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ENHANCING URBAN DISASTER RISK MANAGEMENT: A TRANSNATIONAL ANALYSIS OF SEISMIC RISK ASSESSMENT FRAMEWORKS IN EUROPE

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Abstract

This paper presents a comparative analysis of seismic risk assessment frameworks within the context of urban disaster risk management (DRM) in European transnational borders, as part of the BORIS2 project. BORIS2 project aims to enhance multi-risk assessment methodologies for emergency conditions at urban scales across country borders in Europe. The project seeks to establish a replicable model of cross-border cooperation in the prevention phase of natural disasters, thereby enhancing the capacity of EU countries to manage and mitigate risks associated with seismic and flood events. In this paper, the synthesis of methodologies from Italy, Slovenia, Austria, Turkey, and Montenegro is presented, highlighting the integration and implementation challenges of DRM strategies in managing seismic risk. The research is focused on the evaluation of current seismic risk assessment methods at urban scale. Each country's approach is reviewed, with special attention to hazard, vulnerability, and exposure models for critical structures and infrastructures. The findings reveal significant variation in seismic risk preparedness and response frameworks, underlining best practices and pinpointing areas needing alignment or improvement. For instance, some countries developed advanced tools for evaluating operational efficiency of DRM based on the concept of emergency limit conditions compared to more basic approaches in other countries. The paper discusses these disparities and suggests recommendations for the harmonization of civil protection systems to enhance cross-border disaster preparedness, contributing to the overall goals of BORIS2 in advancing multi-risk assessments in Europe.

Keywords: disaster risk management, urban scale, seismic risk, seismic hazard, vulnerability, exposure models, damage and impact indicators, emergency limit conditions.

1. Introduction

Building on the foundations laid by the BORIS project [1], project Cross BOrder RISk assessment for increased prevention and preparedness in Europe: way forward (BORIS2) [2] aims to extend and

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enhance multi-risk assessment methodologies for emergency conditions at urban scales across transnational borders in Europe. The project seeks to establish a replicable model of cross-border cooperation in the prevention phase of natural disasters, thereby enhancing the capacity of EU countries to manage and mitigate risks associated with seismic and flood events. This paper presents a comparative analysis of seismic risk assessment frameworks within the context of urban disaster risk management (DRM) in European transnational borders, that has already done within work package 2 of the BORIS2 project [2]. It also reviews and evaluates the diverse DRM frameworks, decision-making processes, and legal and institutional arrangements adopted by different countries, highlighting areas for potential alignment.

The approach undertaken in this paper involved an analysis of methodologies from Italy, Slovenia, Austria, Turkey and Montenegro used for seismic risk assessments at the urban level, focusing on their effectiveness in DRM. This analysis covered the hazard, vulnerability, and exposure models used for structures and infrastructures deemed critical during emergencies. Additionally, this paper scrutinized the DRM frameworks of the countries by examining the coordinated responsibilities, prevention, preparedness, and response plans. Overviews of national assessments are later used for a comparative review, ensuring a comprehensive understanding and highlighting points for further alignment.

2. Comparison of seismic risk assessment procedures at urban scale

This section provides summary of an extensive analysis of seismic risk assessment procedures across Italy, Slovenia, Austria, Turkey, and Montenegro. Each country exhibits unique methodologies tailored to their specific environmental and urban challenges, reflecting diverse approaches to seismic risk management at an urban scale. The analysis conducted for each country covers the hazards, vulnerabilities, exposure, damage and impact indicators and tools (platform) for risk assessment. Special attention is given to the role of seismic risk analysis in effective DRM at urban scale.

