

Pan-European seismic risk assessment: a proof of concept using the Earthquake Loss Estimation Routine (ELER)

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Abstract One of the key objectives of the new EU civil protection mechanism is an enhanced understanding of risks the EU is facing. Developing a European perspective may create significant opportunities of successfully combining resources for the common objective of preventing and mitigating shared risks. Risk assessments and mapping represent the first step in these preventive efforts. The EU is facing an increasing number of natural disasters. Among them earthquakes are the second deadliest after extreme temperatures. A better-shared understanding of where seismic risk lies in the EU is useful to identify which regions are most at risk and where more detailed seismic risk assessments are needed. In that scope, seismic risk assessment models at a pan-European level have a great potential in obtaining an overview of the expected human and economic losses using a homogeneous quantitative approach and harmonized datasets. This study strives to demonstrate the feasibility of performing a seismic risk assessment at a pan-European level with an open access methodology and using open datasets available across the EU. It also aims at highlighting the challenges and needs in datasets and the information gaps for a consistent assessment of seismic risk at the pan-European level. Results are expressed as expected casualties and economic losses for a return period of 475-year. The study constitutes a “proof of concept” that can complement the information provided by Member States in their National Risk Assessments. Its main contribution lies in pooling open-access data from different sources in a homogeneous format, which could serve as baseline data for performing more in depth risk assessments in Europe.

Keywords Intensity based damage and casualty estimation · Risk assessment · Economic loss · 28 EU countries

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1 Introduction

Earthquakes are the second deadliest natural events after extreme temperatures causing more than 33,000 deaths and 62 billion Euros worth of damage (source: EMDAT¹) in Europe over the 35-year period between 1980 and 2014. They represent a societal challenge particularly in the Euro-Mediterranean region as well as globally necessitating practical and operational solution for mitigating risk and reducing losses. This is achievable through earthquake risk assessment.

Earthquake risk assessment is considered here as the likelihood of human and economic losses resulting from the exposure and the vulnerability to seismic hazard. Human losses are usually measured in terms of expected casualties (deaths and injuries), while economic losses are measured in terms of direct economic loss (repair and replacement costs) and indirect economic loss (declines in output or revenue as a consequence of direct economic loss or disaster impacts). This definition implies that the evaluation of earthquake risk is dependent on three components: (i) the earthquake hazard, (ii) the inventory of assets at risk (i.e. human and physical exposure) and (iii) the vulnerability of the exposed assets to seismic hazard. Hence, earthquake risk assessment is a complex exercise involving the assimilation of geological, seismological, engineering, demographic and economic data within a risk assessment model.

The knowledge and understanding of seismic hazard and risk has advanced through a number of projects with European and global scope. The Global Seismic Hazard Assessment Program (GSHAP) (Giardini et al. 1999) is the first global hazard map of peak ground acceleration for a return period of 475-year. Recently, in the framework of the Global Assessment Report (GAR) 2015 (UNISDR 2015), a fully probabilistic seismic hazard assessment at global level was developed and used for a probabilistic risk assessment estimating the order of magnitude of potential losses.

At the European level, several initiatives have focussed on different components of seismic risk. The SHARE project (2009–2013) delivered a European wide probabilistic seismic hazard assessment. The project produced more than sixty time-independent European Seismic Hazard Maps (ESHMs) spanning spectral ordinates from PGA to 10 s and yearly exceedance probabilities ranging from 10^{-1} to 10^{-4} . The SYNER-G project (2009–2013) developed an innovative methodological framework for the systemic assessment of physical as well as socio-economic seismic vulnerability at urban and regional level (Pitilakis et al. 2013). The NERA project (2010–2014) aimed at integration seismic and engineering infrastructures to establish an effective network of European research infrastructures for earthquake risk assessment and mitigation. Building on past-achievements, the project identified key players in European building inventory collection and summarized the state-of-the-art knowledge of building inventory data in Europe. RISK-UE project (2001–2004) (Mouroux and Brun 2006) involved the assessment of earthquake scenarios based on the analysis of the global impact of one or more plausible earthquakes at city scale, within a European context (Mouroux and Brun 2006). A comprehensive building type classification for Europe that incorporated the characteristic features of the European building taxonomy was also developed in that project.

In terms of seismic risk, the fully probabilistic seismic risk assessment produced as part of the GAR 2015 is the first example of globally, publically available information on loss

¹ <http://www.emdat.be/database>—The economic and human losses reported here may be underestimated due to the fact that EMDAT database focuses on the response phase of the disaster management by considering losses reported within three months after the event.

levels determined for five return periods (250, 475, 975, 1500 and 2475-year) and on Average Annual Loss (AAL) calculated for each country. Another outcome from the analysis in the GAR is the estimation of the Probable Maximum Loss (PML), which corresponds to the maximum losses associated to each of the defined return periods. The GAR 2015 is the first of its kind to provide worldwide coverage of risk assessments for multiple hazards. The earthquake risk was calculated within the CAPRA-GIS platform, which is the risk-modelling tool of the CAPRA suite. The AAL values produced as part of the GAR 2015 were derived from proxies and expert judgment in cases where empirical data was absent. Hence, the results of the global seismic risk assessment are very sensitive to most of the variations in the input data and to the modelling assumptions and cannot be considered or exploited at local scale.

Despite all the previously cited EU projects and the wealth of knowledge and data generated by research in the field of seismic risk, none of the initiatives succeeded in assessing seismic risk at the European level. A possible explanation could be related to the challenges in combining different datasets with different formats and levels of details. In addition, to the heterogeneity in the dataset, the availability of exposure data including the value of the exposed assets remains a critical information gap.

1.1 Objective of the study

The new EU civil protection mechanism² calls for an enhanced understanding of risks over the EU territory. This is the basis for a more effective disaster management and a starting point for developing contingency plans for a collective European response to major disasters. Risk assessment is “the building block” for developing strategic activities of disaster risk management. It requires the use of reliable methods, which can provide quantitative estimations of individual and coupled risks.

At present, the ranking of the typologies of risks affecting the EU can hardly be made because the available scenarios and risk assessment in general are often qualitative or semi-qualitative (e.g. ESPON project); they are related to one reference event and rarely account for the related uncertainties. “Moreover different types of risks (as volcanic, fast mass movements, floods, earthquakes) are often estimated using different procedures so that the produced results are not comparable” (Marzocchi et al. 2009). In addition to the possibility of comparing risks from multiple hazards, risk assessment models can help (i) evaluating the amount of acceptable loss; (ii) assessing the necessary investments in disaster risk reduction measures (e.g. structural retrofitting); (iii) tracking risk-based loss information; and (iv) measuring progress against targets set out in the Sendai Framework for Disaster Risk Reduction (Corbane et al. 2015).

In an overview of disaster risks in the EU (European Commission 2014) based on National Risk Assessment reports provided by 18 Member States in the context of the new Civil Protection Mechanism legislation (Art.5), 9 countries have identified seismic hazards and their socio-economic impacts as a great concern (i.e. Bulgaria, Cyprus, Czech Republic, Germany, Greece, Hungary, Italy, Romania, and Slovenia). By their very nature, earthquakes are unpredictable hazards that occur irrespective of national borders. The cross-border dimension of the earthquake risk is correlated to the exposure of areas along the fault lines in the Eastern Mediterranean and the Black Sea regions. A better shared understanding of where seismic risk lies in the EU is useful to identify which regions are

² 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), 20.12.2013.

most at risk and where more detailed seismic risk assessments are needed. In that scope, seismic risk assessment models at a pan-European level have a great potential in obtaining an overview of the expected economic and human losses using a homogeneous quantitative approach and harmonized datasets.

This study strives to demonstrate the feasibility of performing a seismic risk assessment that is conditional on the ground motion resulting from probabilistic hazard analysis for a return period of 475-year at a pan-European level with an open access methodology and using open datasets available across the EU. The results of this work are not meant to support decision-making nor for establishing inter-country comparisons of seismic risk. Their main purpose is to assess the possibility of performing a seismic risk assessment with advanced methods and datasets that could help in drawing attention to the areas where necessary refinements are required.

2 The risk assessment methodology

The choice of an approach will depend on the purpose of the seismic risk assessment: financial planning of earthquake losses, disaster risk mitigation, retrofit design, etc. Other factors enter into modelling choices such as data availability and data access, the degrees of complexity and usability and whether the software packages are proprietary, open-access or open-source.

At the time of writing, the most up-to-date and comprehensive seismic hazard model across Europe was the one provided in the context of the SHARE project. The project delivered a European wide probabilistic seismic hazard assessment (Woessner et al. 2015). The new reference European Seismic Hazard Map (Fig. 1) displays the ground shaking (i.e. Peak Ground Acceleration) to be reached or exceeded with a 10 % probability in 50 years, corresponding to an average recurrence of such ground motions every 475-year, as prescribed by the national building codes in Europe for standard buildings (although some countries do not use this return period for building codes, e.g. Spain). The values of expected ground shaking are in many areas higher than previously estimated and reach over 0.5 g (“g” standing for gravitational acceleration) in the areas of highest seismicity. It is noted that due to its statistical nature the map shows mean values meaning that uncertainties exist and that higher ground motions are possible at each location on the map. The uncertainty varies with location and arises from the uncertainty in the data and modeling approach used.

