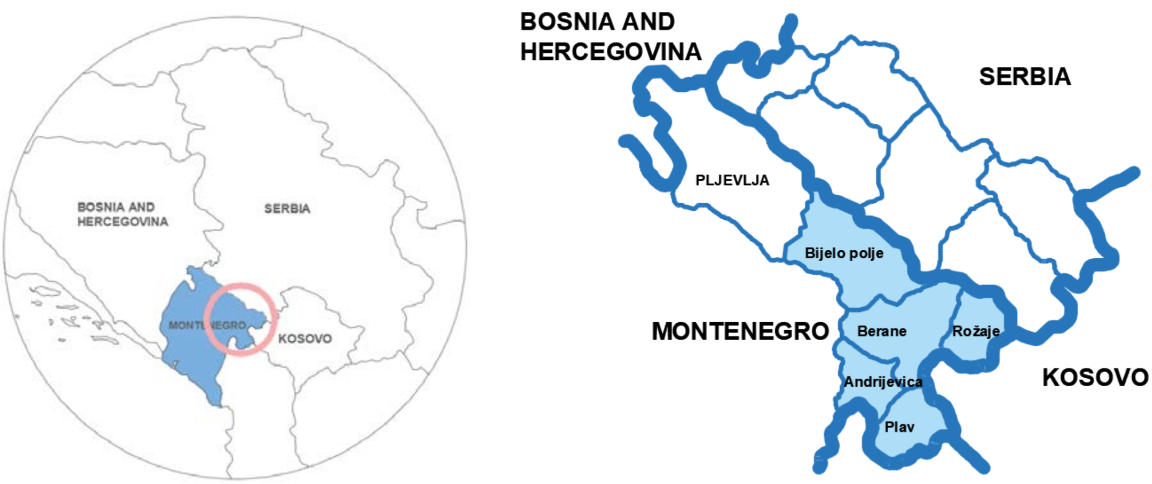

Figure 4. Selected pilot region in Montenegro.

The selected area is populated with 121174 residents according to the latest census data from 2011, which is approximately 20% of the Montenegro population. The total number of buildings in the pilot area region amounts to 28,614. These buildings can be categorized into two primary types: masonry buildings (comprising 77% of the total) and reinforced concrete buildings (making up 23% of the total). Most buildings (99.7% of masonry and 91.3% of reinforced concrete) are low-rise buildings with 1-2 stories. In scenario-based RA, according to intensity distribution and EMS-98 definitions of intensity, two out of the five municipalities under consideration should not experience any damage.

3.2 Results and discussion

Based on the described methodology, consequences derived using different approaches in RA are presented in Table 1 and Table 2 for scenario-based and time-based RA, respectively.

Table 1. Consequences for two considered scenarios in selected pilot area of Montenegro derived in scenario-based RA.

Earthquake recurrence intervals in Scenarios (in years)	Municipality	Econ. losses [€]	Econ. losses [€/m^2]	Victims	Injured
95	Plav	1146110	0.31	0	0
	Berane	2716913	0.14	0	0
	Andrijevica	592562	0.42	0	0
475	Rožaje	908676	1,97	0	0
	Plav	1146110	2,78	0	0
	Bijelo Polje	3309818	2,91	0	0
	Berane	2716913	3,07	0	0
	Andrijevica	592562	3,77	0	0

Economic losses are presented as the total amount in euros and the relative amount concerning square meters of residential buildings for both types of analysis. According to scenario-based RA, economic losses range from 0.14 to 0.42 €/m^2 for the most likely event and from 1.97 to 3.77 €/m^2 for the worst-case consequence event. When these losses are compared to those obtained in time-based risk assessment (using comparable time frames), it can be observed that the time-based approach produces losses of up to 10 times higher.

For almost all considered return periods, the most severe economic losses (EUR/m^2) in time-based RA are obtained for Plav, Berane and Andrijevica municipalities. This can be explained by the higher seismic hazard of these municipalities compared to others. This conclusion also implies for average annual losses, computed here only for economic losses and presented in Table 3. In the context of the time-based approach RA, losses are quantified in terms of expected losses over a specific period, such as a one-year time frame. This average annual loss provides valuable information unique to this particular type of analysis, and it cannot be compared to any results derived from scenario-based risk assessment. Having access to such information is instrumental in several critical ways. It enables the judicious allocation of resources for seismic retrofitting, facilitates comprehensive cost-benefit analyses to assess the viability of various risk reduction measures, and serves as the cornerstone for insurance and financial companies to establish well-informed policies and premiums.

Table 2. Consequences for six return periods in the selected pilot area of Montenegro derived in time-based RA.