Italy's seismic risk assessment at the urban scale integrates probabilistic and scenario-based approaches to inform emergency management and disaster planning. Ground motion scenarios, based on probabilistic seismic hazard analysis (PSHA), consider events with a 10% probability of exceedance in 50 years (475-year return period) as specified in the Italian National Guidelines (DPCM 30/4/2021) [3]. If available, localized seismic microzonation studies refine these assessments by accounting for site-specific factors, such as soil amplification and topographical effects, enabling detailed evaluations of seismic hazards [4]. The exposure model combines census data with municipal inputs to map residential populations, strategic infrastructures, and essential services. For instance, ISTAT (Istituto Nazionale di Statistica, National Institute of Statistics) census data – which is available across the overall country - provide building typology, construction age, and structural material details, enabling vulnerability assessments through classification into EMS-98 vulnerability classes [5]. However, the availability of detailed data varies significantly between municipalities, limiting the granularity of assessments. Vulnerability assessments rely on fragility models, such as EMS-98 and region-specific methodologies like Damage Probability Matrix [6] or fragility curves for residential ([7], [8]) and strategic [9] buildings, such as school, based on a scientific consensus-approach. These models estimate building damage levels and their impact on populations, including injuries, fatalities, and homelessness. For strategic infrastructure, such as hospitals and emergency centers, functionality assessments consider operational performance under earthquake scenarios. Indicators also address cascading effects, such as landslides and service disruptions, although their inclusion varies by municipality. Loss estimation models predict population impacts based on building typology, damage state, and occupancy rates, while functionality assessments use serviceability limit states for infrastructure.

Italy's seismic risk assessment incorporates the concept of Emergency Limit Conditions (ELC), established by the Civil Protection Department to ensure urban resilience during and after disasters. ELC defines thresholds for the physical and functional damage levels of urban systems, aiming to protect residents' safety, preserve essential infrastructures, and maintain urban functionality for emergency operations [10], [11] (Fig. 1). The primary objectives of ELC are to safeguard lives, protect buildings and infrastructures, and preserve the social and environmental identity of urban areas [12].

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Critical components of the ELC system include strategic buildings, emergency areas, road networks, and interfering buildings whose collapse could obstruct emergency operations (Fig. 2). Municipalities are required to identify these elements, collect standardized data, and integrate the information into the SoftCLE platform for emergency planning. To support ELC evaluations, advanced tools like the I.OPà.CLE method [13] assess the operational efficiency of emergency systems, while the SMAV method [14] provides an estimate of the operational condition of strategic assets based on data of dynamic response obtained by ambient vibration tests. These tools aid decision-makers in prioritizing interventions and enhancing disaster preparedness. For example, the schematic representation of Fig. 2 illustrates the identification of some ELC components in the urban environmental as preliminary step for assessing their functionality under seismic events according to the procedure currently established in Italy.

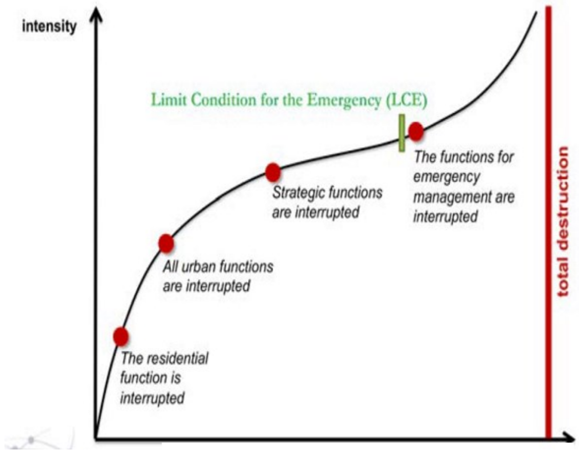

Figure 1. Loss of functionality of the urban system.