Hence, the natural choice was to perform the pan-European seismic risk assessment using the results from SHARE project, taking stock of experiences and knowledge and building on the outcomes of previous EU projects.

Regarding the modelling and analysis tools, some available open access state-of-the-art software packages tailored for earthquake risk assessment are: CAPRA GIS- Earthquake module, EQRM, HAZUS-MH earthquake module, InaSafe-Earthquake, MAEviz/mHARP, OpenQuake, ELER, RiskScape-Earthquake, SELENA. The CAPRA-GIS risk-modelling tool used for conducting the Global Risk Assessment as a contribution to the 2015 GAR was considered as a potential platform for the present study. However, at the current state the platform cannot accommodate external hazard data and thus not used in this analysis. In fact, we attempted to input the hazard data obtained from the SHARE project in the form of AME objects (formed by a collection of possible scenarios of occurrence of seismic hazard) but unsuccessfully as confirmed by the developers of CAPRA-GIS.

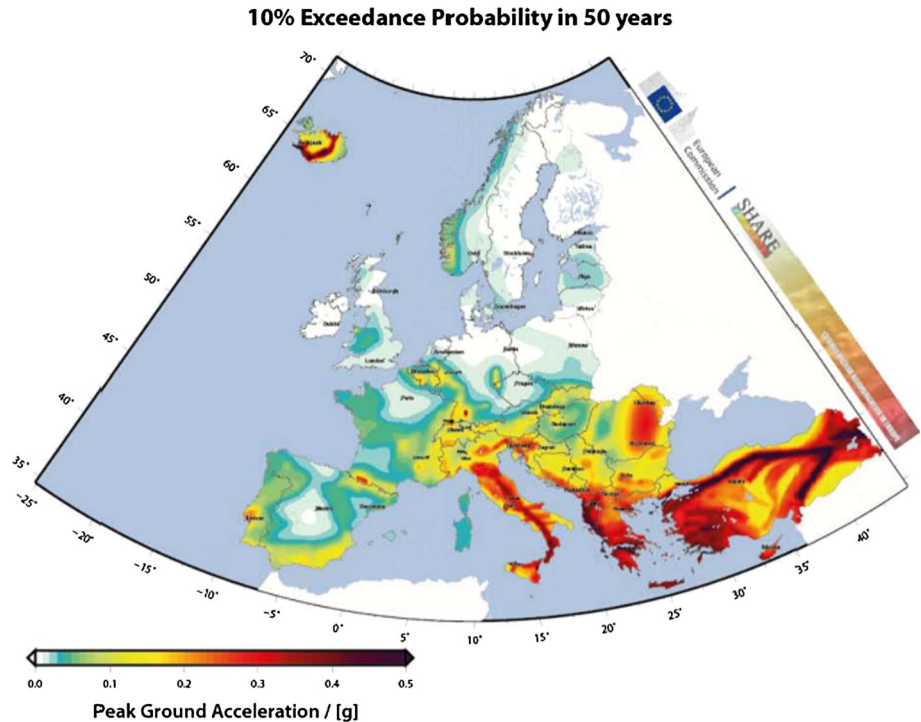


Fig. 1 A European Seismic Hazard Map (ESHM) illustrating the probability to exceed a level of ground shaking in terms of the peak ground acceleration with a 10 % probability in 50 years (corresponding to a return period of 475-year) (Source <http://www.share-eu.org/node/90>)

ELER was the alternative software to CAPRA-GIS. Both codes are capable of running end-to-end scenario-based risk analysis and in outputting the results in the form of shape files for further processing and analysis. The latest version of ELER (v3.0) allows the user to input hazard maps, and to define easily new building types and their associated vulnerability values. The most interesting feature of ELER was the availability of a building inventory data approximated from Corine Land Cover and population databases, in 150 s arc grids for 27 countries in Europe.

2.1 Overview of the risk assessment approach using ELER v3.0

The Earthquake Loss Estimation Routine (ELER) was developed under the NERIES FP6 project (2006–2010) for rapid estimation of earthquake damages and casualties. The loss estimations can be conducted under three levels of sophistication (namely level 0, 1 and 2). The ground motion estimation methodology is common to all three levels. The choice of computing earthquake losses using one of the three levels of calculation is essentially controlled by the availability of input data (Erdik et al. 2010; Hancilar et al. 2010). The methodology employs the following steps:

- In the hazard module, for a given earthquake magnitude and epicenter information, spatially distributed intensity and ground motion parameters (Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV), Spectral Acceleration (S_a), Spectral

Displacement (S_d) are estimated through region specific ground motion prediction equations and gridded shear wave velocity information.

- Level 0 module can be run using intensity-based maps (i.e. shake maps). The casualty estimation is done utilizing regionally adjusted intensity casualty or magnitude-casualty correlations based on the LandScan population distribution inventory.
- Level 1 module is also based on seismic hazard intensity distribution maps. The intensity based empirical vulnerability relationship is employed to estimate the number of damaged buildings and associated losses. The casualty estimation is derived from the number of damaged buildings.
- Level 2 module corresponds to the highest sophisticated level in the loss estimation methodology. Ground motion maps in terms of spectral accelerations at short and 1.0 s periods are used. The number of damaged buildings and associated casualties are obtained using analytical fragility relationships and building damage related causality fragility models, respectively. The methodology is similar to HAZUS-MH. The spectral acceleration-displacement-based vulnerability assessment methodology is utilised for the building damage estimation. The casualty estimation is done through number of damaged buildings using HAZUS99 and HAZUS-MH methodologies.

The advantages of ELER are:

- The HAZUS, EMS'98 (Grünthal 1998), and RISK-UE (2001–2004) building taxonomies are used as the default main classification systems in the development of ELER. However, the software is structured in such a way that a building inventory can be accommodated in terms of any classification system as long as the vulnerabilities associated with each building type are defined by the user.
- The outputs are in the form of a shape file can be manipulated with GIS editors for custom visualisation and further analysis.
- The software is tailored to scenario based risk analyses as well as for quasi-real time rapid earthquake loss assessment.
- A default building inventory (used in Level 1 analysis) corresponding to an approximated European database of number of buildings and their differentiated structural types in each EU country is available within the software aggregated to 150 s arc grids.

The drawbacks of ELER are:

- There is not a command line interface if a user would like to perform automated, scheduled or event triggered runs (Crowley et al. 2010).
- The platform allows calculating damage/loss maps that are conditional on the hazard with a given return period: it reads and provides losses using a single probabilistic seismic hazard map at a time, which makes it difficult to perform a fully probabilistic risk assessment.

A flowchart for the three levels of analysis available in ELER for assessing earthquake losses (damage and causality) is provided in Fig. 2. Both levels 1 and 2 include the calculation of direct monetary losses due to building damage. These tools allow for repair-cost estimations and specific investigations associated with earthquake insurance applications. The differentiation of the levels of analysis is mainly controlled by the availability of building inventory and demographic data (Erdik et al. 2010). As mentioned in the previous section, a regional-scale building inventory tailored for level 1 analysis was developed in the context of NERIES project. The availability of the 150 s arc building

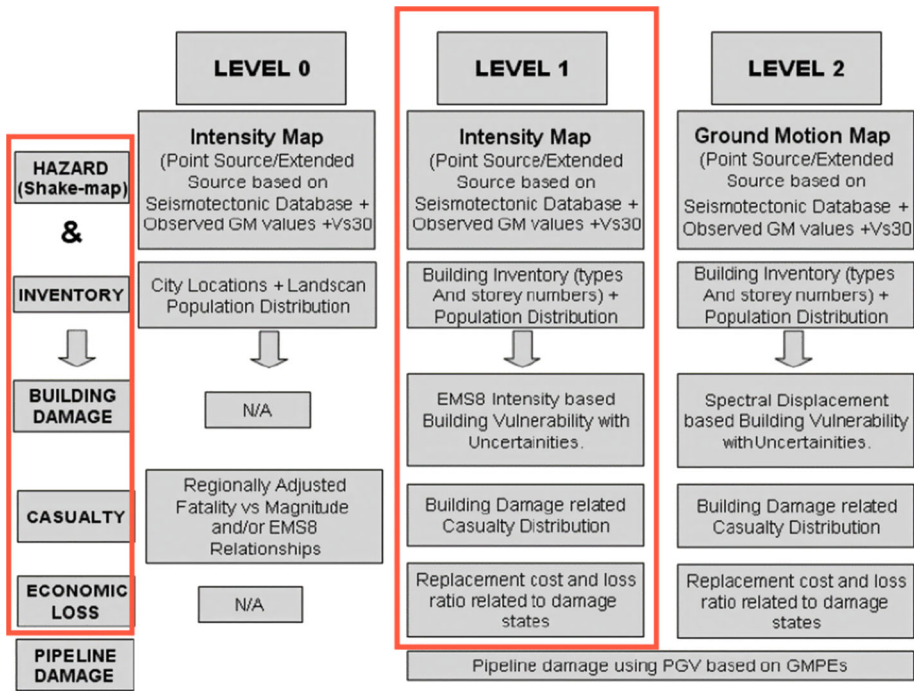


Fig. 2 The three levels of earthquake loss assessment incorporated in ELER v3.0. The red rectangles correspond to the level of analysis implemented in this study

inventory for 27 EU countries was the main motivation behind the selection of level 1 type analysis for modelling the seismic risk at the European level.

