Natural Hazards
https://doi.org/10.1007/s11069-024-07008-y

ORIGINAL PAPER

National seismic risk assessment: an overview and practical guide

Maria Luísa Sousa[1] · Georgios Tsionis[2]

Received: 31 October 2023 / Accepted: 29 October 2024

Abstract

In order to promote an effective approach to the prevention of and preparedness for disasters, the countries participating in the Union Civil Protection Mechanism (UCPM) shall develop risk assessments, risk management capability assessments and disaster risk management planning at national or appropriate sub-national level. The European Commission is providing scientific support to the countries participating in the UCPM, publishing updated guidelines to facilitate the development of their National Risk Assessments (NRAs). Earthquake is among the most common hazards considered in NRAs prepared by the countries participating in the UCPM. Indeed, in 2018 NRAs, more than 20 countries performed risk assessment for earthquakes, and some considered cross-border and cascading effects, such as tsunami, landslides, disruption of infrastructure and industrial accidents. This paper surveys and summarises the current state of research that can be utilized for national seismic risk assessment. It aims to facilitate the development of consistent NRAs with respect to earthquakes and ensure their utility in seismic risk management planning. It also aims to support the use of the new reporting guidelines on disaster risk management among countries participating in the UCPM. The seismic risk assessment process is described as outlined in ISO 31000: 2018. A wealth of hazard, exposure, vulnerability and damage-to-loss models, methodologies and tools are presented to serve the purpose of conducting national seismic risk assessment. References to relevant European research projects, good practices, and software to support the assessment are also provided.

Keywords Guidelines · National seismic risk assessment · NRA

✉ Georgios Tsionis
Georgios.TSIONIS@ec.europa.eu

1 National Laboratory for Civil Engineering (LNEC), Lisbon, Portugal

2 European Commission, Joint Research Centre (JRC), Ispra, Italy

Published online: 29 January 2025

1 Introduction

Risk mitigation and disaster prevention in the European Union are advocated for by the Union Civil Protection Mechanism[1] (UCPM, Regulation (EU) 2021). Countries participating in the UCPM develop and regularly update risk assessments, risk management capability assessments and disaster risk management planning at national or appropriate subnational level. Earthquake is among the most common hazards considered in the national risk assessments (NRA) of the countries participating in the Union Civil Protection Mechanism (European Commission 2021). Indeed, 19 countries (Austria, Bulgaria, Croatia, Cyprus, France, Germany, Greece, Hungary, Iceland, Italy, Malta, Norway, Portugal, Romania, Serbia, Slovakia, Slovenia, Spain and Sweden) included earthquake in their 2015 risk assessment and more four countries (Belgium, the Netherlands, North Macedonia and the United Kingdom) in 2018.

Considering the impact of a single event, earthquakes are among the most devastating natural hazards in history, posing the greatest threat to human life (UNDRR 2020). The effects of earthquakes can vary from localised impacts to dramatic consequences on communities, the economy and the environment, across large regions. In some cases, they can cause cross-border impacts and cascading events, namely tsunamis, landslides, liquefaction phenomena, fire, industrial accidents, business interruption, etc. Earthquakes may have long-lasting and in certain cases multi-generational effects, depending on the severity of the event, vulnerability and accumulation of assets in seismic prone areas, individual and societal resilience to disruptive events. Besides population exposed to seismic risk, the assets that may be impacted by earthquakes include the built environment, for instance, buildings, infrastructures (transportation, water, sewage, energy, communication, etc.), daily life facilities (health facilities, emergency services, educational facilities, etc.), cultural heritage, economic activities, and natural environment. A recent example of destructive events with significant transboundary impacts are the Kahramanmaraş earthquakes of 6 February 2023, of magnitude (Mw) 7.8 and 7.5, which affected southern Türkiye and northern Syria. In Türkiye alone, 14 million people were affected, the death toll reached 48 000 individuals, approximately 233 000 buildings were severely damaged or collapsed, and the economic impact was assessed as $103.6 billion, equivalent to nine percent of Türkiye's GDP in 2023 (Gunasekera et al. 2023; Hancilar et al. 2023; Türkiye government 2023).

This paper conducts an overview and synthesis of existing research applicable to national seismic risk assessment aiming to offer scientific support for the development of consistent national assessments focused on earthquake-related hazards, thus enhancing their effectiveness in guiding seismic risk management strategies. We acknowledge the dynamic nature of this evolving field of research, characterized by persistent challenges. Our goal is to aid the development of up-to-date national seismic risk assessments, aligned with the new reporting guidelines on disaster risk management for countries participating in the UCPM.

The seismic risk assessment process is outlined as in ISO 31000 (ISO 2018). Earthquake risk analysis has perhaps reached the highest level of maturity among all-natural hazards risk analyses, partly due to the early efforts made by the nuclear industry to

[1] UCPM at DG ECHO website: https://civil-protection-humanitarian-aid.ec.europa.eu/what/civil-protection/eu-civil-protection-mechanism_en.

incorporate seismic hazard in power plant design (Hills et al. 2013). A wealth of hazard, exposure, vulnerability and damage-to-loss models, methodologies and tools are presented to serve the purpose of conducting national seismic risk assessment. References to relevant European research projects, good practices, and software to support the assessment are also provided.

2 Regulatory framework for national risk assessment

The Action Plan on the Sendai Framework (European Commission 2016) encourages investment in disaster risk reduction and integrates ‘Build Back Better’ principles for a more resilient built environment. Furthermore, the UCPM objectives are to achieve a high level of protection against disasters by preventing or reducing their potential effects, enhancing preparedness, facilitating rapid and efficient response, and enhancing public awareness and preparedness. The UCPM seeks to encourage an effective and coherent approach for preventing and preparing for disasters. Member States are required to develop risk assessments, improve their assessment of risk management capability, and further develop and fine-tune their disaster risk management planning at national or relevant sub-national level. This includes considerations for cross-border cooperation, in line with the European Union disaster resilience goals (European Commission 2023a), and addressing the risks associated with disasters that can have transboundary implications across multiple countries. Member States are obliged to provide a summary of the significant aspects of the assessments, focusing on key risks, and to outline priority prevention and preparedness measures for key risks capable of having cross-border impacts. The 2023 Strategic Foresight Report (European Commission 2023b) has highlighted the importance of complementing civil protection with civil prevention as one of the ten key areas for action. Moreover, the recently launched European Union (EU) disaster resilience goals include improving risk assessment, anticipating, and planning for disaster risk management, increasing risk awareness and preparedness among the population, improving early warning systems, enhancing the Union Civil Protection Mechanism’s response capacity, and ensuring a robust civil protection system. Earthquake is one of the 16 hazards upon which disaster scenarios will be developed to improve preparedness.

The European Commission is providing scientific support to the countries participating in the UCPM, publishing updated guidelines to facilitate the development of their National Risk Assessments (NRAs) (Poljanšek et al. 2021). Within the UCPM, the EU peer review programme[2] of disaster risk management and civil protection systems emphasises the importance of **risk assessment** as the foundation for guiding all phases of the risk management cycle. The Peer Review Assessment Framework (Mysiak et al. 2021) follows approximately the common general approach for risk assessment provided by the ISO Guidelines for risk management (ISO 2018).

The ISO 31000 process (ISO 2018) is an iterative process comprising several stages such as establishing the scope, context and criteria, risk assessment, risk treatment, monitoring and review, communication and consultation and recording and reporting. In this section, we will provide a concise overview of the risk assessment stage discussing the

[2] The Union Civil Protection Knowledge Network web page of the UCPM Peer Review Programme: https://civil-protection-knowledge-network.europa.eu/disaster-prevention-and-risk-management/ucpm-peer-review-programme.

need of initially establishing risk criteria. Aspects of the remaining stages, such as risk treatment and risk communication, will be discussed in subsequent sections of this paper, providing a summarized or overview perspective.

The risk assessment stage comprises three main components: risk identification, risk analysis, and risk evaluation. In brief, **risk identification** aims to identify the pertinent risks. **Risk analysis** involves assessing the causes and sources of risk, their potential consequences, and the likelihood that those consequences occur. **Risk evaluation** assists in making informed decisions regarding risk treatment priorities by comparing risk levels against context-based **risk criteria,** which can, for instance, be thresholds against which risk levels are evaluated (as discussed in chapter 5). According to Mysiak et al. (2021), risk criteria serve as "the terms of reference against which the significance of a risk is evaluated".

It is essential to set up the **risk criteria** in the process initial stage that identifies its scope and establishes its context. This groundwork is necessary before proceeding with the assessment, as the criteria will be pivotal in conducting risk evaluation. These criteria can encompass factors like associated costs, benefits, legal requirements, socioeconomic and environmental considerations, as well as concerns of stakeholders. ISO 31000: 2018 notes that the criteria can be qualitative, semi-quantitative or quantitative and outlines various relevant criteria to be reviewed, such as determining risk acceptability or evaluating the relative significance of risks.

3 Risk identification

3.1 Potential impact of earthquakes and its cause

Ground shaking is the most damaging effect of earthquakes. It results from the passage of seismic waves through the ground, affecting built and natural environments. Ground shaking triggers other hazards, for example, liquefaction and subsidence, which can disrupt lifelines, harbours and originate bridge and building foundation failures. Examples of earthquake-induced environmental effects are rockfalls and landslides. Those were observed to cause significant soil erosion or block river streams creating quake lakes of major concern to neighbouring urban regions. Severe shallow earthquakes causing vertical displacements on the ocean floor may generate tsunami waves able to produce destruction over large areas. Surface faulting and ground failure can cause the disruption of tunnels, railroads, power lines, water supply networks and other lifelines. Fires following earthquakes, e.g. the 1906 San Francisco, 1995 Kobe, 1999 Türkiye, 2011 Tohoku and 2011 Christchurch earthquakes, linked for instance to the rupture of gas mains, are important secondary effects of earthquakes, eventually aggravated by the disruption of water supply systems (Khorasani and Garlock 2017). Potential disastrous secondary damage caused by earthquakes can also result in Natech events, i.e., natural hazard triggering technological disasters, such as the release of hazardous materials and the destruction of vital transport and technical infrastructure, industrial buildings and facilities (e.g. BARPI 2013; Necci and Krausmann 2022). Earthquakes are indeed among the most common hazards addressed in Natech risk assessment with a variety of methodologies (Mesa-Gómez et al. 2020). Recent developments in Natech seismic risk analysis aim to support decision-making and apply performance-based principles, probabilistic methods that consider uncertainties, and models for the interdependencies between networked systems (Paolacci et al. 2024). Other examples of earthquake secondary effects are air pollution due to the burning of chemicals,

Table 1 Earthquakes in Europe since 2002, for which the EU Solidarity Fund intervened (https://ec.europa.eu/regional_policy/funding/solidarity-fund_en)

Occurrence	Country	Category	Damage (million €)
October 2002, Molise	Italy	Regional	1558
April 2009, Abruzzo	Italy	Regional	10,212
May 2011, Lorca	Spain	Regional	843
May 2012, Emilia Romagna	Italy	Regional	13,274
January 2014, Kefalonia	Greece	Regional	147
November 2015, Lefkada	Greece	Regional	66
August 2016 – January 2017, Central Italy	Italy	Major	21,879
June 2017, Lesbos	Greece	Regional	54
July 2017, Kos	Greece	Regional	101
March 2020, Zagreb	Croatia	Major	11,573
October 2020, Samos	Greece	Regional	101
December 2020, Petrinja	Croatia	Major	5509
September 2021, Crete	Greece	Regional	143

demolition of damaged buildings and traffic congestion after a major earthquake (Gotoh et al. 2002; Lin et al. 2008). In the reconstruction phase, the increased demand for construction materials in a very short time may lead to a shortage of natural building materials and subsequently to environmental impacts like coastal erosion, saline intrusion, and illegal mining (Khazai et al. 2006).

The occurrence of a major seismic event in an urban area can have a particularly severe impact, resulting in the disruption of economic and social functions in the community. Table 1 lists important earthquakes that occurred in Europe during the last two decades that affected whole regions and caused significant losses reaching billions of euros, and for which the European Union Solidarity Fund intervened. Earthquakes account for 45% of the total aid approved by the EU Solidarity Fund for natural disasters since 2002.

Seismic risk is often expressed in terms of a combination of the magnitude of the consequences of an earthquake and the likelihood of these consequences to occur. It is normally obtained considering the seismic hazard of the site or region, the exposed assets that may be impacted by an earthquake and the vulnerability of those elements at risk, i.e. the vulnerability of different types of buildings or constructions.

The following sections discuss the main drivers of earthquake risk, namely hazard, exposure and vulnerability. The objective is to offer a state-of-the-art review of the topic, while bearing in mind that these aspects are continually evolving and subject to ongoing development.

3.2 Seismic hazard

Many countries in Europe are exposed to earthquakes, particularly in the South-Eastern part, which is consistent with the main fault lines in Europe located where the Eurasian plate meets the African plate and runs through the Mediterranean Sea.