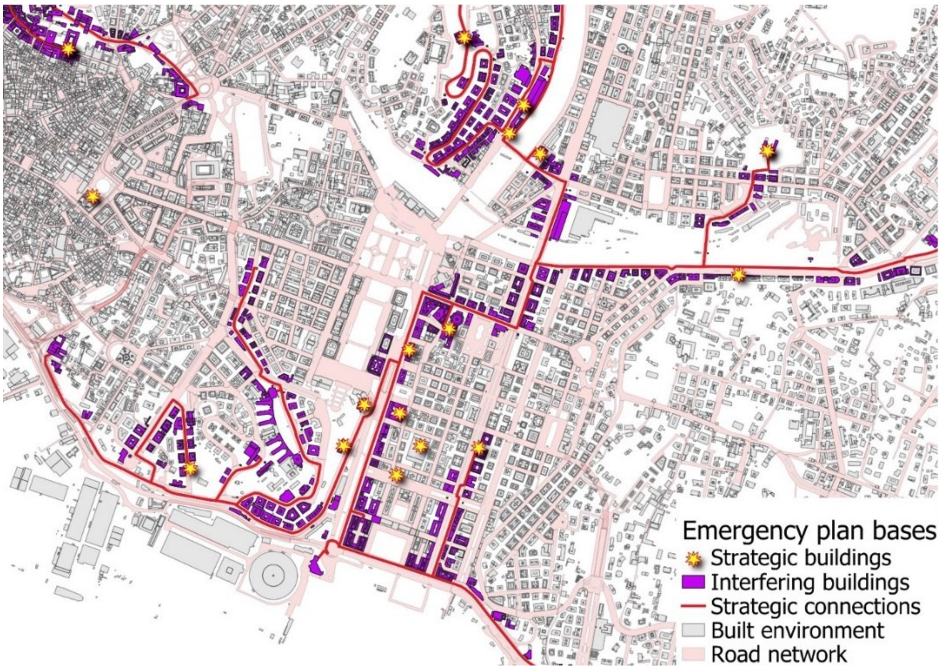

Figure 2. Schematic representation of the ELC components for a portion of the Municipality of Genoa.

In Slovenia, seismic risk assessments for emergency management are carried out at national, regional, and municipal levels, guided by regulatory frameworks such as the Decree on the Content and Elaboration of Protection and Rescue Plans (Official Gazette RS 24/12, 78/16, 26/19) and the Protection Against Natural and Other Disasters Act (Official Gazette RS 51/06, 97/10, 21/18, 117/22). Hazard

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models are based on EMS-98 intensity maps for a 475-year return period, developed using probabilistic spatial smoothing of seismic activity [15]. Vulnerability assessments rely on the POTROG initiative, which categorizes buildings into six vulnerability classes (A to F) using fragility functions derived from the EMS-98 scale [5]. Exposure models integrate data from the Slovenian Real Estate Register, considering buildings, population, and critical infrastructure. While economic losses are primarily based on the value of permanently unusable buildings, indirect losses and repair costs for minor damages are not considered. Additionally, debris volume calculations and road transportability impacts are included, though these indicators are often limited in scope and not consistently integrated into strategic planning. However, limitations include qualitative fragility assessments for infrastructure and the exclusion of indirect economic losses. Scenario-based risk assessments, such as those in Ljubljana [16], incorporate epicenter-specific data and quantitative fragility models but are primarily utilized for post-event response rather than proactive planning. Tools like the POTROG platform [17] support consequence assessment, road transportability analysis, and building damage evaluations, but their integration into strategic DRM planning remains limited (Fig.3).

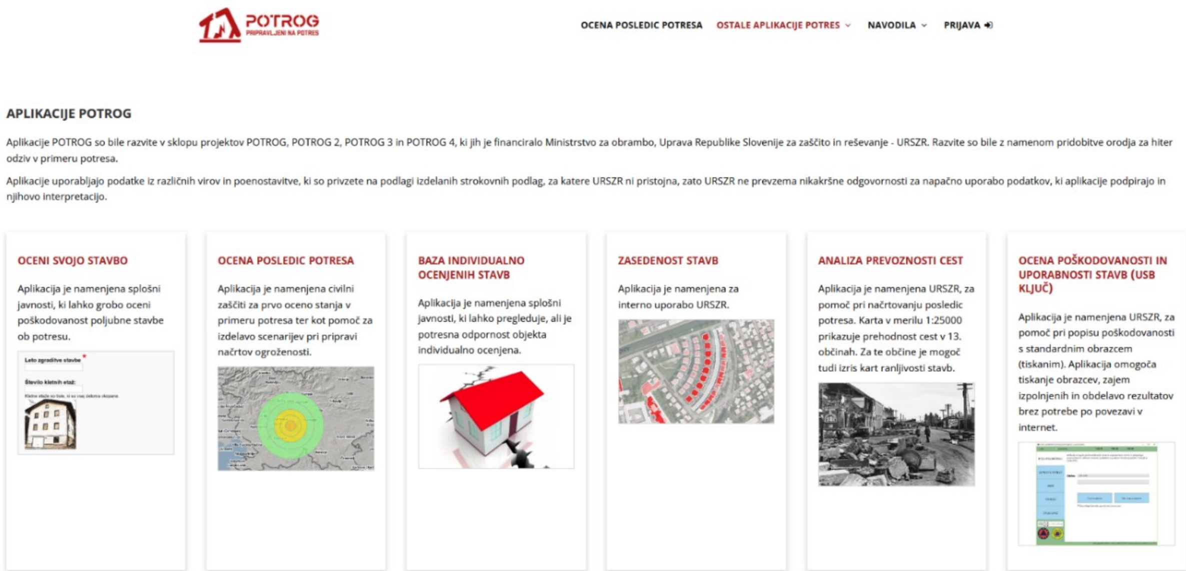

Figure 2. The online POTROG platform [17].

