Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2019) 5464-5477

ECCOMAS
Proceedia

COMPDYN 2019
7th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Crete, Greece, 24–26 June 2019

SEISMIC RISK MAP FOR THE ITALIAN RESIDENTIAL BUILDING STOCK

M. A. Zanini[1*], L. Hofer[1], F. Faleschini[1], K. Toska[1] and C. Pellegrino[1]

[1] University of Padova
Via Marzolo 9, 35131 Padova
e-mail: marianoangelo.zanini@dicea.unipd.it

Abstract

The paper illustrates the seismic risk maps derived for the residential building stock of Italy by using a general framework specifically set up by the authors for mapping seismic risk for a generic asset of interest. Seismic risk maps are computed taking into account a seismogenic model of the analyzed area, and properly characterizing vulnerability and exposure of an asset of interest. A risk-targeted indicator named Municipal Expected Annual Loss (MEAL) is introduced and used as suitable metric for the development of the maps, and for the subsequent seismic risk rating.

Keywords: Seismic risk map, Italy, Expected Annual Loss, Risk Reduction, Structural retrofit

ISSN:2623-3347 © 2019 The Authors. Published by Eccomas Proceedia.
Peer-review under responsibility of the organizing committee of COMPDYN 2019.
doi: 10.7712/120119.7318.19470

1 INTRODUCTION

In the last decade, the number of significant losses following natural disasters worldwide, has been rapidly growing [1]. This is mainly due to the growing of urbanization, world population and Gross Domestic Product (GDP). This main three factors, imply a concentration of people, thus increasing the exposure of our society to natural hazards more than in the past [2]. In addition, the vulnerability of many structures and infrastructures is still high, since retrofitting and re-building are time and money consuming processes. Furthermore, in many cases the vulnerability of old structure is increased by degradation phenomena [3]. Earthquake represent one of the most destructive natural events that can significantly affect the economy of a region and lead to long-term restoration processes [4]. In particular, in Italy, several significant losses occurred in the last decades: in 2009 a moment magnitude M_w = 6.1 stroke the Abruzzo Region, in 2012 a M_w = 6.0 and M_w = 6.1 earthquake occurred in Emilia Romagna, while within the summer of 2016 and the winter of 2017 several significant seismic events with M_w = 6.0-6.5 occurred in the Central Italy area [5-6]. The rapid succession of these seismic events unavoidably ended up to weight on public financial funds. For this reason, the Italian government has recently approved specific incentives for householders interested in seismically retrofitting their properties [7]. In this way, a private citizen can take advantage of a tax relief when reducing the seismic vulnerability of his private home with structural retrofit and improvement. The reduction of structural vulnerability is the most immediate way for addressing the problem of the seismic risk mitigation. Nowadays seismic risk evaluation is a well-known and established procedure, mostly applied for the risk assessment of punctual structures or spatially distributed portfolio of structures [8-9]. The use of this procedures is then commonly extended for a quantitative assessment of seismic risk at regional level. In this case, a multidisciplinary approach is needed for fully describing the seismic activity of the region of interest, its vulnerability distributions, and the associated exposure. In particular, the development of seismic risk maps is the key point when dealing with the seismic risk assessment at territorial level, since they provide a quantitative representation of the current risk and are a fundamental tool for computing the benefit associated to the structural retrofit. Their use is thus needed when dealing with the design of possible sustainable risk reduction programs at regional and national scale. In scientific literature, several authors investigated issues related to the computation of seismic risk maps. In 2000, Musson [10] proposed a framework the seismic risk assessment at regional level adopting as reference measure the EMS-98 scale [11], and highlighting the significant difference between hazard and risk curves. In Germany, Tyagunov et al. [12] developed a risk map based on the EMS-98 macroseismic intensity, in which they computed the mean damage ratio and losses for the German residential building stock. Worldwide, Zhongchun et al. [13] computed the seismic risk mortality map for the Chinese state, Huttenlau and Stotter analyzed the seismic risk of the Austrian Province of Tyrol [14], and Frolova et al. showed different approaches for the seismic risk computation in Russia, basing on the different extension of the considered area [15]. Regarding Italy, some first works adopting the MCS intensity scale for representing the seismic hazard and damage probability matrices can be found in [16-17-18]. Recently, researcher focused their attention on the development of more detailed fragility functions [19] and seismic risk maps, adopting quantitative intensity measures for the ground shaking, as the Peak Ground Acceleration (PGA). In 2011, Rota et al. [20] developed typological seismic risk maps for Italy, by simply convolving hazard, in terms of PGA, and vulnerability expressed by empirical typological fragility curves derived from data collected during post-earthquake survey after the main Italian events of the past 30 years. In [20], authors did not included exposure, due mainly to the lack of data. The contribute of exposure has been considered by Asprone et al. 2013 [21], who computed a possible seismic insurance premium for five different types of building categories within all the Italian territory, starting from the Italian seismic hazard map. In the last few years, the OpenQuake engine [22] has been adopted for developing maps of losses conditioned on ground motion with a specific return period, for Portugal [23], Nepal [24] and Turkey [25]. In these latter cases, the OpenQuake engine has been used with the s-called PSHA-approach, consisting in the calculation of the loss exceedance curve starting from the output of the hazard analysis, coupled with vulnerability and exposure. Literature review, showed as the computation of seismic risk maps is mainly subdivide into two main steps, the hazard computation, and then the risk estimation starting from hazard outputs. For this reason, this work proposes a novel-approach for computing the Italian seismic risk map for the residential building stock, directly starting from simulation of earthquake scenario consistent with the national seismogenic source model. This paper adopts as seismic synthetic risk indicator the Expected Annual Loss (EAL) that represents the potential economic loss to be yearly sustained to repair the seismic damage to the residential building asset of each Italian municipality. EAL is computed at three different levels of granularity, i.e. the most detailed municipal level (Municipal Expected Annual Loss, MEAL), the intermediate provincial level (Provincial Expected Annual Loss, PEAL), and the less refined regional level (Regional Expected Annual Loss, REAL), accordingly with the cogent administrative subdivision of Italy.