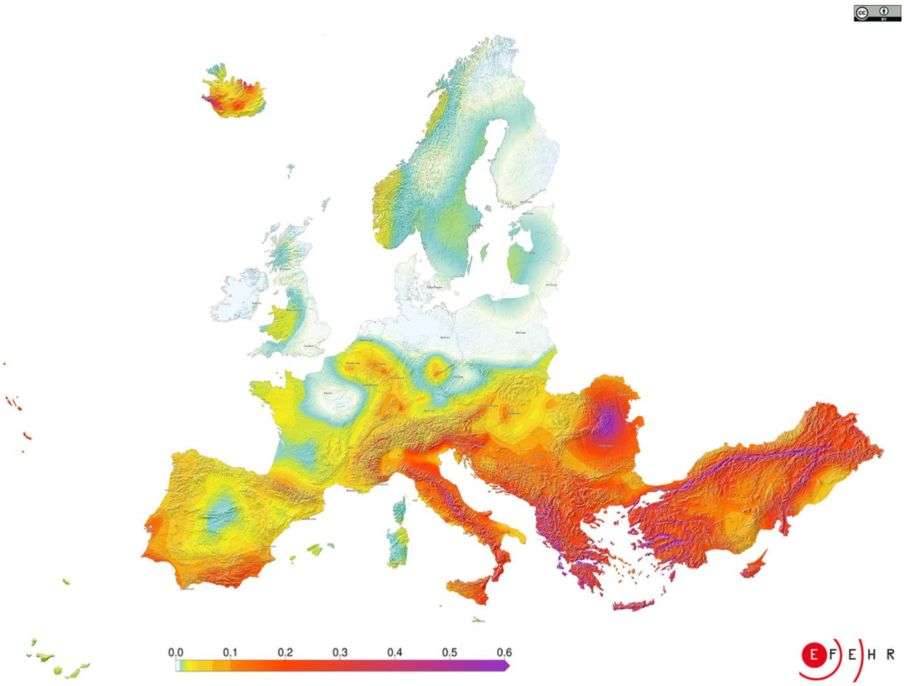

Fig. 1 Spatial distribution of mean PGA [g] across Europe from the ESHM20 with a exceedance probability of 10% in 50 years (475 years return period). *Source*: Danciu et al. (2021)

Earthquake hazard may be assessed using scenario studies (e.g. Coburn and Spence 2002) or probabilistic methods for seismic hazard analysis (called PSHA). The latter have evolved significantly in the last decades and are widely used nowadays. Depending on the available data, they make use of historical and instrumental seismic records, seismogenic models, geological and geodetic data, time-dependent trends in earthquake recurrence, and ground motion prediction equations. Uncertainties in seismic hazard assessment originate from the models for the seismogenic source and ground motion, from the parameters used in those models, and from the random nature of seismic events (Silva et al. 2017).

The analysis is usually carried out for reference rock sites. More reliable site-specific ground motion estimates require geotechnical data and microzonation studies for calculating possible site amplifications. Recently, the SERA project has investigated different methods to address soil amplification within seismic risk assessments, from a local to a regional scale (Crowley et al. 2019).

The output of seismic hazard analysis are intensity measures, such as peak ground acceleration, peak ground displacement, spectral acceleration and spectral displacement for the fundamental period of the structure, spectrum intensity, etc. In probabilistic seismic hazard assessment methods, the reference values of intensity measures are calculated for prescribed return periods (e.g. 475 years) or for the probability of exceedance of intensity levels in a period of time (e.g. 10% in 50 years). A hazard curve provides a relationship between intensity and probability of exceedance.

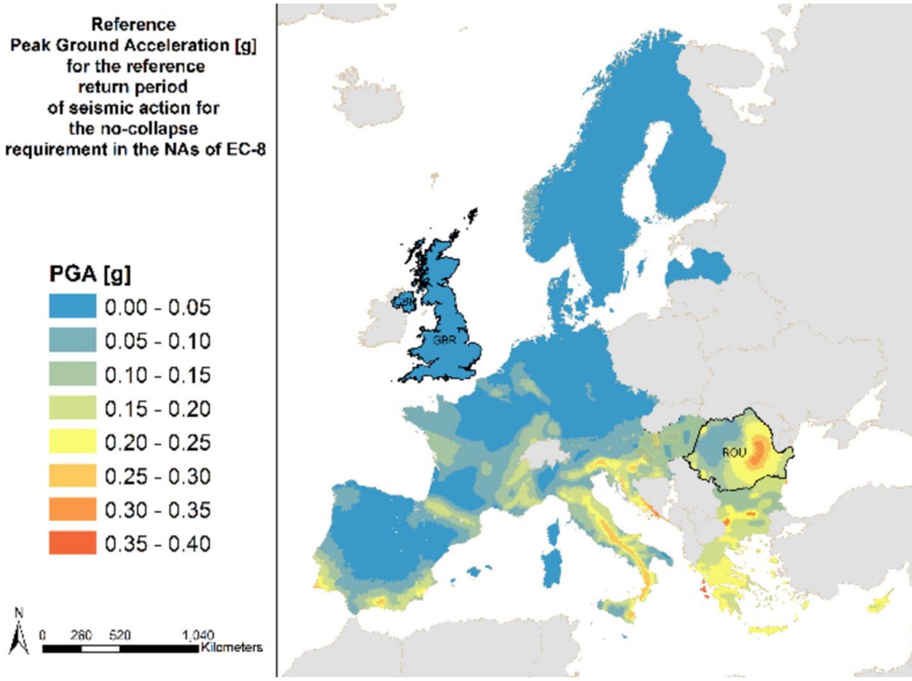

Fig. 2 Reference peak ground acceleration from the National Annexes to Eurocode 8 (CEN 2004). *Source*: Adapted from Palermo et al. (2018)

The 2020 European Seismic Hazard Model (ESHM20), developed as part of the SERA[3] project (Danciu et al. 2021), represents the latest update to earthquake hazard assessment across the entire Euro-Mediterranean region. It employs a state-of-the-art probabilistic framework ensuring a cross-border harmonization of inputs and models all over Europe. The model was developed using recently compiled datasets, updated data and models, encompassing tectonic and geologic information, active fault data, a unified earthquake catalogue, ground shaking records, seismogenic sources and ground shaking models. The ESHM20 mean peak ground acceleration (PGA) for rock conditions and 475 years return period is illustrated in Fig. 1.

Earthquake hazard studies also serve for informing the provisions of seismic design codes. For example, within the suite of EN Eurocodes, the European standards for structural design, Eurocode 8 (CEN 2004) applies to the design and construction of buildings and civil engineering works in seismic regions. The National Annexes to the Eurocodes contain country-specific data, such as maps used for the design of structures for earthquake resistance, which are themselves based on seismic hazard studies. Figure 2 shows the reference peak ground acceleration values on rock sites given in the National Annexes of Eurocode 8. Note that the countries' seismic zones were developed at different times, with different hazard models and data. Moreover, all countries adopted a 475-year reference

[3] The Seismology and Earthquake Engineering Research Infrastructure Alliance for Europe (SERA) project webpage: http://www.sera-eu.org/en/home/.

return period of seismic action for the no-collapse requirement, except Romania and the United Kingdom, which adopted 100 and 2500 years, respectively.

European standards governing earthquake-resistant design and the assessment and strengthening of existing structures typically rely on seismic hazard maps for a given return period, referred to as a "uniform hazard maps" such as the ones shown previously. However, when structures are designed based on a prescribed hazard-exceedance probability, the seismic risk depends on both uncertainties in structural capacities and the specific location of the structure with respect to the level of the national hazard map. Consequently, adhering to a uniform hazard does not necessarily guarantee a uniform risk of collapse in a country. Seismic hazard assessment and structural design are constantly evolving, an example is the ongoing research into risk-targeted hazard maps that aims at ensuring a consistent risk of collapse across different regions of a country (Kharazian et al. 2021; Monti et al. 2023).

3.3 Exposure

Exposure databases for seismic risk assessment include data for buildings, infrastructure and population, often incomplete and geographically disaggregated in a non-homogeneously way. Exposure data for buildings have been collected specifically for seismic risk studies, and with a high level of spatial resolution, in a few cities around Europe.

Alternative sources of information regarding the building stock encompass cadastres and national housing censuses. The latter, typically conducted every decade, are not originally designed for seismic risk research. However, they are noteworthy for their accessibility to the public and for counting a country's entire population and housing stock along with the collection of key characteristic data. Since 2011, European statistical legislation established a set of harmonised data to be collected across the EU countries. In certain countries, the census provides supplementary data relevant to seismic risk studies, such as information on the main materials used in building construction. Eurostat offers a web tool, the Census Hub[4], through which census data sourced from national statistical institutes is disseminated with varying levels of geographic disaggregation.

The seismic exposure model (Crowley et al. 2020) of the European Seismic Risk Model 2020 (ESRM20) (Crowley et al. 2021a) is available through the EFEHR EU Earthquake Risk service[5]. The exposure model includes the spatial distribution of the number of residential and commercial buildings, dwellings, occupants, floor area, settlement type and replacement cost within the EU-27 for defined seismic performance classes of buildings and it is provided on request. This exposure model was the basis to create a database inventorying the European building stock for a European pilot project on integrated seismic and energy renovation of buildings[6] (Gkatzogias et al. 2022b).

Previous studies have examined the effect of detail of exposure data on the seismic risk assessments conducted for extensive European regions. For instance, Sousa et al. (2017) have determined that data sourced at regional level from the Eurostat Census Hub, which is easily accessible, can be employed to evaluate seismic risk at a national level with a

[4] Census Hub Eurostat website: https://ec.europa.eu/CensusHub2/.

[5] http://risk.efehr.org is a web platform hosted at the EUCENTRE (Italy) that provides the risk services of the European Facilities for Earthquake Hazard and Risk (EFEHR).

[6] Website of the project:"Integrated techniques for the seismic strengthening and energy efficiency of existing buildings": https://buildings-renovation-makerspace.jrc.ec.europa.eu/.

satisfactory degree of accuracy, in comparison to the losses calculated using detailed datasets specific to smaller regions (municipality level).

Exposure data for population is available through the new open and free tool Global Human Settlement Layer[7] that produces global spatial information for assessing human presence on the planet, in the form of built-up maps, population density maps, and settlement maps. Based on a population exposure catalogue, the U.S. Geological Survey's PAGER (Prompt Assessment of Global Earthquakes for Response) system automatically estimates the population exposed to severe ground shaking for given intensity levels of an earthquake (Earle et al. 2009).

3.4 Vulnerability

The updated United Nations Terminology on Disaster Risk Reduction (UNDRR 2016) defines vulnerability as "the conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards" in the current case, earthquakes.

Most of the dwellings throughout European countries are situated in aging structures that are approaching or have already surpassed their conventional service lifespan. Moreover, most buildings within the European stock are vulnerable to earthquakes, as they have been designed without provisions for earthquake resistance or with moderate-level seismic codes. This situation is of particular concern for nations in Southern and Eastern Europe with moderate to high seismicity as illustrated in Fig. 1. This may have substantial implications for a large portion of the population, so interventions are needed to reduce vulnerability and potential socioeconomic losses (Gkatzogias et al. 2022a).

Socioeconomic vulnerability of exposed people may complement physical vulnerability of exposed assets and enrich risk assessment studies. Gkatzogias et al. (2022a) combined three composite indicators, i.e. the regional EU Human Development Index (Bubbico and Dijkstra 2011), the EU2020 index (Becker et al. 2020) and the regional EU Social Progress Index (Annoni et al. 2016), to define a single measure of socioeconomic vulnerability. As shown in Fig. 3, the 100 regions with the highest socioeconomic vulnerability include 23 regions in Bulgaria (excluding Sofia), 33 in southern Italy, 30 in Romania (excluding Bucharest), 11 in south-western Spain and three in northern Hungary.

3.5 Scenario-building process

An earthquake scenario-building-process is composed of two major steps: the first involves the characterization of earthquake occurrence and ground motion, and the second the assessment of the potential impact and consequences. The first step provides the necessary data and models to understand the seismic hazard, while the second informs risk reduction and mitigation strategies, being particularly useful to prepare emergency plans for civil protection, provide to government and insurance companies a first order estimate of the impact, and analysing funding requests in the aftermath of a seismic event (De Martino et al. 2017). Risk scenarios may encompass future and emerging risks, risks that have

[7] European Commission website of the Global Human Settlement Layer: https://ghsl.jrc.ec.europa.eu/dataToolsOverview.php.