Return period (in years)	**Municipality**	**Econ. losses [€]**	**Econ. losses [€/m^2]**	**Victims**	**Injured**
50	Rožaje	36558	0,08	0	0
	Plav	49304	0,12	0	0
	Bijelo Polje	166925	0,15	0	0
	Berane	146389	0,17	0	0
	Andrijevica	26672	0,17	0	0
101	Rožaje	494614	1,07	0	1
	Plav	2322112	5,64	1	4
	Bijelo Polje	1058184	0,93	1	2
	Berane	1519165	1,72	1	3
	Andrijevica	318226	2,02	0	1
475	Rožaje	3729800	8,07	2	9
	Plav	13152109	31,93	7	27
	Bijelo Polje	9097028	8,01	5	21
	Berane	12306878	13,92	7	28
	Andrijevica	3745144	23,81	2	8
976	Rožaje	24297379	52,57	21	76
	Plav	39800599	96,61	34	121
	Bijelo Polje	70257456	61,87	62	222
	Berane	84040323	95,04	90	314
	Andrijevica	14568492	92,61	13	46
2050	Rožaje	34952011	75,62	36	128
	Plav	63078243	153,12	75	255
	Bijelo Polje	105821381	93,19	115	404
	Berane	139952551	158,28	211	716
	Andrijevica	23500890	149,39	29	98
5000	Rožaje	48090467	104,05	61	213
	Plav	96582321	234,45	163	535
	Bijelo Polje	141607872	124,70	186	641
	Berane	213114057	241,02	451	1480
	Andrijevica	36715542	233,39	64	210

Table 3. Expected economic losses in 1 year period derived in time-based RA.

Municipality	Average annual losses [€/m^2]
Rožaje	0,15
Plav	0,41
Bijelo Polje	0,18
Berane	0,30
Andrijevica	0,34

Regarding the impact on people, scenario-based risk assessment does not show any impact for both scenarios considered, unlike the time-based approach where no victims or injured individuals are observed only for the 50-year return period. However, with the increasing return periods in time-based risk assessment, the number of victims rises and becomes significant, even in municipalities with lower seismicity but higher population density.

4 Conclusion

This paper presents a seismic risk analysis conducted on a specific case study in Montenegro, focusing on a designated pilot area in the northern region. This area is populated with approximately 20 percent of the country's population and, alongside being in a zone with moderate seismic activity, it is susceptible to other natural hazards, i.e. floods. The significance of precise and accurate risk assessment cannot be overstated, particularly in regions where authorities grapple with mitigating risks arising from multiple sources of hazards. Until now, seismic risk assessments in Montenegro have been conducted nationally, utilizing the scenario-based approach, with no incorporation of a time-based seismic approach.

In this study, the extent of the existing analysis is conducted by employing both scenario and time-based approaches to derive seismic risk assessment results specific to the selected pilot area. The focus is on assessing the impact on people (including the number of victims and injured) and evaluating the economic consequences, now at the municipal scale. This shift in scale and methodology is a crucial advancement in understanding the seismic risk in Montenegro.

Based on the results presented from a case study in the selected pilot area, it becomes evident that the scenario-based approach in risk assessment can lead to significant underestimation of both economic and human impacts when consequences are assessed at the municipal scale and in regions with moderate seismicity. The primary limitation of the scenario-based approach lies in its subjective nature, particularly in defining the scenario itself. In the case of Montenegro, the selected scenarios aimed to produce the most severe consequences in the southern part of the country, where significant economic activities occur. However, using the same scenario leads to neglecting the local seismic potential in the analyzed region, which remains relevant for the area under consideration. These findings emphasize the need for a different approach to risk assessment at more minor scales, considering a broader range of hazard definitions, such as global hazard models.

Present calculations are focused only on residential buildings, and future research should also incorporate public buildings, road and rail infrastructure, and cultural heritage. In economic losses, indirect economic losses due to malfunctions of services should also be considered. In that sense, the results presented here can be an underestimation of the consequences for both types of analyses conducted.

In conclusion, the choice between scenario-based and time-based seismic risk analysis depends on the specific objectives and the nature of the assessed risks. While deterministic scenario-based approaches offer clarity and precision for seismic risk estimation at the national level, probabilistic time-based approaches provide a broader perspective when comparing risks across diverse hazard types and return periods and more precise results at the local level. In addition, time-based seismic risk analysis offers results such as expected losses over a specified period, which can be valuable information for risk mitigation. Careful consideration of these methodologies is essential to ensure that seismic risk assessments are well-suited to their intended purposes and contexts. Finally, it is worth of mentioning that further analysis should be extended to comparison of results presented here, to time-based seismic risk assessment for the territory of Montenegro presented in ESRM20, where the main difference would rise from different vulnerability approaches.

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