2 SEISMIC RISK COMPUTATION FRAMEWORK

The computation of the seismic risk in each municipality, and concretely the EAL estimation, requires a set of suitable models able to represent the spatial distribution of the hazard and the exposure, and the all the possible structural classes of the considered buildings assets.

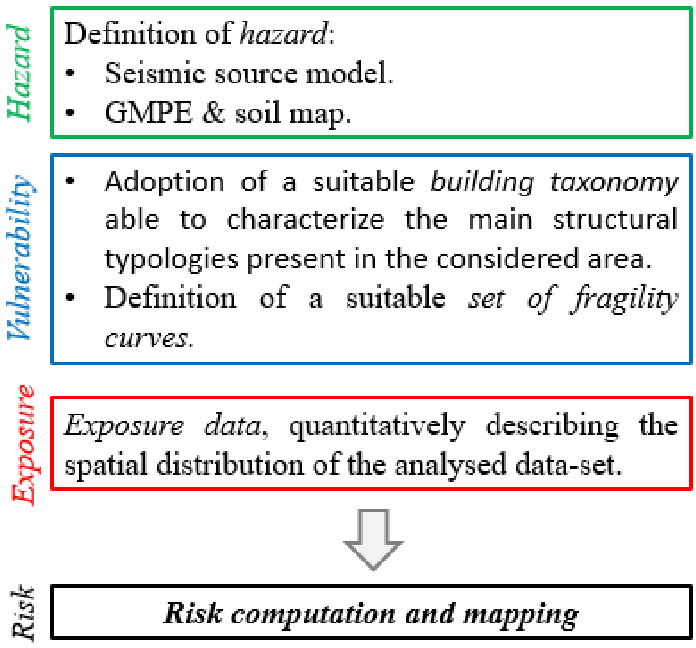

Figure 1: Main steps of the proposed framework

Figure 1 shows the main steps for the *MEAL* computation, whose input data are:

- Seismic source model represented by a set of *s* seismogenic zones (ZSs). Each ZS is characterized by a specific spatial shape, and by a Gutenberg–Richter law representing the seismogenic potential of the considered ZS. Furthermore, a suitable Ground

Motion Prediction Equation (GMPE) has to be adopted for the computation of the shaking field, jointly with a soil map representing the shear wave velocity in the first 30 m soil-depth ($v_{s,30}$);
- A building taxonomy able to represent all the structural typologies that are present in the considered area. Each of the *p* taxonomy classes (TCs) is characterized by common seismic vulnerability features. Formally, each TC is characterized by a set of fragility curves able to express the exceedance probabilities of a set of *q* mutually-exclusive and collectively-exhaustive damage states (DSs). Commonly, fragilities are derived analytically via the use of structural models [26], or empirically, starting from evidences of structural damage due to occurred earthquakes [27].
- Exposure data: they have to provide the spatial distribution of the analysed asset. In particular, exposure data provides the built area of each *p* taxonomy class, for every municipality.

The first passage consists in the creation of a grid of *e* epicenter, and in the definition of a set of *m* magnitude values between $M_{w,min}$ and $M_{w,max}$ for each i^{th} SZ, with $t=1...s$. Earthquakes scenario analysis have thus to be run in every x^{th} municipality centroid ($x = 1 \dots n$), for every j^{th} epicenter ($j = 1 \dots e$) and for every k^{th} ($k = 1 \dots m$) magnitude, belonging to each i^{th} SZ ($i = 1 \dots s$). By using the GMPE it is possible to compute the correspondent value of the adopted intensity measure *IM*, in each x^{th} municipality, namely $IM_{x,k,j,i}$, and consequently the associated total losses $L_{x,k,j,i}$ as sum of direct losses over the *p* TCs