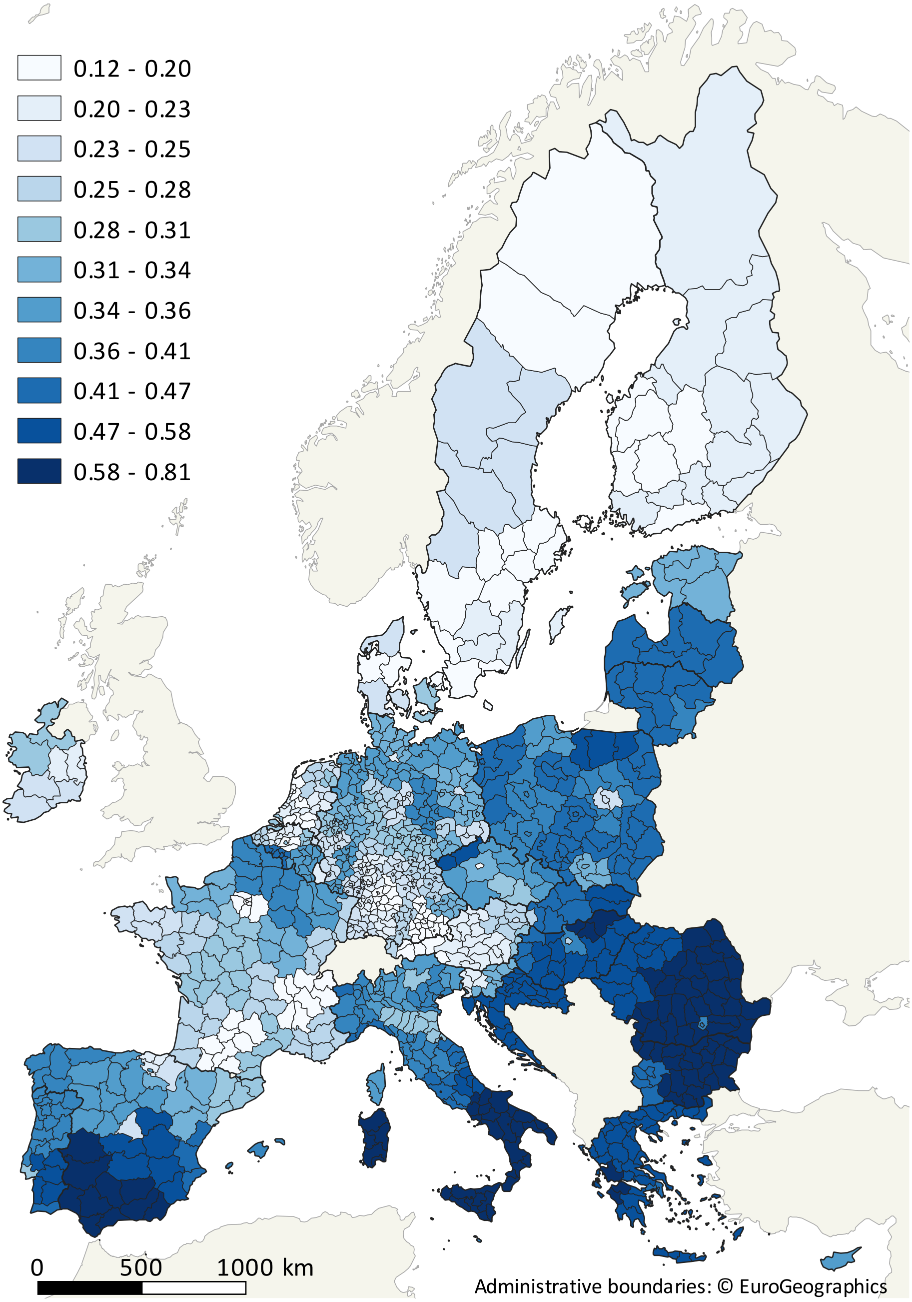

Fig. 3 Socioeconomic vulnerability in the European Union (Gkatzogias et al. 2022a)

cross-border implications, and those with a low probability but high impact. In national risk assessments, efforts may be made to not only examine individual risk models or scenarios but also to explore multi-risk scenarios or models. According to Mysiak et al. (2021), multi-risk analysis considers both multiple hazards, occurring simultaneously or consecutively, and multi-vulnerabilities of various exposed elements. It considers the potential for amplification and cascading consequences resulting from interactions with various risks. In simpler terms, one risk can be intensified by another risk, or due to a significant change in the system's vulnerability or exposure caused by a different type of event.

An example of an earthquake hazard scenario is the maximum probable or credible earthquake, which refers to the largest earthquake that can reasonably be expected to occur in a particular region. This is often based on the estimate of the magnitude of the most severe historical event reported in the region, and its best-guess location derived from known geologic faults, or seismic source zones. In addition, probabilistic seismic hazard disaggregation analysis can determine the most likely earthquake scenario that governs the hazard at a particular site. The scenario may be characterized by a pair of magnitude-distance, conditional on a given level of ground motion, or a given return period.

Various approaches are used to model ground motion, ranging from empirical ground-motion prediction equations (Danciu et al. 2021) to more sophisticated models that involve simulation of non-stationary stochastic ground motions (Sabetta et al. 2021; Vlachos et al. 2018). The former approach assesses ground-motion attenuation at a certain distance from the earthquake source using magnitude, distance, and site conditions as predictor variables. In contrast, the latter method calculates the time histories and duration of ground motion for a user-specified seismic scenario, which are increasingly important for applications such as nonlinear dynamic analysis, seismic design, and retrofitting (Baker and Lee 2018; Sousa and Campos Costa 2009).

The aleatory variability of the ground motion, the fragility of the elements at risk (see Sect. 4.1 for more details) and exposure models are taken into consideration to assess the impact of a historical event or a simulated earthquake hazard scenario in a region.

Probabilistic seismic risk assessment considers all possible earthquakes that can affect a site, along with their respective probabilities of occurrence, and results in a probabilistic estimate of damage and losses, including relevant uncertainties.

In practice, a seismic risk scenario includes the assessment of several Sendai Framework indicators, such as the number of fatalities, injured people, people whose dwellings were damaged or destroyed, direct economic loss relative to the global gross domestic product, direct economic loss in the housing sector, damage to critical infrastructure, and disruption of basic services.

Certain regions in Europe are prone to infrequent but extremely severe seismic events, where earthquakes can be identified as a key risk with low probability and high impact in a regional and national context, with possible adverse transboundary impacts. For example, the Great Lisbon 1755 earthquake caused unusual devastation with significant impacts in Portugal, Spain and Morocco. The event was felt in other regions of Western Europe, such as Southern France and Northern Italy (Solares and Arroyo 2004).

Machine learning and deep learning techniques for seismic risk identification (hazard and vulnerability), analysis (fragility and damage assessment) and treatment (mitigation through structural control) have been extensively explored, resulting in significant progress over the past 20 years (Xie et al. 2020). However, these methods are not yet mature for implementation in seismic risk assessment at the national level.

To conclude this section, it is important to highlight the flagship initiative known as "Europe-wide scenarios," which is part of the "Anticipate" key area within the European

Union Disaster Resilience Goals (European Commission 2023a). It will develop comprehensive transboundary, cross-sectoral scenarios encompassing 16 main hazards and potential cascading effects that Europe may face, earthquakes included. This initiative is aimed at enhancing Europe's collective capacity to prepare to forthcoming crises, prioritize preventive actions, and adjust risk management planning accordingly.

4 Risk analysis

4.1 Damage assessment

Damage of physical assets at risk is evaluated by means of fragility functions describing the probability that, for a given value of the earthquake intensity, structures of a certain typology will exceed different damage levels. Surveys of observed damage from past earthquake and laboratory tests are the basis for constructing empirical fragility functions. Alternatively, analytical fragility curves can be produced from the results of numerical simulations of varying degrees of sophistication (Maio et al. 2017; Martins et al. 2021).

Uncertainties in probabilities of damage originate from the variability of the seismic action, geometric and material parameters of the studied structures, type of structural model and analysis, resistance models, the definition of damage states, etc. A collection of fragility curves for buildings, bridges, highway and railway infrastructure, harbour elements, health care facilities, electric power stations, gas and oil distribution networks, water and waste-water systems, may be found in Crowley et al. 2021b; Pitilakis et al. 2014; Romão et al. 2019, 2021; Rosseto et al. 2014, Yepes-Estrada et al. 2016 and the GEM Vulnerability Databases[8].

Traditional masonry structures are particularly vulnerable to seismic events and specific fragility curves representative of building typologies made of rubble stone masonry walls and flexible timber floor are being developed (Bernardo et al. 2023). Different collections of vulnerability and fragility curves are used to estimate damage to cultural heritage, taking into consideration the particularities of these structures such as aging and state of conservation and relevant degradation factors (e.g. Bernardini and Lagomarsino 2018; Despotaki et al. 2018).

Various models have been developed to provide decision-makers with more useful risk metrics describing the impact of earthquakes. The models, presented below, transform earthquake damage (e.g. the number of buildings collapsed) to consequences, such as direct-economic losses, debris estimates, business interruption, casualties or shelter needs.

4.2 Damage-to-loss models

Generally, damage-to-loss models assess the total repair cost for a class of buildings, or building typology, correlating a given damage threshold to the repair cost, knowing the building replacement cost in the region (ATC 1985; D'Ayala et al. 2015; De Martino et al. 2017; FEMA 2018; Martins et al. 2016; Wehner and Edwards 2013). Empirical models, e.g. by Lehman et al. (2004) and Mackie and Stojadinović (2006) for bridges, relate the

[8] GEM Vulnerability Databases can be found at: https://www.ucl.ac.uk/epicentre/resources/gem-vulnerability-databases.

functionality of basic services and infrastructures to structural damage. The latter can be obtained, for a given earthquake intensity, by fragility functions. Empirical models are also available for estimating business interruption (ATC 1985; FEMA 2018) as a function of structural damage. The European Seismic Risk Model (Crowley et al. 2021a) defines the ratio of repair cost to the replacement cost for four common damage states (slight, moderate, extensive, and complete) of buildings, based on recent expert-based and empirical European damage-to-loss models.

4.3 Estimation of casualties

Injuries and casualties during earthquakes are caused by structural and non-structural damage, accidents, heart attacks, etc. Coburn and Spence (2002) report that more than 75% of deaths in past events were due to building collapse and propose a 'lethality ratio', i.e. the ratio of people killed to the number of people present in a building, to estimate casualties for each building class. This ratio depends on the characteristics of the ground motion, the building type and function, collapse mechanism, other levels of damage different from collapse, occupancy, behaviour of occupants, and search and rescue effectiveness. A large number of casualty models with different degrees of sophistication have been developed (e.g. ATC 1985; Balbi et al. 2006; Cavalieri et al. 2012; Crowley et al. 2021a; Erdik et al. 2011; FEMA 2022; Hingorani et al. 2020; Jaiswal et al. 2009; Jaiswal and Wald 2012; Jia et al. 2019; Khazai et al. 2014; Porter et al. 2008; Reinoso et al. 2017; So and Pomonis 2012; So and Spence 2013; Spence et al. 2007, 2011; Zuccaro and Cacace 2011). The models are grounded in empiricism, drawing upon observations from prior earthquakes and expert input. They provide a wide range of information including the percentage of individuals who have been lightly, moderately, seriously injured, or killed following an earthquake. The models range from relatively simple ones providing loss rates corresponding to various ground motion levels, to more sophisticated models that estimate casualty ratios for different building types under diverse damage conditions, including structural collapse and other damage levels.

Numerous challenges persist in this field. One of the primary concerns is the need for a dynamic estimation of population exposure. The estimate should take into account daily commuting to and from work, as well as weekly or seasonal population movements, and whether people are inside or near buildings at the time of the earthquake (Guérin-Marthe et al. 2021). The Global Human Settlement Layer (GHSL)[7] helps alleviate the problem to some extent; nevertheless, the relatively low level of geographic disaggregation of the GHSL for seismic risk studies and the difficulty of linking the location of exposed individuals during an earthquake to specific building types persists. Other challenges are associated with the shortage of well-validated high-quality data for calibrating models to estimate human losses. For all these reasons, most of these models emphasize the significant uncertainty associated to casualty estimations. Further research is needed to quantify this uncertainty. One of the few examples of research on the uncertainty associated to casualty estimations is the work by Gobbato et al. (2014) cited by Guérin-Marthe et al. (2021).

4.4 Estimation of shelter needs

Data from past earthquakes show that the number of displaced people is almost an order of magnitude higher than the number of collapsed and severely destroyed buildings.

Multi-criteria models for estimating the number of displaced households, population needing temporary shelter and shelter supplies (e.g. food and water) consider the physical habitability of buildings, the occupants' desirability to evacuate and to seek public shelter, and the change of demand and supply of temporary shelter facilities after the event (Bakhshi Lomer et al. 2023; Khazai et al. 2014; FEMA 2018; Vecere et al. 2017; Wang et al. 2022; Zhao et al. 2019). The habitability of buildings is based on the physical damage, the loss of utilities (e.g. water and energy supply), the access to the transport network and services (health, education, sports, culture, firefighting, police, etc.), and the weather conditions. The desirability to evacuate and seek public shelter facilities depends on several social factors, such as household tenure and size, household type, age, ethnicity, income, employment and education level of occupants, perception of security in the area, distance and ease of access to shelters. Data for these indicators are available through the national statistical institutes and Eurostat. These methods are applied at the dwelling or normally the city or regional level. They require high expertise and calibration on the local characteristics of physical and social vulnerability.

4.5 Estimation of demolition waste

Large earthquakes may produce demolition waste in amounts that would normally take decades to be produced and require several years to be properly disposed or reused and recycled, even in economically advanced countries with good preparedness levels (Sakai et al. 2019). The amount of waste generated by the demolition of damaged structures can be estimated from exposure (number of exposed assets, average volume, or surface area of classes of assets) and damage data (number of assets in different damage states) and empirical models that relate damage to the volume of demolition waste (FEMA 2018; Santarelli et al. 2018; Xiao et al. 2023).

The Hazus methodology (FEMA 2022) to estimate earthquake-related demolition waste considers two distinct categories of debris. The first category includes large debris items, called "heavy debris", like steel components or reinforced concrete elements of structures, which requires specialized procedures for demolition and removal. The second category consists of "light debris", such as bricks, wood, glass, building contents, and other materials that are more easily removable. Buildings that have not collapsed but sustained severe damage, rendering them uneconomical to repair, should be accounted for in the estimates of the earthquake-generated debris.

As an illustration, in May 2023, the debris resulting from the collapsed and damaged buildings following the 2023 Kahramanmaraş earthquakes in Türkiye, amounted to about 100 million tons, as reported by Hancilar et al. (2023).