Some background information on level 1 analysis is given hereafter. Technical details on the algorithms implemented in ELER can be found in the software manual (BU-KOERI 2010).

2.1.1 Hazard, exposure and vulnerability

Level 1 risk assessment engine relies on macroseismic damage estimation. The intensity based empirical vulnerability relationships of Giovinazzi and Lagomarsino (2005) are utilised. Hence, for the representation of seismic hazard, an intensity based hazard map for a specific return period needs to be provided to the system. A grid based building database is specified for the study area as a shape file containing the building distribution for each cell. It may also contain population data for each cell for computing human losses. The software requires to using the building inventory classified based on the Risk-UE building taxonomy. However, ELER is structured in a way that a building inventory can be classified in any classification system as long as the vulnerability/ductility indices are specified by the user. Besides, a correspondence matrix between the PAGER, EMS98 and Risk-UE taxonomies allowing an easy conversion from one typology to another is available in ELER manual.

Intensity based empirical vulnerability functions are used for estimating building damage. They are based on macroseismic method originally developed by Giovinazzi and

Lagomarsino (2005) from the definition provided by the European Macroseismic Scale (EMS-98, Grünthal 1998). The approach makes use of classical probability theory and of the fuzzy-set theory. For each building type, three vulnerability indices need to be defined in order to follow an intensity-based macroseismic damage assessment approach: vulnerability (V), ductility (Q) and the t parameter. V is a measure of the ability of a building/building class to resist lateral seismic loading. The higher is the value of V , the lower the building resistance. Possible amplification effects due to different soil conditions are accounted for inside the vulnerability parameter. Q describes the rate of increase in the damage with earthquake demand level. The distribution of building damage is represented using beta distribution. The shape of the distribution is controlled by the t parameter where increasing t decreases the scatter.

2.1.2 Building damage and casualty calculations

Building damage estimation is obtained from the normally distributed cumulative damage probability for each building type as function of V , Q and t (Lagomarsino and Giovinazzi 2006). The analytical expression for the relationship between the mean damage grade, μ_D (mean of the discrete beta distribution)—intensity (I) and vulnerability index, V (Eq. 1), allows estimation of the building damage distribution once vulnerability index V is known. The cumulative damage probability is discretized to obtain the five damage states: D1-Slight Damage; D2-Moderate Damage; D3-Substantial to Heavy Damage; D4-Very Heavy Damage; D5-Destruction.

$$\mu_D = 2.5 \left[1 + \tanh \left(\frac{I + 6.25V - 13.1}{Q} \right) \right]. \quad (1)$$

The mean damage grade values (Eq. 1) are then connected to the two parameters r and t (Eqs. 2, 3) describing the continuous beta distribution with a 3rd degree polynomial of the form shown below (Eq. 3). In the study of Giovinazzi and Lagomarsino (2005) based on empirical data, t values were assigned to different building types. The only unknown parameter required to describe the damage distribution is r .

$$pdf_{\beta}(x) = \frac{\Gamma(t)}{\Gamma(r)\Gamma(t-r)} \frac{x^{r-1}(6-x)^{t-r-1}}{6^{t-1}} \quad (2)$$

where Γ is the gamma function and

$$r = t(0.007\mu_D^3 - 0.0525\mu_D^2 + 0.2875\mu_D). \quad (3)$$

Human losses are estimated considering that building damage as the root cause for injuries and fatalities. The assessment of human losses requires the knowledge of building occupancy and the probability of a certain casualty rate by each damage state. The lack of information on casualty data makes it difficult to derive empirical relations between building damage states. In ELER three different approaches for casualty assessment are proposed: BU-KOERI (2003), Coburn and Spence (2002) and Risk-EU based on the findings of Bramerini et al. (1995). The BU-KOERI (2003) method which relies on casualty data in urbanized areas from Turkish earthquakes (i.e. 1992 Erzincan earthquake, 1999 Kocaeli earthquake) assumes that the number of fatalities will be equal to the number of buildings in D4 and D5 damage states. The models proposed by Coburn and Spence (2002) and Bramerini et al. (1995) evaluate the consequences of building damage on

people only with respect to collapsed buildings (building damage = D5). The correlations proposed in these two models refer to building damage and provide the results in terms of four severity levels: S1-Light injury non necessitating hospitalization; S2-Injury requiring hospital treatment; S3-Severely injured and S4-Death. For this study, the casualty vulnerability relationships used in the Risk-UE project and based on the findings of Brammerini et al. (1995) are used. The model computes together the percentage of dead S4 and severely injured S3 (Eq. 4):

$$P_{S3+S4} = 0.3P_5 \quad (4)$$

where P_5 is the probability associated with damage grade D5. Equation 4 projects the rate of dead and severely injured people as being 30 % of the residents living in collapsed and unusable buildings, with the survivors assumed to require short term shelters.

2.1.3 Economic loss

Economic loss refers here to the conversion of physical damage into monetary value using local estimates of repair and reconstruction costs. In ELER, direct economic losses corresponding to the losses caused by damage to the built-up environment can be estimated. Losses due to damaged buildings are usually expressed in terms of “Mean Damage Ratio (MDR)” defined as the cost of repairing the structure divided by replacement cost:

$$MDR = \frac{\text{repair cost}}{\text{replacement value}} \quad 0 < MDR < 1. \quad (5)$$

Different correlations (loss functions) between the damage grades and the MDR are proposed in the literature, obtained through processing the data from past significant earthquakes. The economic loss module developed in ELER v3.0 relies on user-defined loss ratios for the EMS98 damage states (D1 to D5). The MDRs are used to convert the number of damaged buildings in each grid to cell based MDR values. ELER computes the monetary value of direct economic losses by multiplying the MDR by the total building cost for each building type of the building inventory. This is expressed with the following equation:

$$\text{Economic Loss (building type, } D_k) = MDR(D_k) * \text{Building Cost (building type)} \quad (6)$$

where the MDR is a function of the building damage state D_k and the building cost is defined for each building type in the building database. For this study, the default MDR values proposed by BU-KOERI (2003) for each damage state are used. Table 1 gives examples of different MDR values found in the literature and in risk assessment models.

2.2 Application of ELER for risk assessment at the EU Level

Obtaining reliable input data that meet the requirements of the risk modelling framework represents the most difficult and time-consuming part of the seismic risk assessment. This is particularly true when pre-processing is required to obtain the data in some standard and uniform format to be input into the selected risk modelling platform. This section discusses the main data that were collected, processed and used for assessing seismic risk at EU level according to level 1 analysis of ELER.

Table 1 MDR values for loss estimations

D_k	BU-KOERI (2003)	Hazus (1999)	Bramerini et al. (1995)	ATC 13 (1987)	Tyagunov et al. (2006)
D1	0.05	0.02	0.01	0.05	0.05
D2	0.2	0.1	0.1	0.2	0.1
D3	0.5	0.5	0.35	0.55	0.4
D4	0.8	1	0.75	0.9	0.8
D5	1	1	1	1	1

2.2.1 Hazard input

As previously mentioned the European probabilistic seismic hazard data produced in the context of the SHARE project was used in this study (Woessner et al. 2015). The results are available in the form of exceedance probabilities of ground motion measures for a specific return period (data for five different return periods and in terms of spectral acceleration for at least twelve periods of vibration are available for download from the European Facility for Earthquake Hazard and Risk³). The present study makes use of data corresponding to 10 % exceedance probability in 50 years (i.e. equivalent to an average recurrence of such ground motions every 475 years) (Fig. 1).

The pan-European hazard data produced in the context of SHARE project is represented through map of PGA and SA. The unit is “g” standing for gravitational acceleration. However, for level 1 analysis in ELER, hazard data in the form of instrumental intensity distribution is necessary for the building damage estimations. Hence, it was necessary to convert the hazard data from PGA into the Modified Mercalli Intensity scale (MMI). The intensity values can be derived from PGA values using a correlation relationship. Focusing either on regional or worldwide data, many empirical relations have been proposed to relate the macroseismic intensity (MMI) to PGA (Murphy 1978; Trifunac and Brady 1976; Wald et al. 1999). The variety of relationships between MMI and PGA and the inherent statistical variability in predicting MMI make it difficult to identify a single relationship to be applied uniformly across EU countries.