In Austria, seismic risk hazard is governed by Eurocode 8 [18] and its national annexes [19], which define hazard levels. The Austrian seismic hazard map, developed using probabilistic seismic hazard assessment (PSHA), categorizes the country into five zones (0–4) based on peak ground acceleration (PGA) with a 475-year return period. This map accounts for localized geological effects and is complemented by a network of seismological monitoring stations. The new hazard map (2021) incorporates enhanced methodologies, including an updated earthquake catalog and advanced ground motion prediction models [20]. Vulnerability modeling in Austria is in its early stages, focusing on regional data collection for developing exposure and vulnerability profiles. Current seismic assessments use the European Macroseismic Scale (EMS-98) [5] to describe damage intensities, but comprehensive building and infrastructure vulnerability models are not yet implemented. The damage and impact indicators for seismic risk assessment are primarily qualitative and based on historical data, public input, and expert analysis. Tools like the HORA platform visualize hazards for public awareness, while applications like ShakeMaps generate near-real-time intensity distributions following seismic events [21]. Although Austria lacks a detailed risk assessment framework, the integration of seismic hazard maps, real-time monitoring, and public tools provides a robust foundation for disaster preparedness.

Turkey employs advanced seismic risk assessment methodologies at the urban scale, underpinned by the National Earthquake Strategy and Action Plan [22]. The seismic hazard map of Turkey, updated in 2019, incorporates probabilistic approaches to estimate peak ground acceleration (PGA) and spectral accelerations for multiple return periods, including 475 years. This map, accessible through a GIS-based

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application, enables local site adjustments using specific soil factors (e.g., Vs30 values) and supports scenario-based assessments by integrating the active fault map of Turkey [23]. Vulnerability assessments are conducted using fragility curves for damage states (slight, moderate, extensive, complete) based on criteria such as local site conditions and building inventories. The National Disaster Risk Assessment Report [23] defines three main impact criteria: human life and health, economy and environment, and societal functionality. These are further represented by eight indicators, including fatalities, injuries, economic losses, and disruptions to daily life. Impacts are categorized into five levels: limited, significant, severe, very severe, and catastrophic, providing a standardized framework for evaluating disaster consequences.

As an example of urban level assessment, for Istanbul, fragility models are refined using data on building height, structural systems, and construction year, enabling precise district-level risk evaluations. The resulting fragility curves and building inventory data provide insights into damage distribution, as illustrated in the moderately damaged building map for Istanbul under a 475-year return period earthquake [24] (Fig. 4). Exposure models integrate comprehensive building and population datasets alongside infrastructure details, as seen in Istanbul's building inventory maps (Fig. 5).

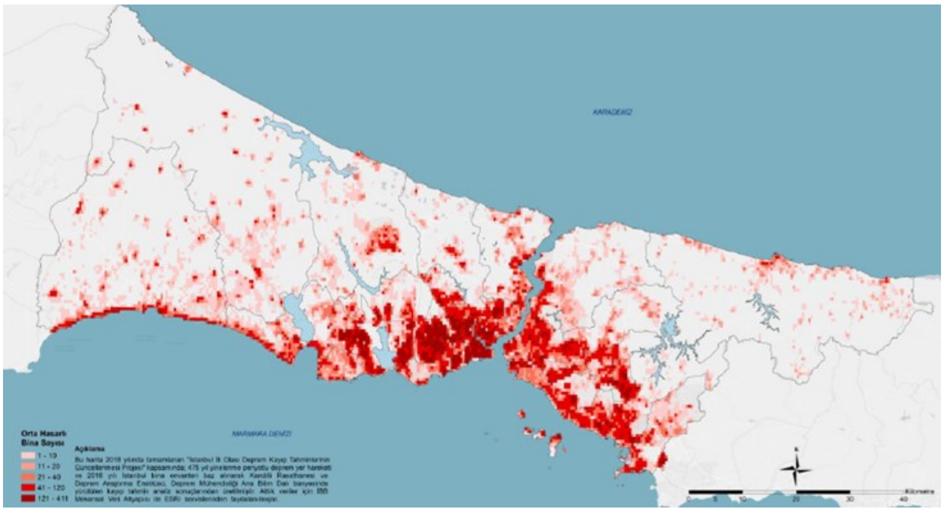

Figure 4. Moderately damaged building distribution estimate for a ground motion with a return period of 475 years (Istanbul, Turkey) [24].