4.6 Risk metrics

Loss exceedance curves are examples of risk metrics that result from the probabilistic analysis of seismic risk. The curves describe the probability of various levels of losses being exceeded. Typically, probabilistic seismic risk analysis looks at the following losses or consequences: fatalities, injuries and economic losses derived from damages. Once the probability distribution of losses is known, other risk metrics can be obtained, for example, average annualized earthquake losses (AEL) or average annualized earthquake loss ratio, AELR (FEMA 2017). AELR is a useful metric to compare the relative risk across different regions since it is normalized by the replacement value of exposed elements. Wellbeing loss is complementary to economic loss and provides insight on the impact of earthquakes on households with different levels of income (Markhvida et al. 2020).

4.7 Tools for seismic risk analysis

Several open-source tools with high degree of sophistication and capabilities have been developed for evaluating the impact of earthquake on the building stock, exposed population, and critical infrastructures. Near-real time earthquake scenarios systems provide prompt evaluations of damage and losses, typically shortly after a seismic event. The assessments rely on data regarding the earthquake's magnitude, timing, and location, or on the availability of ground motion maps and shaking intensity maps (shake-maps). Most of these software packages come equipped with libraries containing pre-defined hazard and vulnerability models, while also providing users with the flexibility to input new ones as well as exposure data (Andredakis et al. 2017, Guérin-Marthe et al. 2021; Makhoul and Argyroudis 2018; Spence 2007).

Andredakis et al. (2017) provide several details on these tools. Example applications with pre-loaded exposure data showed that these tools can produce an early impact assessment within 5–15 min. Comparison of predicted losses with data recorded after real earthquakes demonstrated that, in general, the order of magnitude of economic losses is accurately predicted, but casualties are overestimated.

Recently, Guérin-Marthe et al. (2021) published a state-of-the-art review paper examining an up-to-date collection of currently operational systems for rapid response to earthquakes. The paper places a specific emphasis on tools and methodologies developed for computing shake maps and on various systems providing near-real-time ground motion and loss estimates. The study concentrates on rapid earthquake response systems, primarily originating from Europe. It offers valuable insights into the input and output data, scale, operational capabilities, and status of these systems.

A selection of loss assessment systems identified in the publications by Andredakis et al. (2017), Guérin-Marthe et al. (2021) and others along with their respective website are exemplified below.

- ARCH DSS[9] is a WebGIS decision support system specifically targeted to assess earthquake-induced physical damage on the built environment of historic areas and monitor resilience (Giovinazzi et al. 2021).
- GDACS[10], the Global Disaster Alert and Coordination System results from a cooperative framework between the United Nations, the European Commission (the JRC) and disaster managers worldwide. GDACS offers a map featuring three levels of qualitative disaster alerts for various events, including earthquakes, tropical cyclones, floods, volcanoes, droughts, and forest fires. The casualty estimates for earthquakes are derived from the PAGER tool.
- Hazus-MH Earthquake Module[11] is a standardised methodology for estimating potential disaster losses from earthquakes, tsunami events, floods, and hurricanes. HAZUS

9 Website of ARCH DSS: https://savingculturalheritage.eu/solutions/tools.

10 Website of GDACS: https://www.gdacs.org/.

11 Website of FEMA-Hazus Program: https://www.fema.gov/flood-maps/products-tools/hazus.

uses GIS technology to estimate physical, economic, and social impacts of disasters. It is used for planning mitigation and recovery, as well as preparedness and response.

- IRMA (Borzi et al. 2021; Masi et al. 2021), Italian Risk Maps, was designed for the scientific community and utilizes OpenQuake as the calculation mechanism allowing users to upload various exposure/vulnerability databases and sets of fragility curves. Damage scenarios can also be generated by inputting shake maps from seismic events. In 2018, the Italian Civil Protection Department utilized IRMA to produce the National Risk Assessment required by the UCPM.
- OpenQuake[12] is a freely accessible, open-source software developed by the Global Earthquake Model Foundation. It considers the geographical distribution of residential, commercial, and industrial structures, socioeconomic vulnerability, and the potential of communities and nations to recover and rebuild. The project builds on the Global Earthquake Hazard and Risk Models and aims to assess earthquake risk worldwide.
- PAGER[13], developed as part of the U.S. Geological Survey Earthquake Hazards Program, is a widely recognized near-real-time loss assessment system. It supplies shake maps and first-order estimates of the potential impact in terms of fatalities and economic losses following significant earthquakes. PAGER provides near-real-time post-earthquake loss estimates based on a worldwide building exposure module, making the system suitable for use on a global scale.
- QLARM[14] is a loss estimate system produced by the International Centre for Earth Simulation (ICES Foundation). In collaboration with the Swiss Seismological Service, it furnishes loss estimates within 24 h of a potentially damaging earthquake occurring globally. The system offers alert levels indicating the number of fatalities and an average of buildings damaged.
- Rapid-N[15] has been developed by the European Commission for the assessment of Natech risks at local and regional levels and has currently been implemented for earthquakes.
- The RASOR[16] project developed a platform to perform a multi-hazard risk analysis to support the full cycle of disaster management, including targeted support to critical infrastructure monitoring, and climate change impact assessment.
- The SELENA[17] open risk software is a tool to provide earthquake damage and loss estimates. It uses a logic tree approach, allows for deterministic and probabilistic analysis, and includes a risk illustrator software tool.

Examples of other relevant loss assessment systems primarily operating outside Europe include:

- The CAPRA[18] probabilistic risk assessment platform, which is an initiative that aims to strengthen the institutional capacity for assessing, understanding, and communicating disaster risk, with the ultimate goal of integrating disaster risk information into devel-

12 Website of GEM: https://www.globalquakemodel.org/.

13 PAGER Data, Products and References website: https://earthquake.usgs.gov/data/pager/references.php.

14 QLARM, webpage of the ICES Foundation: http://www.icesfoundation.org/Pages/QlarmEventList.aspx.

15 Website of RAPID-N: https://rapidn.jrc.ec.europa.eu/.

16 Website of RASOR: http://www.rasor-project.eu/.

17 Website of SELENA: https://selena.sourceforge.net/.

18 Website of the CAPRA Probabilistic Risk Assessment Platform https://ecapra.org/.

opment policies and programs. The CAPRA platform has been used for different types of natural hazards and risks in central and south America. It includes free software for assessing geologic (earthquake, soil effects and volcanic) and hydrogeologic hazards (flood, hurricane, landslide, and precipitation).

- READY and SUPREME are two loss assessment systems operating in Japan. READY (Midorikawa and Abe 2000) is connected to a dense network of strong motion accelerometers, which are employed for monitoring liquefaction and conduct rapid evaluations of damage on road structures and wooden houses. SURPREME (Shimizu et al. 2004) is a real-time safety control system that assesses damage to gas pipelines aiding in decisions regarding the need to shut down gas supply.

4.8 Review of recent European research on seismic hazard, risk and mitigation

The European Union has provided significant funding for collaborative research projects dealing with the impact of earthquakes, within the Framework Programmes for research and innovation. The projects listed in Table 2 involved experts from across Europe and produced state-of-the-art methodologies and models for hazard, vulnerability and risk assessment, developed tools that can be deployed in practice for preparedness, mitigation, planning, and risk management activities. The methodologies, models and tools were used for a large number of illustrative case studies at local (city) or regional level.

4.9 Examples of seismic risk assessment studies

Italy
The Italian Civil Protection Department has published a comprehensive report (DPC 2018) addressing the national risk assessment of the potential major disasters in Italy such as earthquakes, volcanic eruptions, tsunami, hydro-geological/hydraulic events, extreme weather, droughts, and forest fires. The report assessed earthquake risk for the country's housing stock using the latest seismic hazard probabilistic evaluation and detailed damage data from eight recent Italian earthquakes. These initial studies were followed by subsequent projects (Dolce et al. 2021) actively supporting a different facet of the new Civil Protection Code, emphasizing non-structural prevention and community awareness to mitigate existing risks. For instance, the dedicated web tool called SICURO+[19] enables citizens to access the newly developed seismic risk maps. In 2019, new risk maps were produced considering enhanced vulnerability models and the framework was extended to encompass distinctive building typologies such as schools and churches (Masi et al. 2021).

Spain
A scenario-based approach was followed for the seismic risk assessment in Spain (DGPCE 2015). This study used the national seismic hazard maps, census, and cadastral data, respectively for population and buildings, vulnerability classes according to the period of construction of buildings, and empirical models for impact on people. The analysis yielded the number of buildings at different damage states, the number of casualties and injuries,

[19] Website SICURO+: https://www.sicuropiu.it.

Table 2 European research projects related to seismic risk assessment

Project	Title	Duration	Website
LESSLOSS	Risk mitigation for earthquakes and landslides	2004–2007	https://cordis.europa.eu/project/rcn/74272_en.html
NERIES	Network of research infrastructures for European seismology	2006–2010	https://cordis.europa.eu/project/rcn/79877_en.html
SERIES	Seismic engineering research infrastructures for European synergies	2009–2013	https://cordis.europa.eu/project/id/227887
SHARE	Seismic hazard harmonization in Europe	2009–2012	www.share-eu.org
SYNER-G	Systemic seismic vulnerability and risk analysis for buildings, lifeline networks and infrastructures safety gain	2009–2013	www.vce.at/SYNER-G
NERA	Network of European research infrastructures for earthquake risk assessment and mitigation	2010–2014	https://cordis.europa.eu/project/id/262330
REAKT	Strategies and tools for real time earthquake risk reduction	2011–2014	https://cordis.europa.eu/project/id/282862
STREST	Harmonized approach to stress tests for critical infrastructures against natural hazards	2013–2016	www.strest-eu.org
SERA	Seismology and earthquake engineering research infrastructure alliance for Europe	2017–2020	www.sera-eu.org
RISE	Real-time earthquake risk reduction for a resilient Europe	2019–2023	http://rise-eu.org
ERIES	Engineering research infrastructures for European synergies	2022–2026	https://eries.eu
Geo-INQUIRE	Geosphere infrastructures for questions into integrated research	2022–2026	https://www.geo-inquire.eu

and the number of homeless people in the event of earthquakes with a return period equal to 500 and 1 000 years.

France

A probabilistic method was adopted for the assessment of seismic risk in 40 cities in metropolitan France (AFPS 2014). The study employed hazard curves for cities in different seismic zones, fragility functions for buildings belonging to four vulnerability classes, and models that relate structural damage to the number of victims, and to economic losses. The results are given in terms of probability of collapse of buildings, expected annual losses, and probability of casualties.

Portugal

The Portuguese National Authority for Civil Protection with the collaboration of several research institutions coordinated two major projects for assessing seismic risk in the metropolitan region of Lisbon and seismic and tsunami risks in Algarve (ANPC 2010; Campos Costa et al. 2010; Costa et al. 2012; Sousa et al. 2010b). The projects aimed at providing scientific foundations to support decision-making concerning regional seismic disaster prevention and preparedness. In addition, over the last years in Portugal, seismic risk assessment studies at both the national and municipal levels have consistently advanced in terms of model's sophistication and the amount of data collected (e.g. Correia Lopes et al. 2024; Marques et al. 2018; Ribeiro et al. 2023; Silva et al. 2014; Sousa and Campos Costa 2015). Of note is the ongoing ReSist[20] program currently underway in Lisbon, which is an example of good practices to improve the municipality's seismic resilience, including the development of a new map for classifying the seismic behaviour of soils, standards for assessing the vulnerability of building and several public awareness campaigns.

5 Risk evaluation

Following the completion of risk analysis, the focus shifts to risk evaluation which constitutes the central theme of this section. Risk evaluation is the process of comparing the level of risk achieved during the analysis stage with the established risk criteria previously defined. i.e., the terms of reference against which the significance of a risk is evaluated (Mysiak et al. 2021). Risk evaluation aims to determine whether a risk level is unacceptable, tolerable or broadly acceptable and assist informed decisions about risk treatment (ISO 2018). A risk-informed decision, rather than a risk-based decision, allows for adjustments considering other relevant factors like political and legal requirements, socioeconomic, technical, and environmental conditions. Indeed, risk evaluation is a multifaceted activity that goes beyond the technical domain and needs the incorporation of assessments from regulatory authorities, in line with political and socioeconomic directives (Baptista 2009), while considering the specific situation of each country. The evaluation process should be a result of extensive discussion, consideration of stakeholder preferences and criteria and the achievability of potential solutions for risk reduction (HSE 2001). Note that society's aversion to events capable of causing a large number of fatalities, such as seismic phenomena,

[20] Website program ReSist: https://informacoeseservicos.lisboa.pt/prevencao/resiliencia-urbana/projetos/resist.

can influence the decision framework. For this reason, the risk of facing death or injuries may be addressed in terms of (i) individual risk, or the risk of a person present in a given location, being exposed to one or more adverse hazardous events, and (ii) societal risk, or the risk of a group of people being simultaneously exposed to an adverse hazardous event. Societal risk is often represented using the so-called F-N curves that provide the probability of exceeding a number of fatalities per year on a log–log graph (Stojadinovic 2016) and incorporate society's aversion to events posing death threats to large populations.

The geographic distribution of risk indicators, for instance, maps of earthquake losses for a given return period, or average annualized earthquake losses are useful tools for communicating the results of the risk analysis and identifying the most at-risk areas across a country. Note that the comparison of risk maps with the spatial distribution of seismic hazard, vulnerability, and exposure can only provide a qualitative indication on the main drivers of risk, owing to the complexity of the process for evaluating earthquake risk. Countries may find helpful to compare their risk analysis with the maps carried out at a world level by the GEM Foundation (Silva et al. 2018), particularly the profiles for available countries (https://downloads.openquake.org/), which include maps of seismic hazard, exposure, average annualized earthquake losses, average annualized earthquake loss ratio, among other information.