Regions with high seismicity (e.g. Greece, Italy) are usually characterized by a better understanding of historical seismicity and are subject to detailed studies for correlating ground motion parameters to macroseismic intensities either at regional or national levels. For these e high seismicity regions, it was decided to use state-of-the art, nationally derived empirical relationships. The general MMI-PGA relationships are expressed as follows:

$$MMI = b_0 + b_1 \log(Y) \quad (7)$$

where Y is the average of the ground motion parameter; b_0 the intercept and b_1 the slope obtained from the linear regression.

The following values for the intercept and slope were applied respectively:

- For Greece (Tselentis and Danciu 2008): $b_0 = -0.946$; $b_1 = 3.563$.
- For Italy (Faenza and Michelini 2010): $b_0 = 1.68$; $b_1 = 2.58$.

³ <http://www.efehr.org:8080/jetspeed/portal/>.

For the rest of Europe the classical empirical relation by Wald et al. (1999), which is also implemented in the Earthquake Hazard Assessment (EHA) module of ELER, has been used, with: $b_0 = -1.66$; $b_1 = 3.66$.

2.2.2 Building inventory for EU-28 countries

The compilation of a consistent building inventory for 28 EU countries is a vital step in this seismic risk assessment exercise. The quality of the available building inventory, both in terms of structural and occupational parameters will determine the quality of the resulting loss estimation (BU-KOERI 2010). A basic but comprehensive European database, was available for 27 EU countries and provided within ELER as the default data of Level 1 analysis. ELER uses a proxy procedure that relies on land use cover and population distributions to develop regional scale building inventories. The countrywide approximated building database was obtained from Corine Land Cover and population databases in 2000. It is provided in 150 s arc grids for 27 countries in Europe for which the Corine Land Cover data were available in 2000 with the exception of Croatia, which joined the EU in 2013. The methodology used in obtaining the country basis geographic distribution of the number of buildings from Corine Land Cover and Population databases is covered in Appendix A of ELER manual (BU-KOERI 2010). Once the grid distributions of the total number of buildings were obtained, the approximate number of buildings in each building class (as defined in the European building classification system) were computed using the countrywide overall building class ratios provided in PAGER database (Jaiswal and Wald 2008). The PAGER project provides the percentages of different construction types in all countries of the world for both urban and rural settlements and residential and non-residential occupancy types, making use of a HAZUS99 type classification. Corresponding European Building Taxonomy classes (Risk-UE) have been identified for the structural types of the PAGER classification system. Then these percentages have been used to convert the approximated grid based number of buildings to an inventory of different structural types in each country.

A slightly different approach was used for deriving the building stock and population distribution in 150 s arc grids for Croatia. The step-wise approach includes:

1. An estimation of the total number of buildings in each cell.

The exposure data used for the GAR⁴ (UNISDR 2015) integrates population and country-specific building typology, use and value (De Bono and Chatenoux 2015). It is represented as a group of buildings in each cell with a resolution of 5×5 km (approximately in the equator). The GAR exposure data provides an estimate of total number of people within each cell together with the main building typology. The geographical distribution of the population corresponds to the coverage offered by LandScan with a 1 km resolution (Dobson et al. 2000). Unfortunately, the GAR exposure data does not include the total number of buildings by building type. In order to calculate the total number of buildings within each cell, the average occupancy value of 5.1 persons per housing unit for Croatia based on the United Nations data (UNECE 2006) was used. With the total number of people in each cell and the average occupancy value, it is then possible to approximate the total number of buildings per cell.

2. An estimation of the number of buildings per cell.

⁴ <http://www.preventionweb.net/english/hyogo/gar/2015/en/home/data.php?iso=NLD>.

- Once the total number of buildings is obtained for each cell, the fractions of different construction types in Croatia derived from PAGER database allows the disaggregation of the total number of buildings (TB) into different building types.

$$\begin{aligned} \text{Total Bldg Croatia} = & 0.15 (W) * TB + 0.57 (M5M) * TB + 0.22 (M7) * TB \\ & + 0.06 (RC2DCLIM) * TB \end{aligned} \quad (8)$$

in which W for wood buildings = 0.15; $M5$ M for mid-rise unreinforced masonry buildings = 0.57; $M7$ for reinforced/confined masonry buildings = 0.22; $RC2DCLIM$ for mid-rise, low-ductility, reinforced concrete shear wall buildings (in seismic zone II) = 0.06 (Jaiswal and Wald 2008).

2.2.3 Estimation of buildings costs

For the assessment of economic losses information on building costs needs to be assigned to each building type of the European building inventory. In this study, the assessment of economic losses is based on the assumption that residential buildings are dominant in the building stock and that the damage affecting these buildings is an indicator of the total direct economic impact. A more complete assessment should consider other components of the physical environment such as commercial, industrial buildings and infrastructure (e.g. transport infrastructure). The default European building inventory provided in ELER does not include information on building replacement value. Collecting information about the monetary value of exposed buildings for all 28 countries is unrealistic despite the availability of data at municipal level in some EU countries (e.g. the uniform database on the reconstruction costs of residential buildings in Germany as estimated by Kleist et al. (2006).

To circumvent the challenge of obtaining a valuation of exposed buildings with a pure bottom-up approach, a top-down or “downscaling” approach was developed in the context of the GAR 2015. Simply presented, the approach relies on national indicators (i.e. socio-economic data, building types and capital stock) successively disaggregated onto 5×5 km grid and used as proxies to estimate the population distribution, building structure typology, ownership (private/public), use sector (e.g. residential, health, education) and the building value. In order to establish the monetary value of exposed assets the World Bank 2011 data on capital stock per country was used. The capital stock was downscaled from the national/sub-national level to the cell level using LandScan population data of 2011 at a resolution of $30''$. Details on the methodology used for estimating the value of exposed assets can be found in De Bono and Chatenoux (2015).

Despite many assumptions, the global exposure data for the GAR 2015 has several advantages:

- It is the only open database including the value of exposed assets that covers all EU-28 countries,
- It ensures a good uniformity allowing the comparison of the results across the different countries,
- The format and the resolution (5×5 km) are compatible with the European building database provided in ELER.

Consequently, the global exposure data was used for deriving the replacement value of the different building types within each of the 28 EU countries.

The average costs for each building type of the European building database were calculated at the country level from the global exposure data. Figure 3 represents the

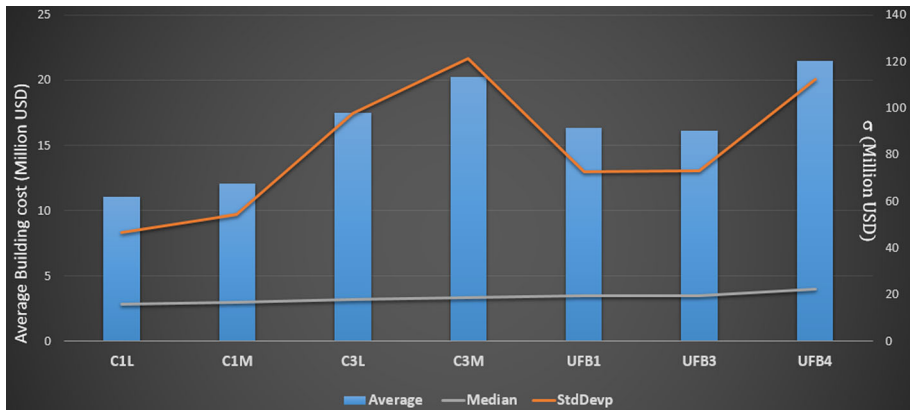


Fig. 3 Average and median building costs (in Million USD) in Italy derived from the global exposure data of the GAR 2015. C1L and C1 M: Low- and mid-rise reinforced concrete moment frames respectively; UFB1, UFB3 and UFB4: Unreinforced brick masonry with wood slabs, unreinforced fired brick masonry with wood slabs and unreinforced fired brick masonry with reinforced concrete floors respectively

average costs of the building types in Italy (following PAGER taxonomy). It shows a high variability in the values of buildings measured by the standard deviation (σ). While the global exposure data takes into account explicitly the spatial variations of the values of exposed assets, ELER allows the assignment of a unique value per building type without consideration of the local variations of property costs. Due to the high variability of building costs observed in most of the countries, it was decided to use the median value instead of the mean as a replacement cost for each building type.

3 Results and discussion

The results are expressed as expected casualties and economic losses for the ground motion level with a 10 % probability of exceedance in 50 years (i.e. with a return period of 475-year). The variety of uncertainties originating from different sources and present at every step of the risk assessment are addressed in the sensitivity analysis with the purpose of shedding light on the influence of methodological and data input choices on the risk estimates.