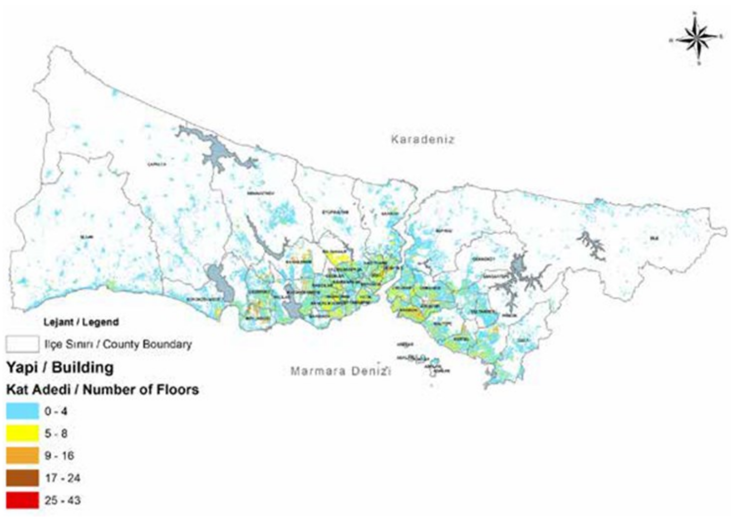

Figure 5. Building stock in Istanbul (Turkey) [24].

AFAD's platforms, such as the Rapid Earthquake Damage and Loss Estimation System (AFAD-RED), facilitate near real-time loss estimations and generate actionable outputs, including damage maps,

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casualty estimates, and lifeline impacts. The system supports the Disaster Management and Decision Support System (DMDS), enhancing response coordination and recovery efforts at provincial and national levels.

In Montenegro, seismic risk assessment methods are integrated into municipal protection and rescue plans, guided by the Rulebook on the Methodology for Developing Protection and Rescue Plans from 2008 [25]. These plans include hazard analyses, vulnerability assessments, and exposure models to inform emergency preparedness and response strategies. Hazard models primarily rely on scenario-based approaches, focusing on credible ruptures and utilizing empirical relationships to estimate peak ground acceleration (PGA) and EMS-98 intensity. Detailed grid analyses refine hazard evaluation, accounting for local soil amplification effects ([26]-[28]). Vulnerability assessments use various models, including the EMS-98 methodology [5], IZIIS model (1984) [29], and ATC-21-1 framework [30], to estimate potential damage across residential buildings and critical infrastructure. Exposure models draw from census data and literature-based distributions of building typologies, incorporating elements like roads, hospitals, and lifelines. While these assessments address critical components of risk, limitations include a lack of unified methodologies and insufficient databases on building characteristics and local geological conditions. The damage and impact indicators focus on economic losses, impacts on people, and structural damages. Economic losses are estimated using simplified methodologies that relate gross national income to regional or municipal budgets. Human impacts are calculated by predicting casualties, injuries, and shelter needs based on building vulnerability and population distribution, using models such as ATC-13 (1985) [31], HAZUS99 [32]. Municipal plans often emphasize response strategies, such as evacuation routes, temporary shelters, and public communication systems, but the direct integration of risk findings into strategic planning remains limited. The absence of dedicated tools or platforms for urban-scale seismic risk assessment further restricts comprehensive analysis and application.

Furthermore, in the following tables, a comparison of seismic risk assessment procedures at urban scale in five countries, is presented. Each component of risk analysis (hazard, vulnerability, exposure and damage and impact indicators) is compared as presented in Tables 1 to 4. Note that the parameters listed in the tables refer to the typical procedures adopted in countries, and these parameters do not necessarily reflect minimum standard requirements.