As regards seismic risk, the literature is scarce to guide decisions on acceptable or tolerable levels of life or economic losses. Risks bellow the broadly acceptability threshold would not require the implementation of reduction measures, whereas risk above the tolerability threshold would require mitigation measures to reduce it to tolerable levels. On this subject, it is worth mentioning the FP7 project STREST (Harmonized approach to stress tests for critical infrastructures against natural hazards) that summarised the European practice regarding the acceptance criteria for fatality risk (STREST Deliverable D4.5; Stojadinovic 2016). The author suggests that the individual risk should not exceed 10^{-6} per year, which in simple terms means that the annual probability of an individual dying due to earthquakes in a given region should be less than one in 1 000 000 people. In terms of societal risk, it should be less than 10^{3} per year for major accidents with up to one fatality, and less than 10^{-5} for accidents ten times larger. Considering that the criteria to evaluate societal earthquake risk was still a controversial issue, Sousa et al. (2010a) used the acceptability threshold for individual risk proposed by ANCOLD (2003) to evaluate the earthquake risk in Lisbon. Accordingly, the acceptability threshold adopted for individual risk was between 10^{-6} and 10^{-8} per year. When risk reduction is impracticable, or the costs to reduce it are grossly disproportionate to the benefits obtainable (ALARP principle – As Low As Reasonably Practicable), the threshold (tolerability threshold in this case) may drop, e.g., to 10^{-5} for new structures, and to 10^{-4} for existing ones (Sousa et al. 2010a). According to HSE (2001), ensuring that a risk has been reduced to As Low As Reasonably Practicable involves balancing the risk against the costs required to further reduce it. To avoid incurring in those costs, authorities must demonstrate that they would be grossly disproportionate to the benefits that would be gained through risk reduction. Therefore, the process doesn't entail balancing the costs and benefits of measures but rather focuses on adopting measures unless they are considered impractical due to grossly disproportionate costs.

The risk-informed guidelines for safety decisions in dam projects (FERC 2016) may provide an indicative reference to identify whether earthquake risk in a region should be addressed as a low-probability and high-impact risk. In fact, a sudden-unexpected dam failure can simultaneously affect many people, as is the case of earthquake

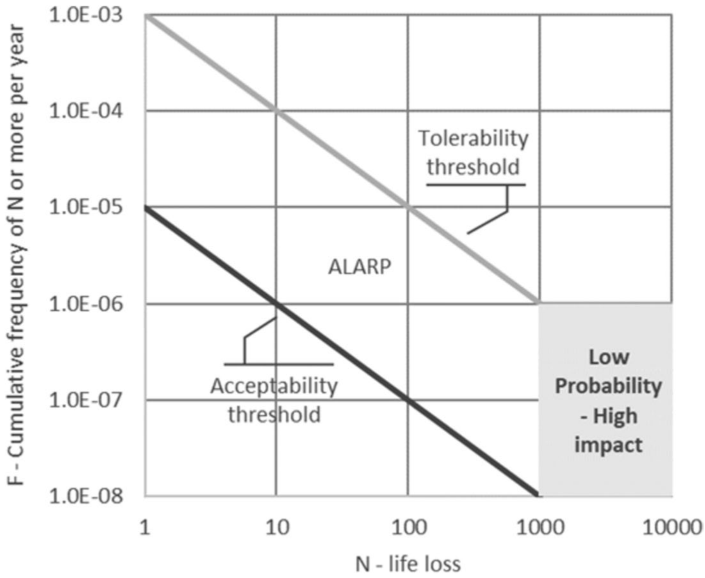

Fig. 4 Low-probability and high-impact risk region in a F-N chart. *Source*: adapted from FERC (2016)

disasters. The guidelines define the attributes of a **low probability – high consequence** region in a F-N chart as follows: incremental life loss estimated to be equal or exceed 1 000 lives with an annual probability of potential life loss less than 1 in 1 000 000 (10^{-6}) (see Fig. 4). Baptista (2009) states that the vast majority of risk tolerability criteria utilize, as an anchor point, the value of 10^{-4} or the value of 10^{-5} for 10 fatalities, with the acceptability limit set 100–1000 times below the tolerability threshold. However, risk criteria can vary significantly depending on the context and nature of hazards, so the proposed values should be seen as merely indicative.

6 Risk treatment

6.1 Overview of risk treatment strategies

It is recognised that it is not possible to avoid the occurrence of earthquakes, except in special cases, such as human-induced seismicity. However, when a risk assessment process results in a decision to address the risk, the next step is to implement **risk reduction** measures or adopt alternative strategies such as **transferring** some or all of the financial consequences of earthquakes to another party, often through insurance mechanisms. In fact, the effects of earthquakes can be significantly mitigated either by reducing the exposure of the elements at risk or by improving the resilience of the built environment through the implementation of structural and non-structural prevention and preparedness measures. Additional strategies, not covered in this paper but discussed in the financial risk management literature (EERI 2000), include: (i) **distribution and diversification,** as exemplified by insurance companies avoiding the concentration of numerous earthquake risk policies in high-hazard prone regions, (ii) **redundancy and duplication,** which involves maintaining duplicate copies of critical information or resources in different locations, and (iii)

Table 3 Cumulative impact assessment for 100 priority regions (Gkatzogias et al. 2022b)

	Scenario A	Scenario B
Reduction of net economic loss (million €)	78	12
Reduction of fatalities	55	71
Affected regions	47	47
Renovated buildings (%)	4	13
Affected population (%)	6	13

retention where individuals or entities bear some or all of the adverse consequences of an earthquake, as observed when owners of at-risk buildings choose not to purchase insurance risk coverage due to their perception of low earthquake risk.

6.2 Reduction of seismic vulnerability

The structural elements of a building are the ones responsible for withstanding various loads, including gravity, earthquakes, and wind. They typically include components such as columns, beams, load bearing walls, floors and roof components, foundations systems and more. In contrast, non-structural elements within a building encompass every part of the building and its contents excluding the structural elements. FEMA (2012) classified non-structural components into three main groups: architectural components (e.g. partitions, ceilings), mechanical, electrical, and plumbing components (e.g. pumps, distribution systems including piping, ductwork and conduit) and furniture, fixtures and equipment (e.g. book cases, computers and desktop equipment, chemicals or hazardous materials, museum artefacts).

Structural prevention measures comprise seismic retrofitting of buildings and infrastructure, following the assessment of seismic risk, possibly considering socioeconomic vulnerability, and the prioritisation of building classes and regions. Retrofitting plans may target assets that were designed according to specific levels of seismic codes, specific percentage of the stock, assets that can be renovated in a cost-beneficial way, etc. The impact of a renovation scenario is assessed through the reduction of economic loss and casualties, the number of affected assets and population, and its cost. Table 3 summarises the results of the impact assessment for two scenarios for the renovation of buildings in 100 regions in the European Union, selected according to criteria that combine seismic risk, energy efficiency and socioeconomic vulnerability (Gkatzogias et al. 2022b). Seismic risk in these regions is estimated to 197 fatalities and a repair cost of 3.1 billion euro a year in residential buildings. Renovating building classes that exhibit individually a net economic benefit (scenario A) reduces annual fatalities by 28% and net economic loss by 78 million euro annually. If the net economic benefit is used to renovate more buildings (scenario B), annual fatalities are reduced by 36%. Gkatzogias et al. (2022b) provide more details on the impact assessment for a number of renovation scenarios.

The application of building codes can considerably reduce the severity of human, structural and economic impacts of earthquakes. The provisions of Eurocode 8 (CEN 2004) contribute to reduce the vulnerability of buildings and ensure that, in the event of earthquakes, lives are protected, damage is limited, and civil protection structures remain operational. This has been demonstrated in all major earthquakes that occurred worldwide, e.g.

the 1995 Kobe, Japan, earthquake (Ranghieri and Ishiwatari 2014), and the 2009 earthquake in L'Aquila, Italy (Dolce and Manfredi 2015), where the large majority of damaged buildings were built without or with low-level provisions for earthquake resistance. The lesson learnt is that building codes have proven to be a valuable mechanism to implement effective mitigation measures, and significantly reduce high costs of post-disaster reconstruction in many developed countries. Moreover, post-disaster reconstruction offers an opportunity for introducing or reforming regulatory processes, aiming to "Build Back Better", i.e., to implement land use planning, to improve the quality and safety of the built environment, to strengthen the resilience of communities to earthquakes, and to capitalise long-term earthquake risk reduction efforts.

Legislation, strategies and financing instruments are useful policy measures to upgrade the building stock. Integrated strategies linking disaster risk reduction and climate change adaptation efforts are becoming increasingly important. In this regard, a joint study conducted by the European Commission and the World Bank provides compelling evidence to assist policymakers and practitioners in making informed investments with the goal of strengthening disaster and climate resilience. Over the period from 1980 to 2020, natural disasters affected approximately 50 million people within the European Union, resulting in an average annual economic cost of €12 billion. However, the study's positive findings reveal that strategic investments in resilience can yield significant social, economic, and environmental benefits, particularly when these investments incorporate sustainable approaches that leverage synergies to mitigate risk from hazards such as floods, earthquakes, heatwaves, and wildfires (World Bank Group and European Commission 2021). A review across the EU Member States that included seismic risk in their 2015 national risk assessment found several measures for combined seismic and energy renovation of buildings (Butenweg et al. 2022). These measures include (i) the 2015 national programme for the energy efficiency of multi-family residential buildings in Bulgaria, (ii) the Ecosisma bonus and Superbonus in Italy offering tax deductions, (iii) a law in Portugal addressing energy efficiency, seismic and fire safety, acoustics and accessibility, (iv) the national programme for increasing the energy performance of apartment buildings in Romania that was extended to include requirements for a detailed seismic evaluation, and (v) the Building Cards instrument in Slovenia to promote renovations for energy efficiency, fire and seismic safety. The energy renovation of buildings is indeed an opportunity to address seismic safety, as recognised in 2020 long-term renovation strategies of Croatia, Cyprus, Hungary, Italy, Romania, Slovenia and Spain and the national recovery and resilience plans of Croatia, Italy, France, Romania and Slovenia.

As for non-structural elements, building codes also include design provisions aimed to make them resistant to seismic loads. The literature provides various guidelines and recommendations for implementing practical measures to reduce or prevent damage to non-structural elements and to enhance both occupants' safety and ensure functionality and business continuity (CEN 2004; CURRE 2009; FEMA 2004a; FEMA 2005; FEMA 2012; KnowRISK project[21]; Murty et al. 2012; Petal 2003).

[21] Webpage of the KnowRISK project: https://knowriskproject.com/the-project/.

6.3 Earthquake early warning systems

Earthquake early warning (EEW) systems are other type of non-structural prevention measures. As a means to reduce disaster risk in real-time, EEW systems are being utilized in urban areas worldwide, e.g. in California, Japan, Mexico and Romania (Cuéllar 2014; Fujinawa and Noda 2013). Early warning systems rely on the difference in arrival time between warning messages and destructive shaking waves. The former are transmitted almost instantaneously when triggered by an earthquake, while the latter may take seconds to minutes to arrive, mainly depending on the distance of the earthquake rupture to the site. This short time lag can trigger automated systems that assess whether an alert should be sent to implement measures to protect lives and assets before strong shaking arrives. The alert enables the implementation of protective measures, including the practice of the 'drop, cover, and hold', shutting off pipeline gas operations to avoid fires, and stopping or reducing train speeds to prevent disasters (Freddi et al. 2021). Recent developments in EEW applications have primarily focussed on enhancing the upstream seismic components of the systems. The improvements aim to offer more accurate estimates of earthquake magnitude and intensity. In addition, new approaches for multi-criteria decision-making in the context of EEW alerts are emerging, for instance taking into account the preferences of the end-users (Cremen and Galasso 2021).

6.4 Seismic risk transfer

Other risk treatment strategies, such as **risk transfer**, lead us to the policy recommendations of the Group of Chief Scientific Advisors responsible for preparing a scientific opinion on "Strategic Crisis Management in the EU" (Group of Chief Scientific Advisors 2022). They suggest exploring insurance gaps at the national level, particularly in Member States facing high risks of natural disasters and climate change, to improve the responsiveness of existing EU financial instruments and resources in meeting the requirements of Member States and regions, and to facilitate a fast response to crises. The Group also recommends exploring new forms of collaboration with the insurance sector to develop innovative insurance products that prevent major disruptions in key sectors of the economy. Especially, they advocate a dialogue with the insurance industry to address issues related to the insurance of assets traditionally considered "uninsurable", such as cultural heritage.

In addition, an OECD study on the "Financial Management of Earthquake risk" indicates that earthquakes, along with floods, are among the hazards with the least insurance coverage (OECD 2018). Despite recent advances in favourable insurance coverage, approximately 85% of earthquake-related losses worldwide since 2000 remain without insurance protection. Indeed, the EIOPA Dashboard shows a high insurance coverage gap in many earthquake-prone countries in southern Europe. Earthquakes are particularly challenging in Greece and Italy, where the protection gap score is the highest, due to the high risk and very low insurance penetration (EIOPA 2022).