3.1 Expected casualties

Casualties in ELER level 1 analysis are calculated based on building damage and at four severity levels: S1 Light injury; S2 Injury requiring hospital treatment; S3 Severely injured and S4 Death. In the present study, both severity levels S3 and S4 (referred to here by casualties), related to building damage state D5 are considered. Figure 4 shows the distribution of casualties (S3 + S4) in the four EU countries with the highest levels of seismic risk: 6665 in Italy (Fig. 4a), 6456 in Cyprus (Fig. 4b), 2825 in Romania (Fig. 4c) and 2709 in Greece (Fig. 4d).

The results presented here correspond to a daytime population. They tend to show a concentration of casualties in the major urbanized areas (e.g. Naples, Bucharest, and Athens). A better understanding of casualties' distribution within each country requires an

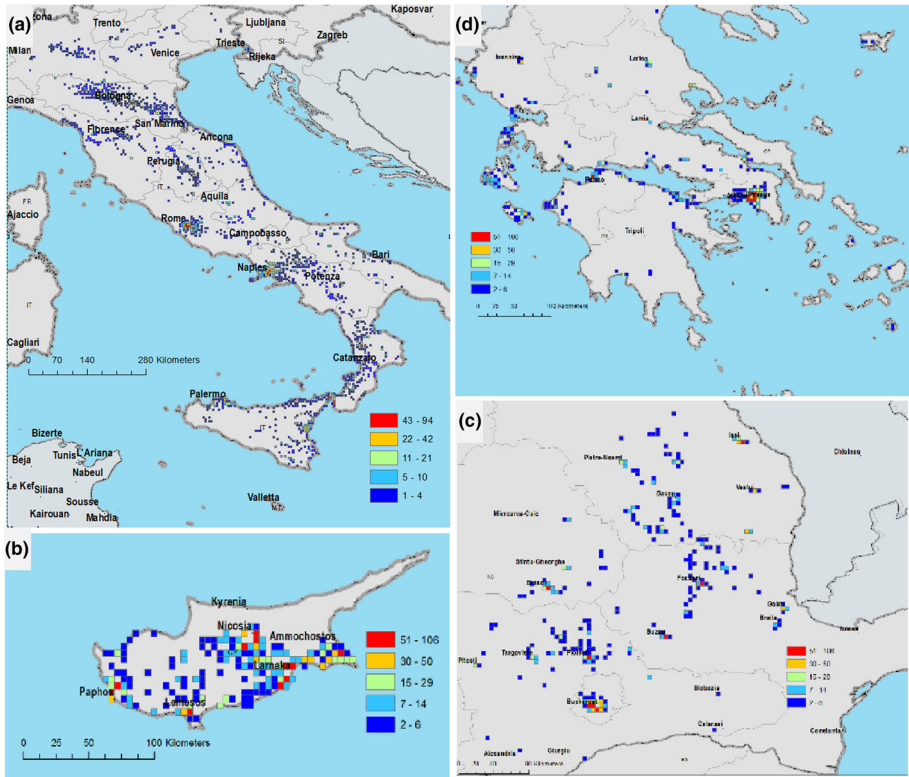


Fig. 4 Spatial distribution of casualties in Italy (a), Cyprus (b), Romania (c) and Greece (d)

analysis of casualty rates by building type to identify the most vulnerable buildings. We plan to address this issue in a follow-up study.

3.2 Expected economic losses

The economic loss was calculated within each cell of the gridded European building database. It was then aggregated at city, NUTS 2 (Nomenclature of Units for Territorial Statistics) and national levels. Aggregation of the results at the regional and national levels is meant to provide an overview of loss estimates for an eventual comparison with the results of other studies (e.g. the PML for 475- year return period calculated as part of the GAR 2015). The aggregated results are not to be used for comparison between the countries nor have any value within a decision-making context.

3.2.1 Aggregation at city level

Several definitions exist for the concept of urban areas and different references are available for the delineation of cities in Europe. Urban Morphological Zones⁵ (UMZ) used by the European Environment Agency (EEA) were used as a reference for delimiting the

⁵ <http://www.eea.europa.eu/data-and-maps/data/urban-morphological-zones-2006>.

extent of EU cities. Those urban areas are defined from land cover classes contributing to the urban tissue and function. UMZ were defined from Corine Land Cover, which is also the basis for the exposure database used in our analysis. They refer to built-up areas without consideration of the population distribution, making them suitable for our analysis in comparison to other definitions that consider functional economic links, community flows and population distribution. They are formally defined as built-up areas lying less than 200 m apart.

Economic losses were assessed for EU cities defined according to the UMZ. The results in Fig. 5 illustrate the top 20 EU cities with the highest expected economic losses expressed in absolute and relative to regional GDP (GDP in 2013 at NUTS2⁶) values. Given the distribution of the seismic hazard (Fig. 1), the cities most at risk are located in areas where large earthquakes and significant damage were recorded. Torino with a moderate seismic hazard is not expected to rank in the top 20 EU cities with high seismic risk. The spatial delineation of cities according to the UMZ concept and the conversion from vector to raster format introduces an error in the “urban footprint” and subsequently in the aggregated economic losses. Using a different delineation of EU cities is likely to produce a different ranking of cities. Out of the 20 cities, 9 are located in Italy, 4 in Slovakia, 3 in Romania, 2 in Greece and 2 in Germany (for the latter, the UMZ covers 5 spatially contiguous cities).

3.2.2 Aggregation at regional level

The aggregated expected losses at NUTS 2 (Fig. 6) show high economic loss estimates in almost all of the 20 Italian regions, with the exception of Sardinia. North-eastern regions of Romania also show moderate to high economic losses. Some regions in Greece, France, Bulgaria and Germany show moderate economic loss. These results are consistent with National Risk Assessment reports in which the same countries identified seismic hazard and their socio-economic impacts as a big concern, with the exception of the Czech Republic, where the modelled seismic risk seems to be relatively low (see Sect. 1.1).

The spatial distribution of the economic loss can be better captured by looking at the spatial distribution of building damage. As an example, the non-aggregated building damage for damage states D4 and D5 is illustrated in Fig. 7a for the Italian territory. The map of building damage exhibits strong correlation with the macro-seismic intensity map derived from ground motion map of SHARE project (Fig. 7b). The similarities between the patterns of building damage and seismic hazard map indicate the dependence of the risk on ground motion intensity.

3.2.3 Aggregation at national level

This section provides a comparison of the expected losses estimated in this study and the Probable Maximum Losses (PMLs) for 475 years return period from GAR 2015. For this purpose, the expected losses were aggregated at the national level. The losses for each country resulting from the two studies are presented in Fig. 8. The PML values stand for the largest losses with a 10 % probability of being exceeded over a 50-year time frame whereas the expected losses are the estimated values conditional on the mean ground motions with 10 % probability of exceedance in 50 years.

⁶ http://ec.europa.eu/eurostat/statistics-explained/index.php/GDP_at_regional_level.

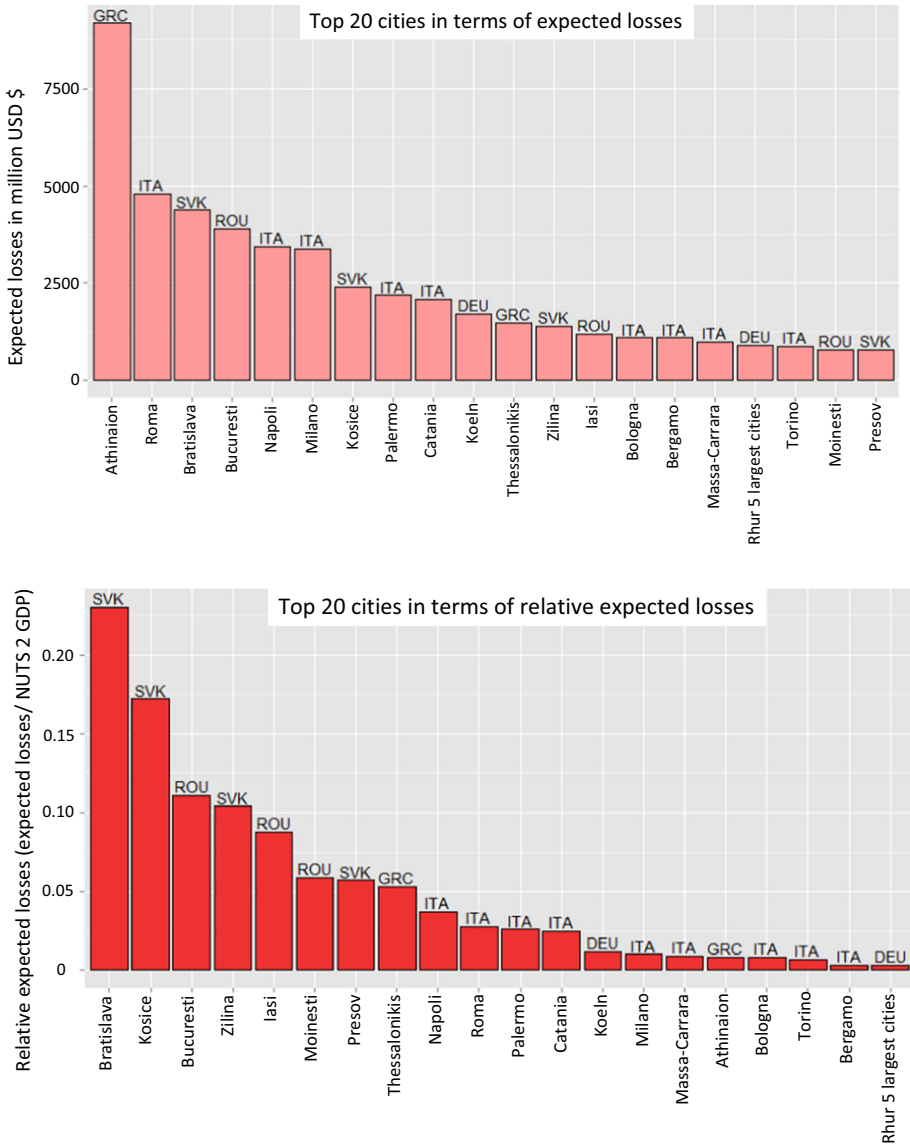


Fig. 5 Top 20 EU cities in terms of expected economic losses expressed in absolute (*upper panel*) and relative to NUTS 2 GDP (*lower panel*) values