$$L_{x,k,j,i} = \sum_{y=1}^{p} L_{x,k,j,i,y} \tag{1}$$

where $L_{x,k,j,i,y}$ can be computed as

$$L_{x,k,j,i,y} = RCR_{Tot,y,x,k,j,i} \cdot A_{y,x} \cdot URC_y \tag{2}$$

In Equation (2), $A_{y,x}$ represents the built area of the y^{th} TC in the x^{th} municipality, URC_y is the unit repair cost for the y^{th} TC (in €/m^2), and $RCR_{Tot,y,x,k,j,i}$ is the total repair cost ratio of the y^{th} TC, that can be computed as

$$RCR_{Tot,y,x,k,j,i} = \sum_{z=0}^{q} P\left[DS_{z,y} \mid IM_{x,k,j,i}\right] \cdot RCR_{z,y} \tag{3}$$

where $RCR_{z,y}$ are a set of repair cost ratios (i.e., ratio between unit cost to repair a building in a specific damage state and the unit replacement cost), assumed deterministic and homogeneous for each y^{th} TC. In Equation (3), $P\left[DS_{z,y} \mid IM_{x,k,j,i}\right]$ is computed as

$$P\left[DS_{z,y} \mid IM_{x,k,j,i}\right] = P\left[DS_{z,y} \mid \geq ds_{z,y} \mid IM_{x,k,j,i}\right] - P\left[DS_{z+1,y} \mid \geq ds_{z+1,y} \mid IM_{x,k,j,i}\right] \tag{4}$$

and assuming $P[DS_{0,y} \geq ds_{0,y} \mid IM_{x,k,j,i}] = 1$ and $P[DS_{5,y} \geq ds_{5,y} \mid IM_{x,k,j,i}] = 0$.
The damage state exceedance probability of the z^{th} DS for the y^{th} TC, in each x^{th} municipality centroid, in computed via fragility curves as

$$P\left[DS_{z,y} \geq ds_{z,y} \mid IM_{x,k,j,i}\right] = \Phi\left[\frac{1}{\sigma_{DS_{z,y}}}\ln\left(\frac{IM_{x,k,j,i}}{\mu_{DS_{z,y}}}\right)\right] \tag{5}$$

At this stage, for each x^{th} municipality a set of *e* losses caused by each k^{th} magnitude, generated by the i^{th} SZ is available. This vector of data represents the probability density function (*pdf*) of direct losses conditioned on the specific magnitude value k^{th}. From this samples, is thus straightforward to compute *ad hoc* statistics, as the sample mean, representing the distribution expected value, and other percentile of interest (25$^{\text{th}}$, 50$^{\text{th}}$, 75$^{\text{th}}$ ecc). In the following the paper assumes the mean value as relevant statistic, namely $L_{x,k,mean,i}$. The final step of the proposed procedure consists in the computation of the $MEAL_{x,mean,i}$ in each x^{th} municipality due to losses cause by the i^{th} SZ. This calculation can be performed according to Figure 2 by associating to each $L_{x,k,mean,i}$ the corresponding mean annual rate $\nu_{k,i}$ of exceeding a certain moment magnitude $M_{k,i}$ in the i^{th} SZ, and applying the total probability theorem. $\nu_{k,i}$ can be easily computed from the Gutenberg-Richter (GR) recurrence law, given by the following expression

$$\log\left(\nu_{k,i}\right) = a_i - b_i \cdot M_{k,i} \tag{6}$$

where a_i is the total seismicity rate and b_i is the negative slope of the GR law for the i^{th} SZ. The expected annual loss, in the x^{th} municipality, due to seismicity arising from the i^{th} SZ is thus given by

$$MEAL_{x,mean,i} = \int_0^{\nu_{M_{\min,i}}} L_{x,mean,i}\left(M\right)\left|d\nu_{M,i}\right| \tag{7}$$

As Figure 2 shows, two additional points are introduced for the computation of Eq. (7), consistently with the following assumption:

- A minimum magnitude value $M_{min,i}$ is assumed for each zone, aiming to remove small events characterized by negligible impacts in terms of structural damage and thus losses. For this reason, earthquakes with magnitudes lower than $M_{min,i}$ are associated to zero loss;
- Since every zone, basing on its seismological characteristics, is characterized by a maximum magnitude $M_{max,i}$, the loss exceedance curve is truncated in correspondence of $M_{max,i}$, excluding in this way from the computation higher impossible losses.

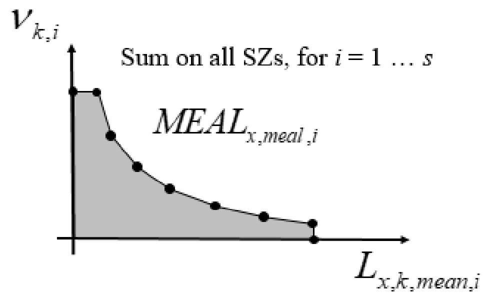

Figure 2: MEAL computation.