7 Risk communication

Another way to save lives is by implementing non-structural prevention measures like **risk communication** to raise public awareness for earthquake disasters. The communication of risk aims to engage and educate different target groups: citizens, infrastructure operators, emergency authorities, regulators, government, etc. The goal is to promote a risk culture about the seismic phenomena and to guide the implementation of prevention and preparedness measures. Examples targeting the public are the implementation of self-protection measures to take before, during, and after an earthquake, such as creating a family plan, preparing an emergency kit, and regularly practicing earthquake drills (e.g. shakeout earthquake drill[22]) (FEMA 2004b; Jones and Benthien 2011). Research efforts have been made to tailor the results of scenario-based rapid impact assessment tools to meet the needs of professionals involved in emergency planning and response, as well as for use in public education and improving societal resilience (Marti et al. 2023). Other aspects of communication include developing infrastructure resilience plans, creating procedures for assessing damage and ensuring the safety of buildings for post-earthquake use while ensuring the dissemination of these procedures inside the organizations (Baggio et al. 2007), or disseminating regulations, standards and policies, and plans for post-event funding.

At this stage, it is worth emphasizing the coherence of European policies in the context of disaster risk reduction and the efforts made to increase public awareness about risks. The second objective within the European Union Disaster Resilience Goals (European Commission 2023a), known as ‘Prepare,’ seeks to enhance public awareness and preparedness for risks. This objective is closely linked to the flagship initiative *prepareEU*, which is a Europe-wide program designed to raise disaster awareness and resilience targeting European citizens. Simultaneously, the Group of Chief Scientific Advisors (2022) supports the idea of incorporating local knowledge into crisis management. They also emphasize the importance of treating educational facilities as critical infrastructure, recognizing the uninterrupted flow of educational programs across all levels as a vital element of societal resilience, and aim to streamline volunteer initiatives by integrating them with formal organizations.

Several other initiatives prioritise citizens engagement and seek to empower local communities in effectively responding to risks. Some of these initiatives, like the establishment of Citizen Observatories, depart from traditional top-down disaster risk management systems and instead focus on disaster risk governance centred around people. Furthermore, the growing popularity of citizen science in recent years is closely tied to the widespread accessibility of technological tools such as sensors, *apps* and online activities. These tools enable citizens to collect and share data regarding risks drivers and their consequences with researchers and professionals in the field of disaster risk management, as noted by Sousa et al. (2024).

8 Cultural heritage risk management

The recent Guidelines for Disaster Risk Management at European World Heritage Sites (RHA 2023) provide different approaches for assessing risks to cultural heritage sites, which certainly have distinctive characteristics from the methods used with contemporary buildings portfolios. The guide aims to develop a common knowledge base that will

[22] Website of Shakeout drill: https://www.shakeout.org/.

help cultural heritage practitioners bring their perspective to risk management, while also enabling risk managers to effectively consider the specificities of cultural heritage assets. These heritage sites are likely to have stood the test of time and suffered the effects of multiple hazards over long periods of time. They may also have undergone various adaptation processes that contribute to their resilience. Probabilistic risk analysis is included in the realm of the quantitative methodologies discussed. However, they present additional challenges when it comes to incorporating intangible elements inherent in heritage into risk analysis.

RHA (2023) advocates for an integrated approach to risk management that involves the identification, analysis, and management of threats to people, cultural heritage sites, and critical assets. Key features include (i) an all-hazards approach, (ii) consideration of prevention, preparedness, response, and recovery, (iii) recognition of the links between nature and culture, objects and sites, tangible and intangible assets and (iv) consideration of the local context and engagement of local actors. Integrated risk management requires a debate on the value of protecting assets, establishing criteria for prioritization and trade-offs, while at the same time setting clear objectives to guide the risk assessment and selection of management actions, identifying the assets to be protected and the desired level of protection. The assessment of cultural heritage vulnerability should be site and asset specific. Risk management treatments should balance the safety of both assets and visitors, while minimizing disruption to the cultural heritage site. In general, when it comes to cultural heritage interventions, the proposed solutions should adhere to three fundamental principles: they should be reversible, durable in time, feasible (Maio et al. 2018). Additionally, interventions should strive to be minimally disruptive and non-intrusive, align with pre-existing materials and structural systems, favour repair-oriented approaches over demolition and replacement, and employ traditional materials and techniques to the greatest feasible extent.

Other recent publication (Rouhani and Romão 2023) features case studies from across the globe demonstrating that cultural heritage protection and disaster management informed by risk assessments can prevent hazards from escalating into disasters.

9 Conclusions

The research community continually refines models for seismic hazard, vulnerability, and damage-to-loss, which will be integrated into upgraded versions of seismic risk analysis software. While most software tools are user-friendly, their high degree of sophistication requires a certain level of expertise to be operated effectively. In addition, for specific risk assessment studies, these tools may require user-supplied input, which can be costly and time-consuming to obtain.

Regarding risk analysis, sufficiently reliable damage and damage-to-loss models are widely available. It is worth pointing out the considerable uncertainty in estimating casualties, resulting from the wide variability in the number of earthquake victims experiencing similar ground motion, and from the lack of reliability and large gaps in post-earthquake casualties' statistics.

A major gap in seismic risk analysis is the absence of georeferenced exposure data, specifically tailored for evaluating the vulnerability of the built environment at a local scale. Current exposure data predominantly covers residential buildings and are aggregated at a regional level. Ideally, inventories should include a wide range of assets including industrial, commercial, and other structures, such as networks and critical infrastructures, to provide a more accurate and comprehensive risk assessment.

Currently, while earthquake risk is usually assessed in a fully probabilistic manner, most seismic risk studies do not progress beyond the risk analysis phase of the risk management process. In other words, they do not go further than determining the level of risk for a region. In practice, the results of seismic risk analysis are occasionally compared with risk criteria to determine whether seismic risks levels are deemed acceptable or tolerable. As regards seismic risk, the literature is scarce to guide decisions on acceptable or tolerable levels of life or economic losses.

Additional challenges include the development of multi-hazard risk assessment procedures, and the need of coordinated approaches that bridge disaster risk reduction, climate change adaptation and sustainable development.

Author contributions Both authors contributed to the study conception and design. Both authors wrote and commented on previous versions of the manuscript, read, and approved the final manuscript.

Funding The work by Maria Luísa Sousa (LNEC) in this article was financed by the Innovation Pact "R2UTechnologies—modular systems" (C644876810-00000019), by "R2UTechnologies" Consortium, co-financed by NextGeneration EU, through the Incentive System "Agendas para a Inovação Empresarial" ("Agendas for Business Innovation"), within the Recovery and Resilience Plan (PRR). The authors have no relevant financial or non-financial interests to disclose.

Declarations The authors have not disclosed any competing interests.

References

AFPS (2014) Quantification effective du risque sismique, Cahier technique N°32. Association Française du Génie Parasismique

ANCOLD (2003) Guidelines on risk assessment. Australian National Committee on Large Dams, ANCOLD Incorporated

Andredakis I, Proietti C, Fonio C, Annunziato A (2017) Seismic risk assessment tools workshop. Publications Office of the European Union, Luxembourg. https://doi.org/10.2760/249272

Annoni P, Dijkstra L, Hellman T (2016) The EU regional SPI: A measure of social progress in the EU regions. Directorate General for Regional Policy, Brussels

ANPC (2010) Estudo do risco sísmico e de tsunamis do Algarve. Autoridade Nacional de Proteção Civil (in Portuguese)

ATC (1985) Earthquake damage evaluation data for California. Applied Technology Council, Redwood City

Baggio C, Bernardini A, Colozza R, Corazza L, Bella M D, Di Pasquale G, Dolce M., Goretti, A, Martinelli A, Orsini G, Papa F, Zuccaro, G (2007) Field Manual for post-earthquake damage and safety assessment and short term countermeasures (AeDES). Editors: Pinto AV, Taucer F. EUR 22868 1018–5593, Office for Official Publications of the European Communities, Luxembourg.

Baker JW, Lee C (2018) An improved algorithm for selecting ground motions to match a conditional spectrum. J Earthquake Eng 22(4):708–723
Bakhshi Lomer AR, Rezaeian M, Rezaei H, Lorestani A, Mijani N, Mahdad M, Raeisi A, Arsanjani JJ (2023) Optimizing emergency shelter selection in earthquakes using a risk-driven large group decision-making support system. Sustainability. https://doi.org/10.3390/su15054019
Balbi A, Galasco A, Giovinazzi S, Lagomarsino S, Parodi S (2006) Scenario sismico: a tool for real time damage scenarios. In: Proceedings of the 13th world conference on earthquake engineering
Baptista L (2009) Abordagens de riscos em barragens de aterro. Colecção: Teses e Programas de Investigação LNEC, Lisbon, Portugal TPI 59, ISBN 978–972–49–2179–2, http://repositorio.lnec.pt:8080/jspui/handle/123456789/17187 (in Portuguese)
BARPI (2013) Overview of the industrial accidents caused by the great Tohoku Earthquake and tsunami. Bureau for analysis of industrial risks and pollution (BARPI). Ministry of ecology, sustainable development and energy, France. https://www.aria.developpement-durable.gouv.fr/wp-content/files_mf/Overview_japan_mars_2013_GB.pdf
Becker W, Norlén H, Dijkstra L, Athanasoglou S (2020) Wrapping up the Europe 2020 strategy: a multidimensional indicator analysis. Environ Sustain Indicators. https://doi.org/10.1016/j.indic.2020.100075
Bernardini A, Lagomarsino S (2018) The seismic vulnerability of architectural heritage. Proceed t Inst Civil Eng-Struct Build 161(4):171–181. https://doi.org/10.1680/stbu.2008.161.4.171
Bernardo V, Karimzadeh S, Caicedo D, Lourenço PB (2023) Preliminary seismic fragility analysis of a URM building typology in Faial Island – Azores. In: Proceedings of the VII ECCOMAS young investigators conference
Borzi B, Onida M, Faravelli M et al (2021) IRMA platform for the calculation of damages and risks of Italian residential buildings. Bull Earthq Eng 19:3033–3055. https://doi.org/10.1007/s10518-020-00924-x
Bubbico RL, Dijkstra L (2011) The European regional human development and human poverty indices. European Commission, Directorate General for Regional Policy, Brussels Regional Focus No 02
Butenweg C, Gervasio H, Gkatzogias K, Manfredi V, Masi A, Pohoryles D, Tsionis G, Zaharieva R (2022) Policy measures for seismic and energy upgrading of buildings in EU Member States. Publications Office of the European Union, Luxembourg. https://doi.org/10.2760/518982
Campos Costa A, Sousa ML, Carvalho A, Coelho E (2010) Evaluation of seismic risk and mitigation strategies for the existing building stock: application of LNECloss to the metropolitan area of Lisbon. Bull Earthq Eng 8:119–134. https://doi.org/10.1007/s10518-009-9160-3
Cavalieri F, Franchin P, Gehl P, Khazai B (2012) Quantitative assessment of social losses based on physical damage and interaction with infrastructural systems. Earthq Eng Struct Dynam 41(11):1569–1589. https://doi.org/10.1002/eqe.2220
CEN (2004) EN 1998–1:2014 Eurocode 8: Design of structures for earthquake resistance - Part 1: general rules, seismic actions and rules for buildings. European Committee for Standardization (CEN), Brussels
Coburn A, Spence R (2002) Earthquake protection (second edition). Wiley
Correia Lopes G, Silva C, Costa V, Sousa Oliveira C (2024) Advancing the understanding of earthquake risk in Portugal. Bull Earthq Eng 22(11):5379–5401. https://doi.org/10.1007/s10518-024-01975-0
Costa P, Pires P, Vicêncio H. (2012) Study of seismic risk and tsunamis in Algarve. Estimative of debris and number of damage assessment inspectors. In: proceedings of the 15th World Conference on Earthquake Engineering
Cremen G, Galasso C (2021) A decision-making methodology for risk-informed earthquake early warning. Comput-Aided Civil Infrastruct Eng. https://doi.org/10.1111/mice.12670
Crowley H, Despotaki V, Rodrigues D, Silva V, Toma-Danila D, Riga E, Karatzetzou A, Fotopoulou S, Zugic Z, Sousa L, Ozcebe S, Gamba P (2020) Exposure model for European seismic risk assessment. Earthq Spectra 36(S1):252–273. https://doi.org/10.1177/8755293020919429
Crowley H, Weatherill G, Riga E, Pitilakis K, Roullé A, Tourlière B, Lemoine A, Hidalgo CG (2019) D26.4 Methods for Estimating Site Effects in Risk Assessments'. WP26 (JRA4: Risk Modelling Framework for Europa) SERA project
Crowley H, Dabbeek J, Despotaki V, Rodrigues D, Martins L, Silva V, Romão X, Pereira N, Weatherill G, Danciu L (2021a) European seismic risk model (ESRM20). European Facilities for Earthquake Hazard and Risk (EFEHR), Technical Report 002, v.1.0.0. https://doi.org/10.7414/EUC-EFEHR-TR002-ESRM20
Crowley H, Silva V, Martins L, Romão X, Pereira N (2021b) Open models and software for assessing the vulnerability of the European building stock. In: proceedings of the 8th ECCOMAS thematic conference on computational methods in structural dynamics and earthquake engineering.
Cuéllar A, Espinosa-Aranda JM, Suárez R, Ibarrola G, Uribe A, Rodríguez FH, Islas R, Rodríguez GM, García A (2014) The Mexican seismic alert system (SASMEX): its alert signals, broadcast results

and performance during the M 7.4 Punta Maldonado earthquake of March 20th, 2012. In: Wenzel F, Zschau J (eds) Early warning for geological disasters. Advanced technologies in earth sciences. Springer