The comparison shows large unsystematic discrepancies. The expected losses computed with ELER software provide higher estimates in Italy, Slovakia, Romania and Slovenia. Whereas for Germany, Greece, Great Britain, Austria and Netherlands, the PML estimates calculated with CAPRA-GIS software are greater.

The differences in the estimates can be explained by differences in both i) the risk assessment models and 2) the input data used in these models including hazard data, the exposure database and the vulnerability functions. Another major factor influencing the

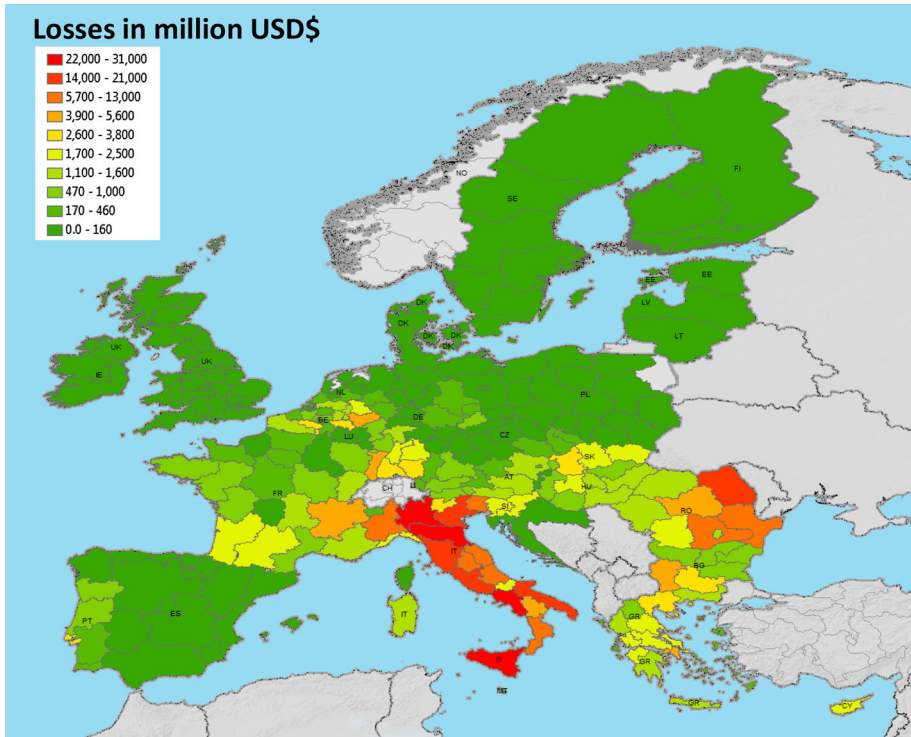


Fig. 6 Distribution of estimated economic losses aggregated at NUTS2 level

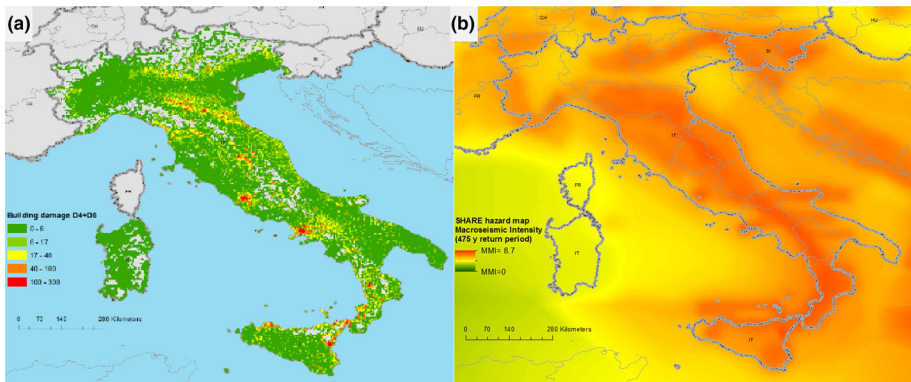


Fig. 7 Spatial distribution of building damage in Italy (a) and seismic hazard map for the 475-year return period (b)

variability of the economic loss estimates is the difference in the approaches used in CAPRA-GIS and in ELER for assigning costs to the exposed assets. While the exposure data in CAPRA-GIS takes into account explicitly the spatial variations of the values of exposed assets, ELER allows the assignment of a unique value per building type without consideration of the local variations of property costs. This limitation of ELER may lead to

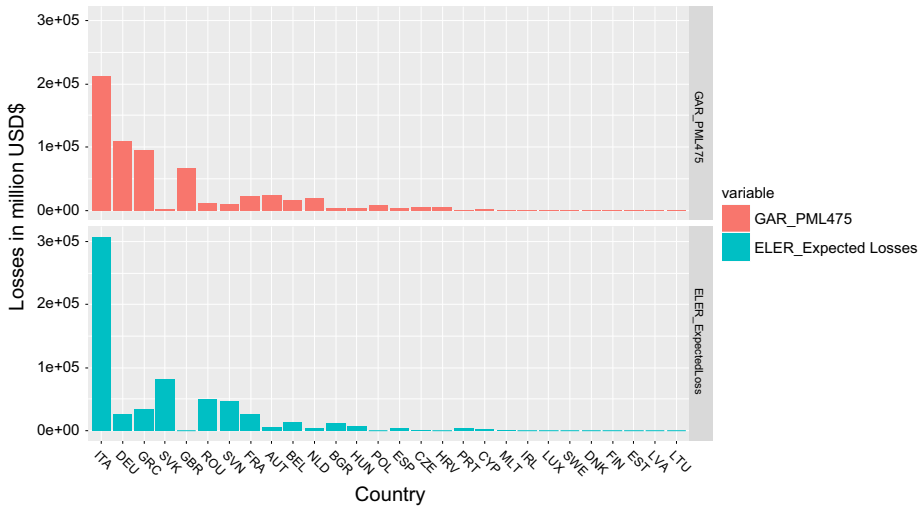


Fig. 8 Probable Maximum Losses (PMLs) from GAR 2015 (*upper panel*) and expected losses obtained with ELER (*lower panel*). Both *graphs* present the results corresponding to economic loss estimates associated with the return period of 475 years of the seismic hazard

unrealistic economic loss estimates especially in large cities with high property and building costs.

The next section, which deals with sensitivity analysis, may give more insights into the sources of variability in the risk assessment.

3.3 Sensitivity analysis

The methodological and input data choices inevitably introduce uncertainty in the results of the seismic risk assessment. A variety of uncertainties and errors originating from different sources are present at every step of the risk assessment process (e.g. natural variability of the phenomena under investigation, incompleteness of input data or inadequacies in the models and methods). Many assumptions had to be made in order to complete the pan-European risk analysis. The impact of each of these assumptions on the results can be assessed through a sensitivity analysis. It is beyond the scope of this study to analyse all sources of uncertainty, especially those related to the risk assessment model, which were already discussed in several publications (BU-KOERI 2010; Erdik et al. 2010; Hancilar et al. 2010).

The emphasis in the current study is placed on the analysis of epistemic uncertainties, which are related to the variability of the input variables including the sensitivity analysis of the resulting seismic risk assessments with regard to the different input datasets: hazard and exposure data. A more comprehensive sensitivity analysis would have to consider the uncertainties associated with selection of MDR functions, i.e. the relationships between the damage state of affected buildings (described by the structural damage grade) and the corresponding level of direct losses (Tyagunov et al. 2013) (see Sect. 2.1.3 on the variability of MDR values).