The MEAL considering the contribution of every SZ determining the seismicity of the considered x^{th} municipality, can be computed by simply adding each contribution as:

$$MEAL_{x,mean} = \sum_{i=1}^{s} MEAL_{x,mean,i} \tag{8}$$

Once the $MEAL_{x,mean}$ is computed for each n municipalities, results can be mapped thus obtaining the seismic risk map. Since $MEAL_{x,mean}$ is strongly influenced by the exposure, it is possible to refer the $MEAL_{x,mean}$ to the build surface in each municipality, i.e. the $MEAL_{x,mean}$ for 1 m^2 of built area in each x^{th} municipality, obtaining in this way the $UMEAL_{x,mean}$ as:

$$UMEAL_{x,mean} = \frac{MEAL_{x,mean}}{\sum_{y=1}^{p} A_{y,x}} \tag{9}$$

Finally, a dimensionless indicator is introduced to easily rank seismic risk throughout a country, i.e. the Municipality Seismic Risk Class (*MSRC*, in % of replacement cost), estimated as:

$$MSRC_{x,mean} = \frac{UMEAL_{x,mean}}{URC_y} \tag{10}$$

The same three risk indicators can be easily computed also for different granularity levels, as the provincial and regional level. The development of a seismic risk map is therefore a key-starting point for the definition of a rational seismic mitigation program for a country, since it allows government to understand needs and priorities, and compare resulting benefits with costs associated to the implementation of specific seismic retrofitting schemes [28].

3 APPLICATION TO ITALY

The proposed framework is applied to compute the seismic risk map for the residential building stock of Italy, considering as target losses the reconstruction cost of damaged structural elements (i.e. the so-called *direct losses*). However, the framework is general and flexible and can be applied to different target losses, as losses due to business interruption [29], losses due to failure of spatially distributed networks [30-31], or losses arising from different natural hazards [32], for which the same conceptual scheme can be applied.

3.1 Hazard model

The ZS9 model [33] has been adopted for describing the Italian seismicity; parameters of the GR law for each i^{th} SZ are taken from [34] and the values showed in Figure 3. In particular, a 5-km mesh grid of epicenters is adopted, for a total of 7237 points. Sardinia has not been considered in the computation, since the ZS9 model does not provide SZs for this region.

Regarding the GMPE model, the formulation proposed by Bindi et al. [35] is adopted, jointly with the $v_{s,30}$ soil map provided by the United States Geological Survey (USGS) [36]. Finally, for each i^{th} SZ a total of m = 6 magnitudes between $M_{min,i}$ and $M_{max,i}$ have been adopted.