CUREE (2009) Nonstructural earthquake damage. Richmond: consortium of universities for research in earthquake engineering (CUREE)

D'Ayala D, Meslem A, Vamvatsikos D, Porter K, Rossetto T, Silva V (2015) Guidelines for analytical vulnerability assessment of low/mid-rise buildings. Vulnerabil Global Compon Project. https://doi.org/10.13117/GEM.VULN-MOD.TR32014.12

Danciu L, Nandan S, Reyes C, Basili R, Weatherill G, Beauval C, Rovida A, Vilanova S, Sesetyan K, Bard P-Y, Cotton F, Wiemer S, Giardini D. (2021) The 2020 update of the European Seismic Hazard Model: Model Overview. EFEHR Technical Report 001, v1.0.0, https://doi.org/10.12686/a15

European Commission (2023b) Strategic Foresight Report 2023 'Sustainability and people's wellbeing at the heart of Europe's Open Strategic Autonomy'.Publications Office of the European Union, Luxembourg. https://doi.org/10.2792/32296

European Commission (2021) Overview of natural and man-made disaster risks the European Union may face. Publications Office of the European Union, Luxembourg. https://doi.org/10.2795/1521

De Martino G, Di Ludovico M, Prota A, Moroni C, Manfredi G, Dolce M (2017) Estimation of repair costs for RC and masonry residential buildings based on damage data collected by post-earthquake visual inspection. Bull Earthq Eng 15(4):1681–1706. https://doi.org/10.1007/s10518-016-0039-9

Despotaki V, Silva V, Lagomarsino S, Pavlova I (2018) Torres J (2018) Evaluation of seismic risk on UNESCO cultural heritage sites in Europe. Int J Architect Heritage. https://doi.org/10.1080/15583058.2018.1503374

DGPCE (2015) Análisis de riesgos de desastres en España. Dirección General de Protección Civil y Emergencias

Dolce M, Prota A, Borzi B et al (2021) Seismic risk assessment of residential buildings in Italy. Bull Earthq Eng 19:2999–3032. https://doi.org/10.1007/s10518-020-01009-5

Dolce M, Manfredi G (2015) Libro bianco sulla ricostruzione privata fuori dai centri storici nei comuni colpiti dal sisma dell'Abruzzo del 6 Aprile 2009. Doppiavoce Edizioni

DPC (2018) National risk assessment. Overview of the potential major disasters in Italy: seismic, volcanic, tsunami, hydro-geological/hydraulic and extreme weather, droughts and forest fire risks. Presidency of the Council of Ministers, Italian Civil Protection Department

Earle PS, Wald DJ, Jaiswal KS, Allen TI, Hearne MG, Marano KD, Hotovec AJ, Fee JM (2009) Prompt Assessment of Global Earthquakes for Response (PAGER): a system for rapidly determining the impact of earthquakes worldwide: U.S. Geological Survey Open-File Report 2009–1131

EERI (2000) Financial management of earthquake risk. EERI endowment subcommittee on financial risk management

EIOPA (2022) The dashboard on insurance protection gap for natural catastrophes in a nutshell. EIOPA-22/507, European Insurance and Occupational Pensions Authority

Erdik M, Şeşetyan K, Demircioğlu MB, Hancılar U, Zülfikar C (2011) Rapid earthquake loss assessment after damaging earthquakes. Soil Dyn Earthq Eng 31(2):247–266. https://doi.org/10.1016/j.soildyn.2010.03.009

European Commission (2023a) Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions – European Union disaster resilience goals: Acting together to deal with future emergencies, COM(2023) 61 final

European Commission (2016) Commission Staff Working Document (SWD): action plan on the Sendai framework for disaster risk reduction 2015–2030 – A disaster risk-informed approach for all EU policies, 205 final

FEMA (2004b) Are you ready? An in-depth guide to citizen preparedness. Federal Emergency Management Agency, Washington DC

FEMA (2004a) Nonstructural Earthquake Mitigation Guidness Manual. Final Report. Washington DC: Federal Emergency Management Agency

FEMA (2005) Earthquake hazard mitigation for nonstructural elements. FEMA 74-FM. Washington DC: Federal Emergency Management Agency

FEMA (2012) Reducing the risks of nonstructural earthquake damage – a practical guide. FEMA E-74. Washington DC: Federal Emergency Management Agency

FEMA (2017) P-366, Hazus®. Estimated annualized earthquake losses for the United States. Washington DC: Federal Emergency Management Agency

FEMA (2018) Multi-hazard loss estimation methodology earthquake model Hazus®–MH 2.1 user manual. Washington DC: Federal Emergency Management Agency

FEMA (2022) Hazus Earthquake Model User Guidance. Hazus 5.1. Washington DC: Federal Emergency Management Agency
FERC (2016) Risk-informed decision-making (RIDM). Risk guidelines for dam safety, Version 4.1. Federal Energy Regulatory Commission Office of Energy Projects - Division of Dam Safety and Inspections, USA
Freddi F, Galasso C, Cremen G, Dall' Asta A, Di Sarno L, Giaralis A, Gutiérrez-Urzúa F, Málaga-Chuquitaype C, Mitoulis SA, Petrone C, Sextos A, Sousa L, Tarbali K, Tubaldi E, Wardman J, Woo G (2021) Innovations in earthquake risk reduction for resilience: Recent advances and challenges. Int J Disaster Risk Reduc. https://doi.org/10.1016/j.ijdrr.2021.102267
Fujinawa Y, Noda Y (2013) Japan's earthquake early warning system on 11 March 2011: performance, shortcomings, and changes. Earthq Spectra 29(1_suppl):341–368. https://doi.org/10.1193/1.4000127
Giovinazzi S, Marchili C, Di Pietro A, Giordano L, Costanzo A, La Porta L, Pollino M, Rosato V, Lückerath D, Milde K, Ullrich O (2021) Assessing earthquake impacts and monitoring resilience of historic areas: methods for GIS tools. ISPRS Int J Geo-Inform. https://doi.org/10.3390/ijgi10070461
Gkatzogias K, Crowley H, Veljkovic A, Pohoryles D, Norlén H, Tsionis G, Bournas D (2022a) Prioritising EU regions for building renovation: seismic risk, energy efficiency, socioeconomic vulnerability. Publications Office of the European Union, Luxembourg. https://doi.org/10.2760/263803
Gkatzogias K, Crowley H, Veljkovic A, Pohoryles D, Tsionis G, Bournas D (2022b) Building renovation in the EU: scenarios and impact assessment. Publications Office of the European Union, Luxembourg. https://doi.org/10.2760/04574
Gobbato M, Yeo WM, Shome N (2014) Uncertainty quantification and sensitivity analysis of earthquake casualties. In: NCEE 2014 - 10th U.S. National conference on Earthquake Engineering: Frontiers of Earthquake Engineering. https://doi.org/10.4231/D3639K592
Gotoh T, Nishimura T, Nakata M, Nakaguchi Y, Hiraki K (2002) Air pollution by concrete dust from the great Hanshin earthquake. J Environ Qual 31(3):718–723. https://doi.org/10.2134/jeq2002.7180
Group of Chief Scientific Advisors (2022) Strategic crisis management in the EU. European Commission. Luxembourg: Publications Office of the European Union. https://doi.org/10.2777/517560
Guérin-Marthe S, Gehl P, Negulescu C, Auclair S, Fayjaloun R (2021) Rapid earthquake response: The state-of-the art and recommendations with a focus on European systems. Int J Disaster Risk Reduc 52:101958. https://doi.org/10.1016/j.ijdrr.2020.101958
Gunasekera R, Ishizawa Escudero OA, Daniell JE, Pomonis A, Macabuag JLDC, Brand J, Schaefer A, Romero Hernandez RA, Esper S, Otálora SG, Khazai B, Cox KD (2023) Global Rapid Post-Disaster Damage Estimation (GRADE) report: February 6, 2023 Kahramanmaraş Earthquakes - Türkiye Report (English). World Bank Group, Washington, D.C. http://documents.worldbank.org/curated/en/099022723021250141/P1788430aeb62f08009b2302bd4074030fb
Hancilar U, Sesetyan K, Cakti E, Safak E, Acikgoz N, Yenihayat N, Malcioglu FS, Donmez K, Tetik T, Suleyman H, Dede S, Acar S (2023) Rapid Estimation of Strong Ground Motion, Building Damage Distributions and the Recovery Efforts in the Aftermath of the Kahramanmaraş-Türkiye M7.7 Earthquake, 6 February 2023. Personnal communication to the 2023 EPOS Seismology Workshop Next-Generation Open Seismological Data Sharing for Science and Society 9 – 11 October 2023 Podgorica, Montenegro
Hill LJ, Sparks S, Rougier J (2013) Risk and uncertainty assessment in natural hazards. In: Sparks S, Hill LJ (eds) Rougier J. Cambridge University Press, Risk and uncertainty for natural hazards
Hingorani R, Tanner P, Prieto M, Lara C (2020) Consequence classes and associated models for predicting loss of life in collapse of building structures. Struct Saf. https://doi.org/10.1016/j.strusafe.2019.101910
HSE (2001) Reducing risks protecting people. HSE's decision-making process. ISBN 0 7176 2151 0, Crown
ISO (2018) 31000:2018 – ISO 31000 Risk management - Guidelines. International Organization for Standardization
Jaiswal K, Wald D (2012) Improving PAGER's real-time earthquake casualty and loss estimation toolkit: challenges. In: proceedings of the 15th world conference on earthquake engineering
Jaiswal K, Wald D, Hearne M (2009) Estimating casualties for large earthquakes worldwide using an empirical approach. Open-File Report 2009–1136, U.S. Department of the Interior, U.S. Geological Survey
Jia H, Lin J, Liu J (2019) An earthquake fatalities assessment method based on feature importance with deep learning and random forest models. Sustainability. https://doi.org/10.3390/su11102727
Jones LM and Benthien M (2011) Putting down roots in earthquake country. Southern California Earthquake Center at the University of Southern California (SCSEC), Department of the Interior United States Geological Survey (USGS), National Science Foundation (NSF), Department of Homeland

Security Federal, Emergency Management Agency (FEMA), and the California Earthquake Authority (CEA)
Kharazian A, Molina S, Galiana-Merino JJ et al (2021) Risk-targeted hazard maps for Spain. Bull Earthq Eng 19:5369–5389. https://doi.org/10.1007/s10518-021-01189-8
Khazai B, Franco G, Ingram JC, Rumbaitis del Rio C, Dias P, Dissanayake R, Chandratilake R, Kannaf SJ (2006) Post-December 2004 tsunami reconstruction in Sri Lanka and its potential impacts on future vulnerability. Earthq Spectra 22(S3):S829–S844. https://doi.org/10.1193/1.2204925
Khazai B, Daniell JE, Düzgün S, Kunz-Plapp T, Wenzer F (2014) Framework for systemic socio-economic vulnerability and loss assessment. In: Pitilakis K, Franchin P, Khazai B, Wenzel H (eds) SYNER-G: Systemic seismic vulnerability and risk assessment of complex urban, utility, lifeline systems and critical facilities. Springer, Dordrecht
Khorasani NE, Garlock ME (2017) Overview of fire following earthquake: historical events and community responses. Int J Disaster Resilience Built Environ 8:158–174
Lehman D, Moehle J, Mahin S, Calderone A, Henry L (2004) Experimental evaluation of the seismic performance of reinforced concrete bridge columns. ASCE J Struct Engneering 130(6):869–879. https://doi.org/10.1061/(ASCE)0733-9445(2004)130:6(869)
Lin WT, Lin CY, Tsai JS, Huang PH (2008) Eco-environmental changes assessment at the Chiufenershan landslide area caused by catastrophic earthquake in Central Taiwan. Ecol Eng 33(3–4):220–232. https://doi.org/10.1016/j.ecoleng.2008.04.002
Mackie KR, Stojadinović B (2006) Post-earthquake functionality of highway overpass bridges. Earthq Eng Struct Dynam 35(1):77–93. https://doi.org/10.1002/eqe.534
Maio R, Ferreira TM, Vicente R (2018) A critical discussion on the earthquake risk mitigation of urban cultural heritage assets. Int J Disaster Risk Reduc 27(2018):239–247
Maio R, Tsionis G, Sousa ML, Dimova S (2017) Review of fragility curves for seismic risk assessment of buildings in Europe. In: proceedings of the 16th world conference on earthquake engineering
Makhoul N, Argyroudis S (2018) Loss estimation software: developments, limitations and future needs. In: Proceedings of the 16th European Conference on Earthquake Engineering
Markhvida M, Walsh B, Hallegatte S, Baker J (2020) Quantification of disaster impacts through household well-being losses. Nat Sustain 3:538–547. https://doi.org/10.1038/s41893-020-0508-7
Marques M, Monteiro R, Delgado R (2018) An improved model for seismic risk assessment in Portugal. Int J Disaster Resilience Built Environ 9(1):70–83. https://doi.org/10.1108/IJDRBE-10-2016-0040
Marti M, Dallo I, Roth P, Papadopoulos AN, Zaugg S (2023) Illustrating the impact of earthquakes: Evidence-based and user-centered recommendations on how to design earthquake scenarios and rapid impact assessments. Int J Disaster Risk Reduc 90:103674. https://doi.org/10.1016/j.ijdrr.2023.103674
Martins L, Silva V, Marques M, Crowley H, Delgado R (2016) Development and assessment of damage-to-loss models for moment-frame reinforced concrete buildings. Earthq Eng Struct Dynam 45(5):797–817. https://doi.org/10.1002/eqe.2687
Martins L, Silva V, Crowley H, Cavalieri F (2021) Vulnerability modellers toolkit, an open-source platform for vulnerability analysis. Bull Earthq Eng 19:5691–5709. https://doi.org/10.1007/s10518-021-01187-w
Masi A, Lagomarsino S, Dolce M, Mnfredi V, Otonelli D (2021) Towards the updated Italian seismic risk assessment: exposure and vulnerability modelling. Bull Earthquake Eng 19:3253–3286. https://doi.org/10.1007/s10518-021-01065-5
Mesa-Gómez A, Casal J, Muñoz F (2020) Risk analysis in Natech events: State of the art. J Loss Prev Process Industries. https://doi.org/10.1016/j.jlp.2020.104071
Midorikawa, S., Abe, S. (2000) Real-time assessment of earthquake disaster in Yokohama based on dense strong-motion network. In: proceedings of the 12th world conference on earthquake engineering
Monti G, Demartino C, Gardoni P (2023) Towards risk-targeted seismic hazard models for Europe. Sci Rep 13:10717. https://doi.org/10.1038/s41598-023-36947-y
Murty CVR, Rupen Goswami, Vijayanarayanan AR, Pradeep Kumar R, Vipul VM (2012) Introduction to Earthquake Protection of Non-Structural Elements in Buildings. Gujarat State Disaster Management Authority. Government of Gujarat
Mysiak J, Casartelli V, Torresan S (2021) Union Civil Protection Mechanism - Peer Review Programme for disaster risk management: Assessment Framework
Necci A, Krausmann E (2022) Natech risk management – Guidance for operators of hazardous industrial sites and for national authorities. Publications Office of the European Union, Luxembourg. https://doi.org/10.2760/666413