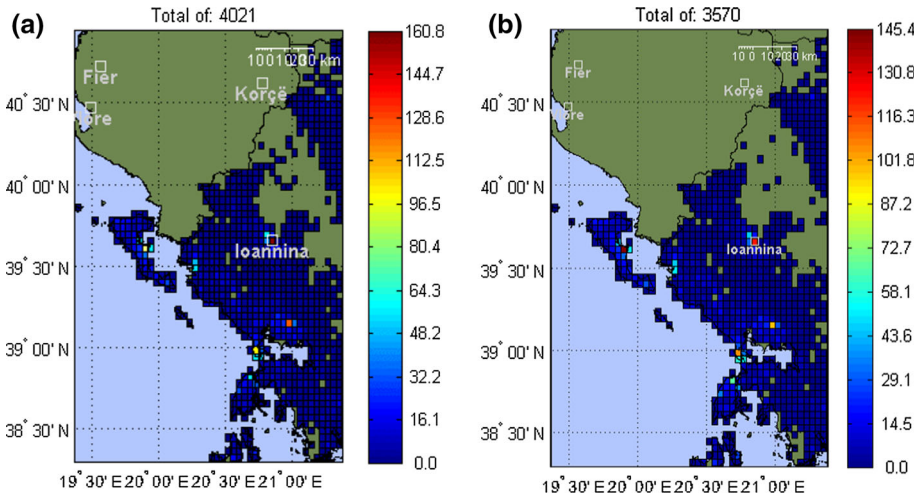


Fig. 9 Distribution of total building damage (D4 + D5) **a** with $b_0 = 1.68$; $b_1 = 2.58$ (Faenza and Michelini 2010) and **b** $b_0 = -0.946$; $b_1 = 3.563$ (Tselentis and Danciu 2008)

3.3.1 Sensitivity to hazard data

Sensitivity analysis to hazard data was investigated through (a) an investigation of the influence of MMI-PGA relationships for the conversion of ground motion data to macroseismic intensities and (b) an analysis of the influence of the input probabilistic hazard map.

(a) Influence of MMI-PGA relationships.

In Sect. 2.2.1, different relationships selected for the conversion of PGA values to MMI values were presented. The choice of the intercept b_0 and slope b_1 was driven by the existing regional or national studies that attempted to derive empirical relationships using observed data. To examine the influence of the choices made when selecting these parameters, a small area (about 334×556 km) around the city of Ioannina in Greece was defined for the analysis. The parameters proposed by Faenza and Michelini (2010) ($b_0 = 1.68$; $b_1 = 2.58$) and by Tselentis and Danciu (2008) ($b_0 = -0.946$; $b_1 = 3.563$) were applied.

Figure 9 shows the distribution of the buildings in damage states D4 and D5 obtained with the two different seismic hazard datasets. The comparison of the results in terms of total building damage D4 + D5 (4021 versus 3570) shows a percentage difference of 12 %. The parameters proposed by Tselentis and Danciu (2008) for Greece lead to more conservative estimates of the building damage.

(b) Influence of the input probabilistic hazard map.

Several studies addressing uncertainty in seismic risk assessment (Bazzurro and Luco 2005; Tyagunov et al. 2013) found that the greatest contribution to the total uncertainty comes from the hazard part (mainly from the selected intensity prediction equations). Besides the resolution of the seismic hazard map may also strongly influence the risk assessment results. In order to study the contribution of the hazard component to the risk assessment results, the probabilistic seismic hazard assessment (PSHA) at global level

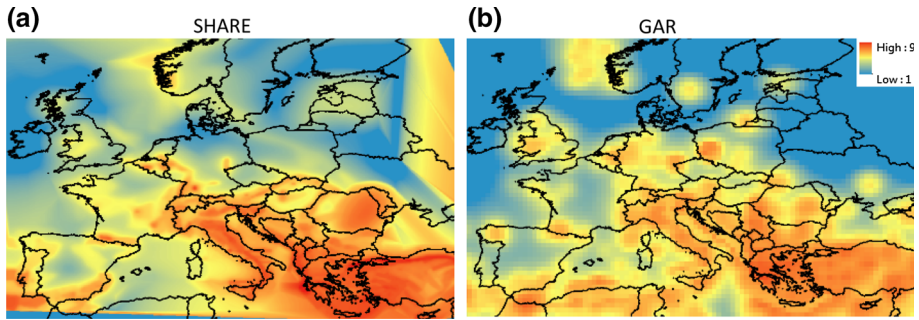


Fig. 10 Probabilistic seismic hazard maps obtained from SHARE project **a** and GAR 2015 **b** represented in MMI scale for the 475 years return period. The spatial resolutions of the hazard maps are 0.06° and 0.5° respectively

developed as part of the GAR 2015 was tested in ELER. For a consistent comparison with the risk assessment using SHARE hazard data, the global hazard map for peak ground acceleration (PGA) and 475-year return period was used in this test. Both datasets were converted to intensity values using the MMI-PGA relationship developed by Wald (1999). The resulting seismic hazard maps represented using the same macroseismic intensity scale are shown in Fig. 10.

The Marmara region in Turkey, for which a detailed building inventory is available as a sample data in ELER, was selected for the test. The grid based building inventory of Marmara region is based on the year 2000 building census tracts carried out by Turkish Statistical Institute. The data include, the occupational type, the construction type and the number of floors of each building. The construction type and number of floors are the main parameters affecting the earthquake performance of buildings. The inventory is classified in accordance with the EMS building classification system.

The results of the comparative risk analysis in terms of building damage, economic losses and casualties are shown in Table 2. The results obtained with the two different hazard maps are significantly different (the percentage differences⁷ are 171, 112 and 186 % for building damage, economic loss and casualties, respectively). They suggest that the use of hazard data intended for global applications, within a seismic risk analysis at regional level, may introduce a considerable (and possibly excessive) uncertainty in the final results. The global seismic hazard map of the GAR 2015, initially intended for global applications should be treated carefully especially in regions of moderate to high seismicity. The authors of the global seismic hazard map acknowledge its limitations, including the non-consideration of localized faults or conditions that could represent an increased seismic hazard (CIMNE-INGENIAR 2015).

3.3.2 Sensitivity to population data

The default grid based population data integrated in the European building database was used in the seismic risk assessment for estimating casualties. The population data for the 28 EU countries was derived from LandScan population data (Dobson et al. 2000). LandScan global population data has an approximate resolution of $1 \times 1 \text{ km}^2$ resolution at the

⁷ The percentage difference is calculated as the difference between two values divided by the average of the two values shown as a percentage.

Table 2 Results of seismic risk assessment in Marmara region obtained with SHARE and GAR 2015 hazard maps

	SHARE hazard data	GAR 2015 hazard data
Building damage D4 + D5	79,690	6759
Economic loss (in Million USD)	289,234	81,323
Casualties S3 + S4	129,958	4720

equator (30 s arc grids) and represents ‘ambient population’. The data was aggregated to 150 s arc grids to match the building database. Recently, new population grids were produced for selected countries in Europe, at 10, 100, and 1000 m resolutions (Freire and Halkia 2014; Freire et al. 2015). These grids were generated by disaggregating residential population from the 2011 round of censuses to built-up areas as mapped in the European Settlement Model (ESM) layer (Ferri 2014; Ferri et al. 2014) developed in the context of the Global Human Settlement Layer (GHSL) project (Pesaresi et al. 2013).

Differently from LandScan, which aims at representing ‘ambient population’, GHSL-based population grids represent residential-based population in buildings. The improved population data represents an interesting input dataset for the assessment of casualties. For the sensitivity analysis, population data for Italy was available at 100 m resolution. It was obtained by disaggregating 2011 census tract population (cezione) into the GHSL built-up layer informed by the Corine Land Cover Refined 2006 layer (Batista e Silva et al. 2013). Figure 11 shows the differences in the level of detail between the default grid based population data provided in ELER and the one obtained with the method of Freire et al. (2015).

The calculated casualty estimates (for severity levels S3 and S4) obtained by the use of the two population datasets for Italy gave the following total casualties (S3 + S4):

- 6665 with LandScan derived population data.
- 10,399 with GHSL derived population data.

The more detailed population data provides predictably higher casualty estimates. The large percentage difference of 44 % in the results can be possibly attributed to:

- The difference in the resolution and accuracy of the demographic data, which can significantly affect the results of seismic risk assessment.
- The differences in the concepts between LandScan, which represents ambient population, and the population data derived from GHSL, which is based on built-up areas. Knowing that casualty estimates are directly derived from building damage (see Sect. 2.1.2), it is then plausible to obtain higher casualties when exploiting the GHSL derived population data.

From this analysis, one may conclude that the results of the seismic risk assessment in ELER tend to show large variations related to differences between the default input population data and user defined data.