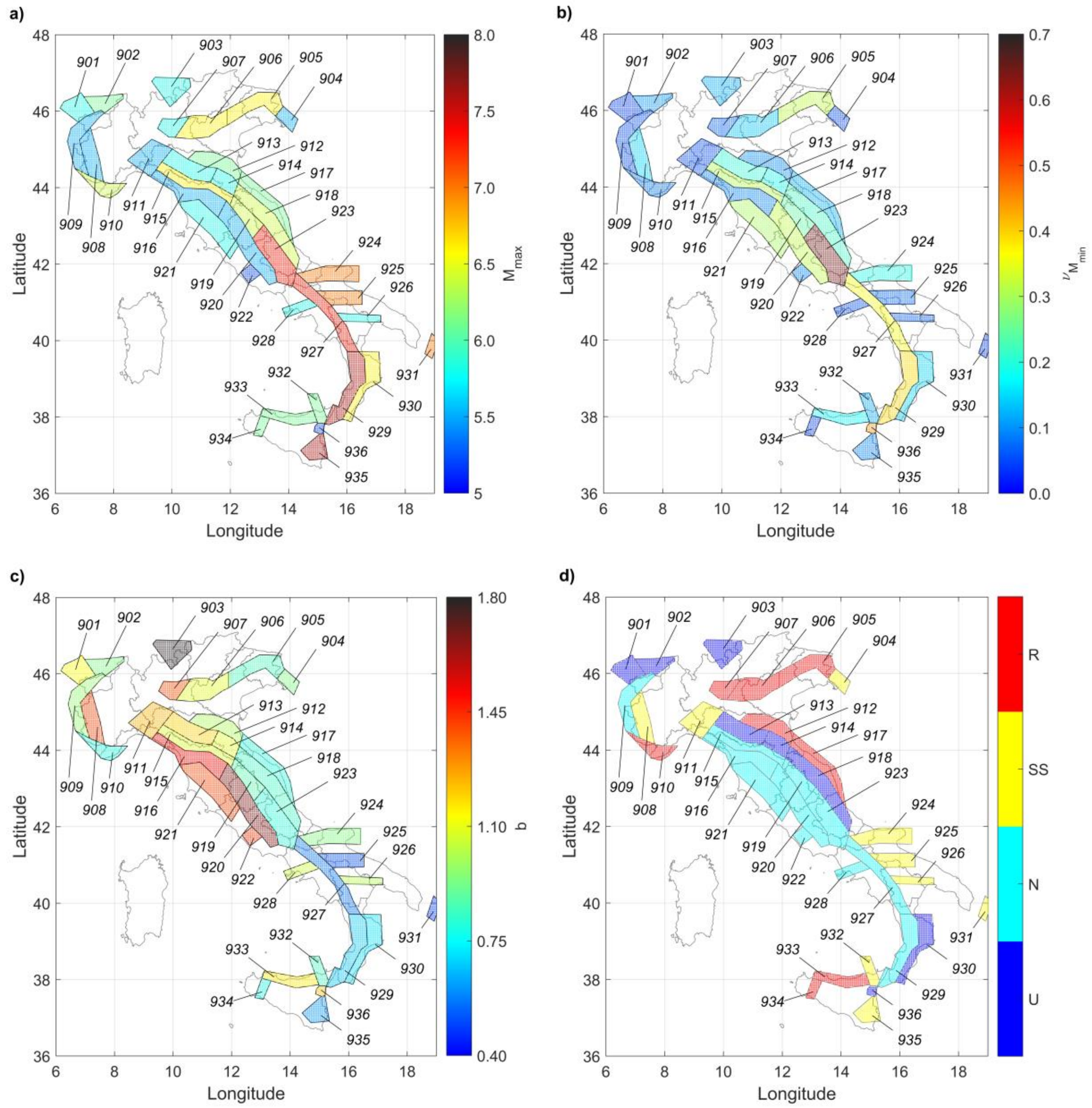

Figure 3: Seismogenic source model: M_{max} (a) and $\nu_{M_{min}}$ (b) values, G-R *b* coefficients, and d) prevailing mechanism of faulting for each SZ (U = undetermined, N = normal, SS = strike-slip, R = reverse).

3.2 Vulnerability Model

For characterizing the seismic vulnerability of the analyzed building stock, a suitable building taxonomy has been adopted. In particular, 8 TC classes have been adopted for representing the residential building stock of Italy, each one characterized by a set of fragility curves related to four mutually exclusive and collectively exhaustive damage states (i.e. DS_1, DS_2, DS_3, DS_4 respectively related to slight, moderate, extensive and complete damage), according to [37]. Two masonry classes have been adopted for characterize masonry buildings, according to Kostov et al. [38]: masonry building built before 1919, and after 1919. As regards reinforced concrete (RC) structures, the first important distinction is between gravity load designed and seismic load designed. The subdivision for each municipality between the two classes, have been performed by using the ECS-IT software which provide the temporal evolution of the Italian seismic code in each municipality [39]. Moreover, since the census data is classified per decade (i.e. in 1971, 1981, and 2001), a linear variation with time was assumed in order to bridge the gap between the milestone years marking the code evolution and the census ten-year classification. A further subdivision has also been performed both for RC-gravity and RC-seismic buildings, considering the number of stories and thus defining two additional subclasses (1-2 story, 3 or more stories). Fragility parameters for the four reinforced concrete TCs have been taken from Ahmad et al. [40]. Finally, two TCs have been considered representative of "other" mixed structural types, particularly combined RC-masonry, again subdivided in gravity-load and seismic-load designed, with the same approach adopted for RC classes [35]. All main parameters of the adopted fragilities are listed in Table 1.

Taxonomy Class	Damage State	$\mu_{DS_{z,y}}$ [g]	$\sigma_{DS_{z,y}}$
Masonry – pre 1919	DS_1	0.10	0.79
	DS_2	0.14	0.80
	DS_3	0.17	0.81
	DS_4	0.24	0.80
Masonry – post 1919	DS_1	0.12	0.79
	DS_2	0.17	0.81
	DS_3	0.19	0.79
	DS_4	0.33	0.79
RC - Gravity | 1-2	DS_1	0.09	0.33
	DS_2	0.12	0.44
	DS_3	0.25	0.37
	DS_4	0.33	0.36
RC - Gravity | 3+	DS_1	0.08	0.32
	DS_2	0.11	0.43
	DS_3	0.17	0.40
	DS_4	0.22	0.38
RC - Seismic | 1-2	DS_1	0.09	0.33
	DS_2	0.12	0.44
	DS_3	0.24	0.37
	DS_4	0.48	0.36
RC - Seismic | 3+	DS_1	0.08	0.32
	DS_2	0.11	0.41
	DS_3	0.17	0.39
	DS_4	0.31	0.36
Other - Gravity	DS_1	0.11	0.79
	DS_2	0.16	0.78
	DS_3	0.27	0.78
	DS_4	0.35	0.79
Other - Seismic	DS_1	0.12	0.79
	DS_2	0.19	0.79
	DS_3	0.30	0.79
	DS_4	0.41	0.79

Table 1: Main parameters of fragility curves for each TC and DS.

3.3 Exposure Model

The exposure of the national residential building is based on the 15th census database of the National Institute of Statistics [41], from which the built area of each TC has been computed, as in [34]. The unit repair cost has been assumed constant among the eight TCs and equal to 1200 €/m^2. Figure 3a shows the total build area in each municipality, while Figure 3b shows the exposed value. Regarding, the percentage disaggregation of the TCs, Figure 3c shows that masonry structures are the most diffused structural typology within all the Italian municipalities. Regarding the $RCR_{z,y'}$ they have been assumed constant among the TCs and equal to [0.15, 0.40, 0.65, 1], respectively for DS_1, DS_2, DS_3 and DS_4, resulting from statistical post-processing of rough data [42].