Decision No 1313/2013/EU (2013) Decision No 1313/2013/EU of the European Parliament and of the Council of 17 December 2013 on a Union Civil Protection Mechanism. Official Journal of the European Union, L 347/924

OECD (2018) Financial Management of Earthquake Risk, www.oecd.org/finance/Financial-Management-of-Earthquake-Risk.htm

Palermo V, Tsionis G, Sousa ML (2018) Building stock inventory to assess seismic vulnerability across Europe. In: proceedings of the 16th European conference on earthquake engineering

Paolacci F, Butenweg C, Vamvatsikos D (2024) SI: Natech risk assessment of hazardous facilities. Bull Earthquake Eng 22:1–4. https://doi.org/10.1007/s10518-023-01799-4

Petal M (2003) NSM Non-structural risk mitigation – Handbook. Istanbul: Disaster Preparedness Education Project

Pitilakis K, Crowley H, Kaynia A (2014) SYNER-G: Typology definition and fragility functions for physical elements at seismic risk. Springer

Poljanšek K, Casajus Valles A, Marin Ferrer M, Artes Vivancos T, Boc, R, Bonadonna C, Branco A, Campanharo W, De Jage, A, De Rigo D, Dottori F, Durrant Houston T, Estreguil C, Ferrari D, Frischknecht C, Galbusera L, Garcia Puerta B, Giannopoulos G, Girgin S, Gowland R, Grecchi R, Hernandez Ceballos MA, Iurlaro G, Kambourakis G, Karlos V, Krausmann E, Larcher M, Lequarre AS, Liberta` G, Loughlin SC, Maianti P, Mangione D, Marques A, Menoni S, Montero Prieto M, Naumann G, Jacome Felix Oom D, Pfieffer H, Robuchon M, Necci A, Salamon P, San-Miguel-Ayanz J, Sangiorgi M, Sousa ML, Theocharidou M, Trueba Alonso C, Theodoridis G, Tsionis G, Vogt J, Wood M (2021) Recommendations for national risk assessment for disaster risk management in EU: where science and policy meet (version 1). Publications Office of the European Union, Luxembourg. https://doi.org/10.2760/80545

Porter KA, Jaiswal KS, Wald DJ, Earle PS, Hearne M (2008) Fatality models for the U.S. Geological survey's prompt assessment of global earthquakes for response (PAGER) system. In: proceedings of the 14th world conference on earthquake engineering

Ranghieri F, Ishiwatari M (eds) (2014) Learning from megadisasters: lessons from the great East Japan earthquake. The World Bank, Washington, DC

Regulation (EU) 2021/836 (2021) of the European Parliament and of the Council of 20 May 2021 amending Decision No 1313/2013/EU on a Union Civil Protection Mechanism. Official Journal of the European Union, L 185/1

Reinoso E, Jaimes MA, Esteva L (2017) Estimation of life vulnerability inside buildings during earthquakes. Struct Infrastruct Eng 14:1140–1152. https://doi.org/10.1080/15732479.2017.1401097

RHA (2023) Resilience and cultural heritage in urban development. Guidance Paper on Integrated Risk Management. RHA - Reicher Haase Assoziierte GmbH, Aachen/Dortmund, Editor. Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR) within the Federal Office for Building and Regional Planning, Bonn. ISBN 978–3–98655–024–0

Ribeiro F, Sousa ML, Silva D, Vicente M, Correia AA, Carvalho A (2023) Increasing earthquake resilience in Almada, Portugal, through public partnerships. Submitted to the 18th world conference on earthquake engineering

Romão X, Castro JM, Pereira N et al (2019) European physical vulnerability models. SERA Deliver 26:5

Romão X, Pereira N, Castro J et al (2021) European building vulnerability data repository (version 2.1), Zenodo, https://doi.org/10.5281/zenodo.408781

Rossetto T, D'Ayala D, Ioannou I, Meslem A (2014) Evaluation of existing fragility curves. In: Pitilakis K, Crowley H, Kaynia AM (eds) SYNER-G: Typology definition and fragility functions for physical elements at seismic risk. Springer, Dordrecht

Rouhani B, Romão X Editors (2023) Managing Disaster Risks to Cultural Heritage ISBN 9781032204536, Routledge, Taylor & Francis Group

Sabetta F, Pugliese A, Fiorentino G, Lanzano G, Luzi L (2021) Simulation of non-stationary stochastic ground motions based on recent Italian earthquakes. Bull Earthq Eng 19:3287–3315. https://doi.org/10.1007/s10518-021-01077-1

Sakai S, Poudel R, Asari M, Kirikawa T (2019) Disaster waste management after the 2016 Kumamoto earthquake: a mini-review of earthquake waste management and the Kumamoto experience. Waste Manage Res 37(3):247–260. https://doi.org/10.1177/0734242X188159

Santarelli S, Bernardini G, Quagliarini E (2018) Earthquake building debris estimation in historic city centres: from real world data to experimental-based criteria. Int J Disaster Risk Reduc 31:281–291. https://doi.org/10.1016/j.ijdrr.2018.05.017

Shimizu, Y, Yamazaki, F, Isoyama, R, Ishida, E, Koganemaru, K., Nakayama, W. (2004) Development of real time disaster mitigation system for urban gas supply network. In: proceedings of the 13th world conference on earthquake engineering

Silva V, Crowley H, Varum H, Pinho R (2014) Seismic risk assessment for mainland Portugal. Bull Earthq Eng 13(2):1–29. https://doi.org/10.1007/s10518-014-9630-0

Silva V, Dolce M, Danciu L, Rossetto T, Weatherill G (2017) Geophysical risk: earthquakes. In: Poljanšek K, Marin Ferrer M, De Groeve T, Clark I (eds) Science for disaster risk management 2017: knowing better and losing less. Publications Office of the European Union, Luxembourg, 2017. https://doi.org/10.2788/842809

Silva V, Amo-Oduro D, Calderon A, Dabbeek J, Despotaki V, Martins L, Rao A, Simionato M, Viganò D, Yepes C, Acevedo A, Horspool N, Crowley H, Jaiswal K, Journeay M, Pittore M (2018) Global Earthquake Model (GEM) Seismic Risk Map (version 2018.1). https://doi.org/10.13117/GEM-GLOBAL-SEISMIC-RISK-MAP-2018.1

So E, Pomonis A (2012) Derivation of globally applicable casualty rates for use in earthquake loss estimation models. In: Proceedings of the 15th world conference on earthquake engineering

So E, Spence R (2013) Estimating shaking-induced casualties and building damage for global earthquake events: a proposed modelling approach. Bull Earthq Eng 11(1):347–363. https://doi.org/10.1007/s10518-012-9373-8

Solares JM, Arroyo A (2004) The great historical 1755 earthquake. Effects and damage in Spain. J Seismolog 8:275–294. https://doi.org/10.1023/B:JOSE.0000021365.94606.03

Sousa ML, Campos Costa A (2009) Ground motion scenarios consistent with probabilistic seismic hazard disaggregation analysis. Application to mainland Portugal. Bull Earthq Eng 7(1):127–147. https://doi.org/10.1007/s10518-008-9088-z

Sousa ML, Campos Costa A (2015) Evolution of earthquake losses in Portuguese residential building stock. Bull Earthq Eng 14(7):2009–2029. https://doi.org/10.1007/s10518-015-9809-z

Sousa ML, Campos Costa A, Caldeira L (2010a) Apreciação do risco sísmico em Lisboa'. Revista Portuguesa de Engenharia de Estruturas (RPEE). Thematic number on risks. Lisbon. Portugal

Sousa ML, Carvalho A, Bilé Serra JP, Martins A (2010b) Simulation of seismic scenarios in Algarve region. In: Proceedings of the 14th European conference on earthquake engineering

Sousa, ML, Tsionis, G, Dimova, S (2017) Effect of the detail of exposure data in large-scale seismic risk assessment". Paper n° 4096, In: proceedings of the 16th European conference on earthquake engineering

Sousa ML, Carreto J, Sousa Silva D, Roque AJ, Bilé Serra J, Caldeira L, Jeremias FT, Ramos R (2024) Citizens Observatories: a tool to improve geohazards risk management and community resilience. In: proceedings of the 18th World Conference on Earthquake Engineering

Spence R, So E, Scawthorn C (2011) Human casualties in earthquakes: progress in modelling and mitigation. Springer

Spence R (2007) LESSLOSS Report 2007/07: Earthquake disaster scenario predictions and loss modelling for urban areas

Stojadinovic B (2016) Development of a coherent definition of societal resilience and its attributes. Deliverable D4.5, WP4 Vulnerability models for the performance and consequences assessment in stress tests of critical infrastructures, FP7 project STREST

Türkiye government (2023) 2023 Kahramanmaraş and Hatay earthquakes report. Türkiye Cumhuriyeti Chumhurbaşkanliği. Strateji ve Bütçe Başkanliği

UNDRR (2016) Report of the open-ended intergovernmental expert working group on indicators and terminology relating to disaster risk reduction. United Nations General Assembly Seventy-first session, A/71/644. https://www.undrr.org/we/inform/publications/51748

UNDRR (2020) The human cost of disasters: an overview of the last 20 years (2000–2019)

Vecere A, Monteiro R, Ammann WJ, Giovinazzi S, Melo Santos RH (2017) Predictive models for post disaster shelter needs assessment. Int J Disaster Risk Reduc 21:44–62. https://doi.org/10.1016/j.ijdrr.2016.11.010

Vlachos C, Papakonstantinou KG, Deodatis G (2018) Predictive model for site specific simulation of ground motions based on earthquake scenarios. Earthq Eng Struct Dynam 47:195–218

Wang C, Costa R, Baker JW (2022) Simulating post-disaster temporary housing needs for displaced households and out-of-town contractors. Earthq Spectra 38(4):2922–2940. https://doi.org/10.1177/87552930221112690

Wehner M, Edwards M (2013) Building replacement cost methodology, version 2.0. Report produced in the context of the Global Exposure Database for the Global Earthquake Model (GED4GEM), Geoscience Australia

World Bank Group and European Commission (2021) Economics for disaster prevention and preparedness. Summary report. Investment in disaster risk management in Europe makes economic sense. International Bank for Reconstruction and Development / The World Bank. https://www.worldbank.org/en/news/feature/2021/06/04/economics-for-disaster-prevention-and-preparedness-in-europe

Xiao J, Deng Q, Hou M, Shen J, Gencel O (2023) Where are demolition wastes going: reflection and analysis of the February 6, 2023 earthquake disaster in Turkey. Low-Carbon Materials and Green Construction. https://doi.org/10.1007/s44242-023-00017-3

Xie Y, Ebad Sichani M, Padgett JE, DesRoches R (2020) The promise of implementing machine learning in earthquake engineering: a state-of-the-art review. Earthq Spectra 36(4):1769–1801. https://doi.org/10.1177/8755293020919419

Yepes-Estrada C, Silva V, Rossetto T, D'Ayala D, Ioannou I, Meslem A, Crowley H (2016) The Global Earthquake Model physical vulnerability database. Earthq Spectra 32(4):2567–2585

Zhao X, Coates G, Xu W (2019) A hierarchical mathematical model of the earthquake shelter location-allocation problem solved using an interleaved MPSO–GA. Geomat Nat Haz Risk 10(1):1712–1737. https://doi.org/10.1080/19475705.2019.1609605

Zuccaro G, Cacace F (2011) Seismic casualty evaluation: the Italian model, an application to the L'Aquila 2009 event. In: Spence R, So E, Scawthorn C (eds) Human casualties in earthquakes, advances in natural and technological hazards research. Springer