3.3.3 Sensitivity to building cost

According to Tyagunov et al. (2013), the main uncertainties in exposure modelling are associated with the spatial distribution of the building stock, the building types and the assessment of their characteristics related to both vulnerability and costs. A comprehensive

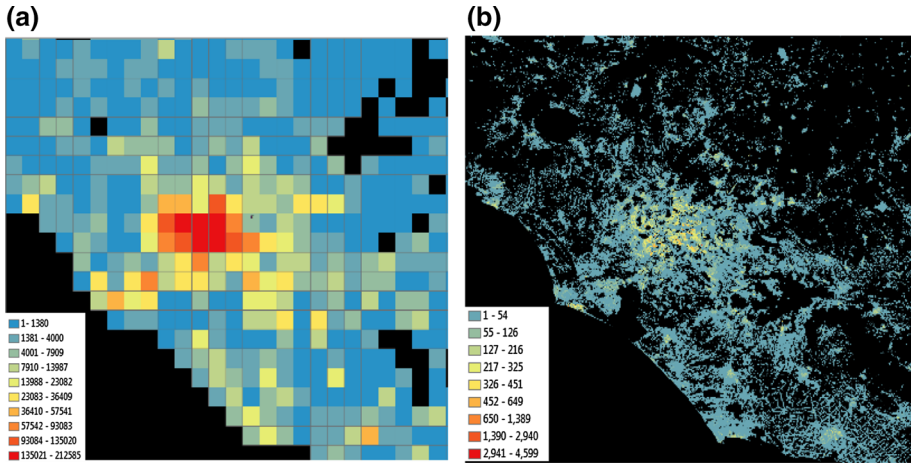


Fig. 11 Gridded population data obtained from LandScan (150 s arc grids) (a) and Population data for Rome, Italy derived from the GHSL (100 × 100 m) (b)

sensitivity analysis should consider the individual components of the exposure model. The aim of the sensitivity analysis performed here is to shed light on the main uncertainties related to methodological choices in data collection. Therefore, consideration is given to the choice of the method for deriving building costs.

The estimation of economic losses in ELER was based on building replacement values derived from the global exposure database used in GAR 2015. Modelling the value of exposed assets for GAR 2015 involved several assumptions and proxies described in De Bono and Chatenoux (2015). In addition to the uncertainty related to these assumptions, the choice made in the current study of using the median value building costs introduces another source of error. To analyse and quantify the influence of this choice on the estimated losses, the economic losses in Slovenia were computed using both the median and average building costs derived from the global exposure database, while keeping all other parameters constant. Figure 12 shows the spatial distribution of the economic loss using the two estimates of building values. The comparison shows that despite the identical patterns of economic loss distribution, there is a percentage difference of 95 % between the two estimates. Assigning a median building cost to each building type gave conservative results with a total of 0.46 Million USD compared to the use of the average building cost which resulted in large (and probably excessive) estimates with a total of 1.3 Million USD. These large differences highlight the criticality of the modelled exposure, in particular the

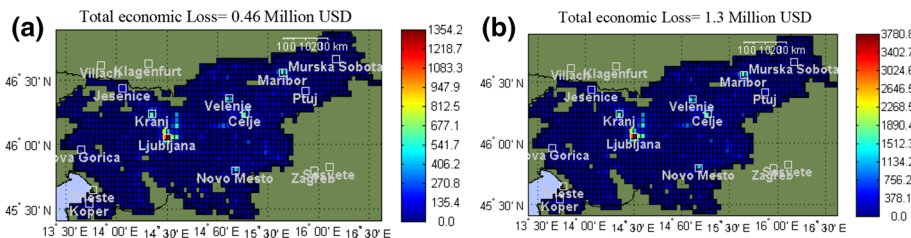


Fig. 12 Total economic losses (in Million USD) in Slovenia obtained with estimates of the median (a) and average (b) building costs derived from the global exposure database of the GAR 2015

estimation of exposed assets values in seismic risk assessment. They also pinpoint the shortcomings of assigning one economic value per building type independently of the spatial location.

4 Concluding remarks

The methods and results presented in this paper should constitute a “proof of concept” which aims to demonstrate the feasibility of performing a seismic risk assessment at a pan-European level with reasonable effort. The exercises conducted in this study were successful in: (i) pooling open-access data from different sources in a homogeneous format for all 28 EU countries, (ii) assessing the applicability of models and the usability of datasets developed in the context of EU research projects (NERIES, Risk-UE and SHARE), (iii) highlighting the main sources of uncertainties that need to be carefully considered when performing a seismic risk assessment, (iv) and finally, demonstrating the potential of conducting a seismic risk assessment at the entire EU level.

Although the risk estimates obtained in this study have limited value in a decision-making context or for inter-country comparisons, they can still be used for the following purposes:

- In benchmarking exercises to monitor changes in loss over time (in relation to changes in human and physical exposure and vulnerability),
- In drawing attention to the areas where necessary refinements are required and detailed seismic risk assessments are desirable,
- In complementing and regularly updating the cross-sector overview of disaster risks at Union level as stipulated in article 5 of the Union Civil Protection Mechanism (*Decision No 1313/2013/EU*),
- In stimulating efforts in the Member States to collect more detailed exposure data at local and regional levels for more refined risk assessments.

The shortcomings of the study carried out so far are related to both methodological and input data choices:

Shortcomings related to the risk modelling platform

- One of the limitations of ELER is the assignment of a unique value per building type without consideration of the local variations of property costs. This introducing an error in the calculated economic losses. One way to reduce this error is to consider the spatial variability of property costs. This can be implemented in a post-processing stage by applying region-dependent correction factors derived from maps of property costs.
- Level 1 seismic risk analysis of ELER is based on macroseismic intensities for modelling vulnerability and assessing damage. It is frequently argued that the use of macroseismic intensity leads to more reliable damage/loss estimates as it is possible to reduce the uncertainty in the empirical vulnerability model with macroseismic intensity data usually available following an event (Crowley 2014). However, the need to convert ground motion data to intensity values require a careful choice of the correlation tailored to area under analysis. A more accurate estimation of macroseismic intensity would need to consider separately high and low intensities: the former correlate fairly well with both PGA and PGV values while the latter correlate best with PGV values (Wald et al. 1999). Given the time constraints for this work, only the

relationships between MMI and PGA were considered and applied for computing the macroseismic intensity based hazard maps.

- Unlike CAPRA-GIS, the risk assessment approach in ELER does not accommodate a fully probabilistic risk assessment where all possible and relevant deterministic earthquake scenarios are considered together with all possible ground motion probability levels. It is still however possible to perform a pseudo-probabilistic risk assessment by running the model with seismic hazard maps with different return periods (at least three e.g. 475, 975 and 4975-year return periods). Since the scope of the current work is to study the feasibility of performing a probabilistic risk assessment, rather than to perform a complete fully probabilistic analysis, it was decided to limit the case study to a conditional loss assessment associated to earthquake hazard with a 475-year return period.

Shortcomings related to the input data

- The exposure data used in the context of this experiment has several limitations related to outdated building stock and population data and to large number of assumptions used for deriving the building stocks, the building typologies and their monetary values. In particular, the rough estimation of building costs from the global exposure database of GAR 2015 introduces large errors in the results. The assignment of uncertainty to exposure data, as well as of any correlations in the uncertainty, is certainly an area that would benefit from increased research attention (Crowley 2014).
- The use of spatially constant vulnerability functions per building type introduces additional errors in the estimation of building damage and consequently in casualty and economic loss estimates. Regionally adjusted building vulnerabilities would allow obtaining more reliable evaluations of losses. This can be achieved, when regional intensity based vulnerability curves or sufficient observed damage data are available, the average curve can be shifted to obtain a better approximation of the regional data (Giovinazzi and Lagomarsino 2004). ELER software allows the incorporation of a regional vulnerability variability factor if such information is available.

There are number of areas that require improvements and further research in view of a fully probabilistic pan-European risk assessment. Some avenues for future investigations are suggested:

1. With the availability of open-source platforms capable of computing human and/or economic losses by considering the probability of all possible events, (e.g. the OpenQuake engine being developed by the Global Earthquake Model (GEM) foundation and the upgraded version of ELER) it would be interesting to run the same experiment using the same input data and to compare the outputs of the different models.
2. Another improvement can certainly be achieved by using the most up-to-date building inventory and population data for Europe. European Settlement Map (2016) by the Joint Research Centre of the European Commission, which provides two raster datasets for human settlements in Europe based on SPOT5 and SPOT6 satellite imagery, can be utilised for this purpose.
3. In view of obtaining reliable results that can be useful to inform policy makers and to complement national risk assessments, the work performed here can be improved by making use of local datasets and national expert elicitations. The latter can be useful for estimating building vulnerability and costs especially in countries where both empirical data and analytical models are missing.

4. It is also necessary to compare the results of the current study with national seismic risk maps. In particular, various studies have looked at the seismic risk to the building stock and population at the national level in Italy. Many of the original seismic risk maps for Italy were based on single ground motion parameters to define the seismic hazard such as peak ground acceleration or macroseismic intensity (Lucantoni et al. 2001) or on mechanics-based vulnerability assessment procedures (Crowley et al. 2009). The aim of these comparisons would be to open the discussion on the best way to produce nationally and regionally relevant seismic risk assessments making use of the most-up-to-date information in the fields of seismic hazard evaluation, vulnerability assessment and exposure modelling.

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