Table 1. Hazard assessment for seismic risk at urban level: comparison of practices in countries

Description	**ITA**	**SLO**	**AUT**	**TUR**	**MNE**
Scenario(s) developed	✓	✓		✓	✓
Hazard expressed in probabilistic manner	✓	✓	✓	✓	✓
Return period:					
T=475 years	✓	✓	✓	✓	
Other periods considered	✓				✓
Intensity measures:					
I_{MCS}	✓				✓
EMS-98		✓	✓		
PGA	✓		✓	✓	✓
PGV			✓	✓	
PSA	✓		✓	✓	
Local soil effects:					

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From available microzonation	✓			✓	
Identified through soil category (A, B, C,…)		✓	✓		✓
Topographically based	✓				
Multi hazard scenario developed					

Table 2. Vulnerability model for seismic risk: comparison of practices in countries

Description	**ITA**	**SLO**	**AUT**	**TUR**	**MNE**
For residential buildings:					
Model based on EMS-98 scale (5 damage D1-D5, 6 vulnerable classes A to F)	✓	✓			✓
discrete values		✓			
Fragility curves	✓			✓	✓
Additional model in use (e.g. empirical driven)					✓
For infrastructure:					
vulnerability is analyzed					✓
model from literature					✓

Table 3. Exposure model for seismic risk: comparison of practices in countries

Description	**ITA**	**SLO**	**AUT**	**TUR**	**MNE**
Population					
floating population number	✓	✓	✓	✓	
vulnerable population	✓				
civil protection members treated separately		✓			
Scale of available data for population and buildings used in RA:					
building by building			✓		
sub-municipal (settlements, district)	✓	✓		✓	✓
Available residential buildings attributes at sub-municipality scale:					
number of buildings	✓	✓	✓	✓	
number of stories	✓	✓	✓	✓	
material	✓	✓	✓	✓	

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age of construction	✓	✓	✓	✓	
number of dwellings		✓	✓	✓	✓
occupancy	✓	✓			
Infrastructure:					
only listed		✓	✓	✓	
listed with details on attributes	✓		✓		
listed with details on capacities (hospital capacities, shelter capacities)					✓
Types of infrastructure listed:					
hospitals and health care	✓	✓	✓	✓	✓
transportation network	✓	✓	✓	✓	✓
schools	✓		✓	✓	✓
public and strategic buildings	✓		✓	✓	
cultural heritage	✓	✓	✓		✓
sports facilities	✓		✓		
green/protected areas	✓		✓		
lifelines	✓	✓	✓	✓	✓

Table 4. Damage and impact indicators for seismic risk: comparison of practices in beneficiary countries

Description	**ITA**	**SLO**	**AUT**	**TUR**	**MNE**
On people:					
number of death and injured	✓	✓		✓	✓
displaced	✓	✓			✓
lack of fulfillment of basic needs				✓	
people that need to be evacuated				✓	
trapped by collapsed buildings					✓
Economic losses	✓	✓		✓	✓
Impact on buildings:					
collapsed	✓	✓		✓	✓
unusable	✓	✓		✓	✓
damaged	✓	✓		✓	✓
volume of debris		✓			
Infrastructure					
damage grade	✓				✓
functionality of roads	✓			✓	
functionality of hospitals	✓			✓	

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functionality of strategic buildings				✓	

3. The comparative review of the DRM frameworks in different countries

This section provides a comparative analysis of the existing DRM frameworks in the five countries involved in this study. To achieve this, country's procedural frameworks for DRM were reviewed, with a focus on decision-making processes, planning measures, responsibilities, policies, and the legal and institutional arrangements implemented by relevant DRM stakeholders. The objective of this comparative review was to identify and present key aspects related to the Emergency Management preparedness phase. A set of recommendations aimed at harmonizing practices across the countries are highlighted.

Based on the key aspects such as coordination of responsibilities, prevention, preparedness, and response plans, role of real-time monitoring and warning and alerting activities and tools and maps specifically used for emergency management, similarities and differences between the partner countries are recignized.

The organization of DRM responsibilities varies among the countries, reflecting their unique governance structures. In Italy, the National Civil Protection Service oversees DRM at all levels, with regional and municipal coordination centers activated depending on the emergency scale. Slovenia's system is centralized under the Administration for Civil Protection and Disaster Relief, with municipal bodies tasked with local implementation. Austria's federated approach assigns disaster management to provincial authorities, supported by national resources for large-scale events. Turkey operates an integrated system under the Disaster and Emergency Management Presidency (AFAD), which coordinates provincial and district-level efforts. Montenegro, with a more centralized structure, assigns responsibilities to the Directorate for Protection and Rescue, while municipal teams handle local execution.