3.4 Seismic Risk computation

For the *MEAL* computation the expected value of the loss distribution *f(L|M)* has been assumed as reference statistic. *EAL* is computed first at municipality level (*MEAL*), and then aggregated for obtaining the *EAL* at provincial level (*PEAL*), and the EAL at regional level (*REAL*), according to the administrative subdivision of Italy.

Figure 4 shows results for the three adopted granularity levels. In particular, it is worth to note as in this case the risk maps in terms of absolute EAL are highly influenced by the spatial distribution of the exposure. The contribution of each SZ to the *EAL* of each municipality can be found in Zanini et al. [43].

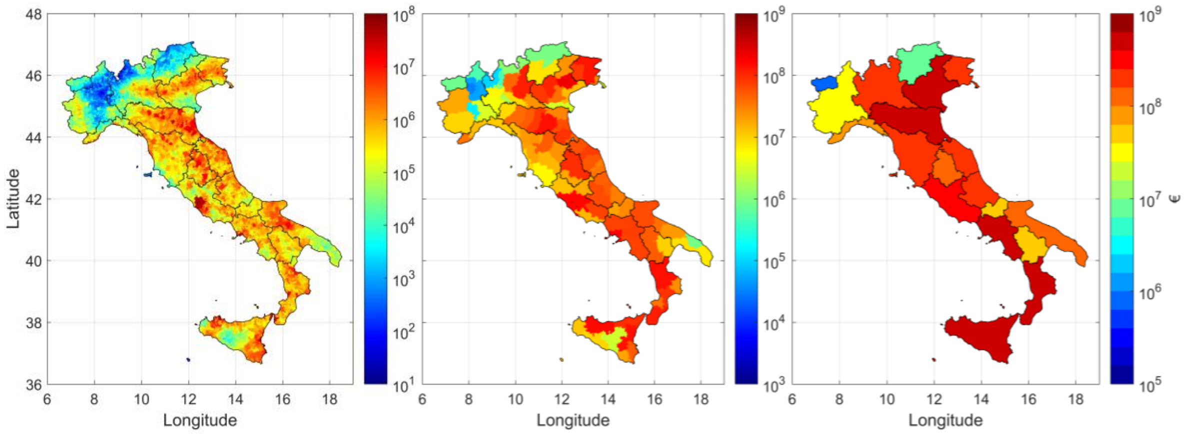

Figure 4: The seismic risk map of Italy in terms of MEAL (left), PEAL (center), REAL (right).

The same maps can therefore be expressed in relative terms using the following unitary metric, the *UMEAL* (i.e. the *MEAL* for 1 m^2 built area in each municipality, in €/m^2), the *UPEAL* (i.e. the *PEAL* for 1 m^2 built area in each province, in €/m^2), and the *UREAL* (i.e. the *REAL* for 1 m^2 built area in each region, in €/m^2). *UMEAL*, *UPEAL* and *UREAL* map, showed in Figure 5, allows to better detail the effective spatial distribution of seismic risk, since they represent risk in relative terms, and can be used as a basic metric when dealing with defining insurance coverage schemes.

In particular, Figure 5 shows the beneficial effect of computing seismic risk at higher granularity levels than respect to the more refined municipal level. Indeed, the maximum amount of *UMEAL* of 17-18 €/m^2 drops to 5-6 17-18 €/m^2 for *UPEAL* and *UREAL*. Previous risk maps reported in Figure 4 and Figure 5, detail seismic risk of Italy quantifying in economic terms its impact: such risk maps are therefore relevant for stakeholders (e.g. government, research institutes, insurance, industry, banks).