DRM planning across all five countries emphasizes hazard and risk assessments, though the level of detail and focus varies. Italy's plans are highly detailed, including vulnerability assessments of at-risk populations and critical infrastructure. Slovenia tailors its plans to risk classifications, requiring detailed plans for high-risk municipalities and facilities. Austria emphasizes topographical and infrastructural conditions in its plans, which are reviewed every three years. Turkey's plans integrate risk reduction, response, and recovery, with separate plans at provincial and district levels. Montenegro's plans, while prescriptive, often remain declarative, with some proactive measures informed by risk analysis.

Monitoring and alert systems differ significantly among the countries. Italy has a comprehensive system integrating meteorological, seismic, and hydrological data, managed by national and regional centers. Slovenia relies on its National Meteorological Service for flood alerts but lacks a real-time seismic warning system. Austria's advanced civil protection siren network is complemented by mobile alerts via the AT-Alert system, which covers a range of hazards. Turkey's Flood Forecast and Early Warning System and earthquake monitoring by AFAD provide real-time data to support response measures. Montenegro's systems are more localized, with earthquake warnings issued by the Institute for Hydrometeorology and Seismology and earthquake notifications managed by the Ministry of Interior.

Each country uses different tools to support emergency management. Italy employs the ELC (Emergency Limit Condition) framework and I.OPà.CLE method for evaluating emergency system operability. Slovenia's POTROG platform provides tools for assessing building damage and transportability after seismic events. Austria's provinces use software like the Executive Information System (FÜIS) to coordinate response efforts in real time. Turkey's AFAD-RED system integrates with its Disaster Management and Decision Support System to generate near-real-time loss estimates.

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Montenegro has developed evacuation maps for some municipalities but lacks a comprehensive digital platform for emergency management.

Based on the conducted analysis, the following recommendations for harmonizing national systems have been identified:

- Nationwide templates for the development of disaster management plans and intervention maps should be provided.
- Harmonization of templates, guidelines and terminology across national borders leads to an improved exchange during preparation and the emergency.
- The content of the plans differs depending on the region and country. This is due to the various hazard processes. A harmonization can be achieved, however, including systematically in the plans the following elements: territory description, identification of hazards and risks and definition of risk/impact scenarios with different levels of information/identification of critical points/exposed elements/objects.
- Standardised collection and availability of data as well as the harmonization of individual datasets are required.
- Emergency management requires the development of operational strategies and intervention options to react efficiently in the event of a crisis and to facilitate the prioritization of resources.
- Specialized tools for emergency management such as ELC might be of interest to other countries/ processes. An exchange across process boundaries and country borders would be beneficial.
- Continuous evaluation, revision and updating of plans, procedures, responsibilities and maps as well as corresponding training and exercises are essential.

4. Conclusions

In this paper, a comparative analysis of seismic risk assessment frameworks within the context of urban disaster risk management (DRM) from Italy, Slovenia, Austria, Turkey, and Montenegro is presented. Each country's approach is reviewed, with special attention to hazard, vulnerability, and exposure models for critical structures and infrastructures. The findings reveal diverse methodologies and practices reflecting their unique environmental, urban, and institutional contexts. For instance, Italy's use of advanced tools like the I.OPà.CLE method, which evaluates the operational efficiency of emergency limit conditions compared to more basic approaches in other countries. Italy and Turkey exhibit the most comprehensive approaches, integrating probabilistic hazard models, detailed vulnerability and exposure assessments, and advanced tools into urban DRM frameworks. Slovenia’s and Austria’s models are limited by a lack of comprehensive infrastructure assessments. Montenegro faces significant gaps in data availability, and standardized methodologies. Standardizing practices across countries, particularly in vulnerability modelling and tool development, could enhance seismic risk assessments and strengthen disaster resilience at the urban scale.

To harmonize national DRM systems, it is essential to establish standardized templates and guidelines for disaster management plans and intervention maps while aligning terminology and methodologies across borders to enhance collaboration. Plans should consistently include key elements, such as hazard and risk identification, impact scenarios, and critical points, supported by standardized data collection and availability. Developing operational strategies and prioritization frameworks, sharing specialized tools like the ELC framework, and fostering cross-border exchanges are crucial for improving efficiency. Regular updates, evaluations, and training are also necessary to ensure adaptability and preparedness across systems.

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