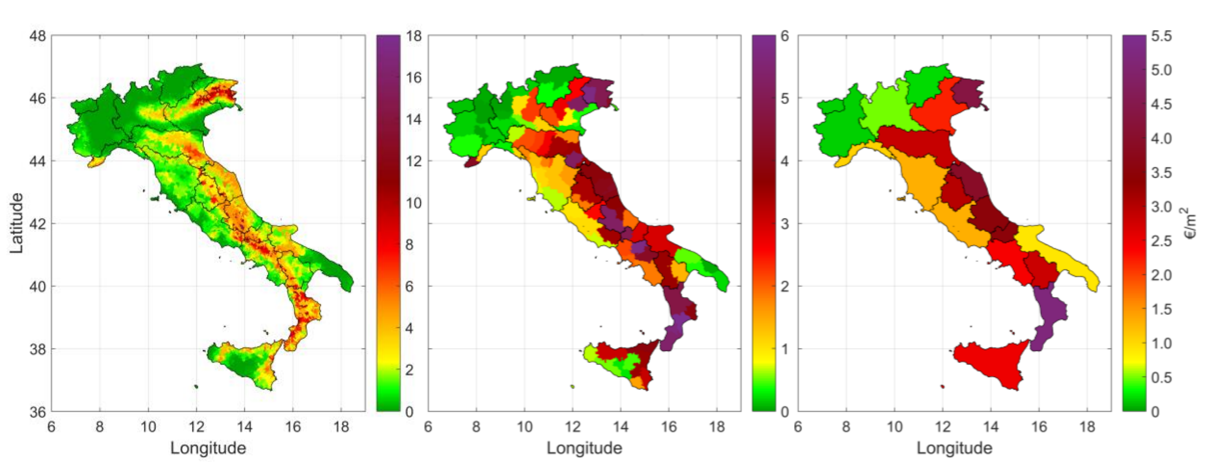

Figure 5: The seismic risk map of Italy in terms of *UMEAL* (left), *UPEAL* (center), *UREAL* (right).

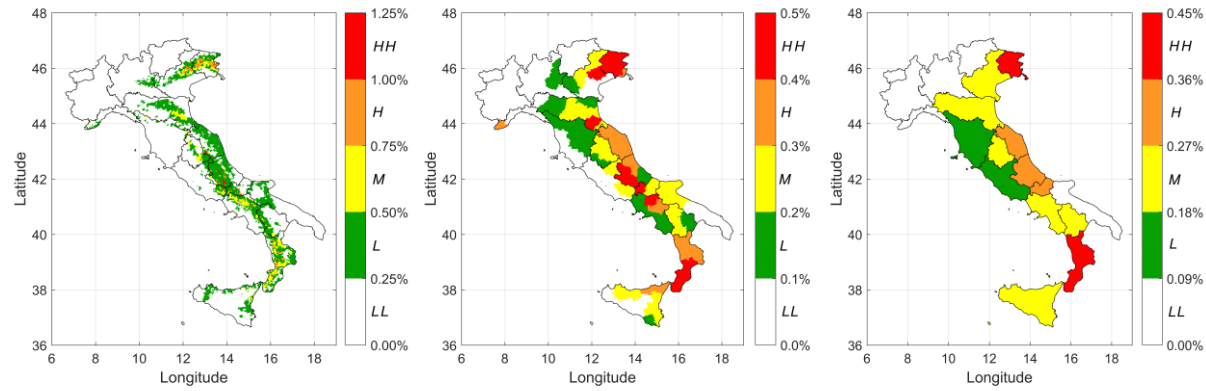

Figure 6: The seismic risk map of Italy in terms of *MSRC* (left), *PSRC* (center), *RSRC* (right).

A qualitative and dimensionless seismic risk indicator can be obtained from the ratio between *UMEAL* and the *URC* value, namely the Municipality Seismic Risk Class (*MSRC*). The same calculation can be performed also at provincial level, obtaining the Provincial Seismic Risk Class (*PSRC*), and at regional level (*RSRC*, Regional Seismic Risk Class).

For all three different granularity levels the range between 0 and the correspondent maximum value, has been subdivided in 5 classes, finding five different risk levels: Very Low Seismic Risk (*LL*), Low Seismic Risk (*L*), Medium Seismic Risk (*M*), High Seismic Risk (*H*), and Very High Seismic Risk (*HH*). Table 2 shows the range on each class for the three granularity levels, while Figure 5 show the *MSRC*, *PSRC* and *RSRC* map.

	LL	*L*	*M*	*HH*	*HH*
MSRC [%]	0.00 - 0.25	0.25 - 0.50	0.50 - 0.75	0.75 - 1.00	1.00 - 1.25
PSRC [%]	0.00 - 0.10	0.10 - 0.20	0.20 - 0.30	0.30 - 0.40	0.40 - 0.50
RSRC [%]	0.00 - 0.09	0.09 - 0.18	0.18 - 0.27	0.27 - 0.36	0.36 - 0.45

Table 2: *MSRC*, *PSRC* and *RSRC* range values for the adopted seismic risk ratings.

4 CONCLUSION

Seismic risk maps are a key tool for public authorities of countries prone to significant losses due to earthquakes, for developing suitable seismic risk transferring solutions. The described formulation deals with this specific topic, proposing an overall framework for computing the seismic risk and introducing some useful risk indicators. In particular, an application to the Italian residential building stock is reported and seismic risk maps for Italy are computed. For this scope, a detailed hazard, vulnerability and exposure models are assumed. Seismogenic zones are used for representing the seismicity of Italy, while eight taxonomy classes are assumed for describing the different vulnerability of the residential Italian buildings. The Expected Annual Loss is used as suitable risk indicator, representing the yearly amount that has to be save for facing possible significant future losses. In the application, *EAL* computation is performed at three granularity levels, municipal (*MEAL*), provincial (*PEAL*), and regional level (*REAL*). Results showed as this first risk indicator, in the Italian case, is strictly related to the exposure. Seismic risk maps have been computed also in terms of *UMEAL*, *UPEAL* and *UREAR*, that represent each municipal, provincial and regional *EAL* referred to the corresponding built area of each municipality, province and region. Results show as considering less refined granularity has an averaging effect on the risk computation. Finally, a-dimensional seismic risk maps have been computed and used for providing qualitative and immediate risk maps of Italy. Resulting maps depict national seismic risk spatial distribution, thus providing reliable information to government agencies, which can promote specific mitigation intervention at the territorial scale to reduce the impact of future earthquakes in the areas mostly. Risk maps are a fundamental tool for knowing the current exposure to seismic risk of a wide territory, and provide a quantitative tool for evaluating the benefit associated to a possible national retrofit scheme, and for designing possible sustainable financial risk reduction programs.

REFERENCES

[1] Munich RE, 2017, Natural catastrophes 2016 - Analyses, assessments, positions, 2017 Issue.

[2] J.E. Daniell, B. Khazai, F. Wenzel, A. Vervaeck, *The CATDAT damaging earthquakes database*, Nat. Hazards Earth Syst. Sci., **11**, 2235–2251, 2011.

[3] F. Faleschini, M.A. Zanini, L. Hofer, Reliability-based analysis of recycled aggregate concrete under carbonation, *Advances in Civil Engineering*, ID 4742372, 2018.

[4] H. Cutler, M. Shields, D. Tavani, and S. Zahran, Integrating engineering outputs from natural disaster models into a dynamic spatial computable general equilibrium model of Centerville, *Sustainable and Resilient Infrastructure*, **1(3-4)**, 169-187, 2016.

[5] L. Luzi, S. Hailemikael, D. Bindi, D. F. Pacor, F. Mele, F. Sabetta, ITACA (ITalian ACcelerometric Archive): A Web Portal for the Dissemination of Italian Strong-motion Data, *Seismological Research Letters*, **79(5)**, 716–722, 2008.

[6] F. Pacor, R. Paolucci, L. Luzi, F. Sabetta, A. Spinelli, A. Gorini, M. Nicoletti, S. Marcucci, L. Filippi, M. Dolce, Overview of the Italian strong motion database ITACA 1.0, *Bulletin of Earthquake Engineering*, **9(6)**, 1723–1739, 2011.

[7] DM 65, Sisma Bonus – Linee guida per la classificazione del rischio sismico delle costruzioni e relativi allegati. Modifiche all'articolo 3 del Decreto Ministeriale n° 58 del 28/02/2017. Ministero delle Infrastrutture e dei Trasporti, Roma (in Italian), 2017.

[8] K.A. Porter, An Overview of PEER's Performance-based Earthquake Engineering Methodology, *Proceedings of Ninth International Conference on Applications of Probability and Statistics in Engineering*, San Francisco, CA, 2003.

[9] K.A., Porter, J.L. Beck, R. Shaikhutdinov, Simplified Estimation of Economic Seismic Risk for Buildings, *Earthquake Spectra*, **20(4)**, 1239−1263, 2004.

[10] R. M. W. Musson, Intensity-based seismic risk assessment, *Soil Dynamic and Earthquake Engineering*, **20**, 353–360, 2000.

[11] G. Grünthal, European Macroseismic Scale 1998. European Seismological Commission, Subcommission on Engineering Seismology, Working Group Macroseismic Scales, *Cahiers du Centre Européen de Géodynamique et de Séismologie*, Luxemburg, 1998.

[12] S. Tyagunov, G. Grunthal, R. Wahlstrom, L. Stempniewski, J. Zschau, Seismic risk mapping for Germany, N*at. Hazards Earth Syst. Sci.*, **6(4)**,573–586, 2006.

[13] X. Zhongchun, W. Shaohong, D. Erfu, L. Kaizhong, Quantitative assessment of seismic mortality risks in China, *J. Resour. Ecol.*, **2(1)**, 83–90, 2011.

[14] M. Huttenlau, J. Stotter, Risk-based damage potential and loss estimation of earthquake scenarios in the moderate endangered Austrian Federal Province of Tyrol, *Georisk: Assess. Manag. Risk Eng. Syst. Geohazards*, **6(2)**, 105–127, 2012.

[15] N.I. Frolova, V.I. Larionov, J. Bonnin, S.P. Sushchev, A.N. Ugarov, M.A. Kozlov, Seismic risk assessment and mapping at different levels, *Natural Hazards*, **88**, S43–S62, 2017.

[16] A. Lucantoni, V. Bosi, F. Bramerini, R. De Marco, T. Lo Presti, G. Naso, F. Sabetta, Seismic risk in Italy, *Ingegneria Sismica*, **17(1)**, 5-36, 2001 (in Italian).

[17] G. Zuccaro, Inventory and vulnerability of the residential building stock at a national level, seismic risk and socio/economic loss maps. CD-ROM, Naples, Italy, 2004 (in Italian).

[18] F. Bramerini, G. Di Pasquale Updated seismic risk maps for Italy. *Ingegneria Sismica*, **15(2)**, 5-23, 2009 (in Italian).

[19] H. Crowley, M. Colombi, B. Borzi, M. Faravelli, M. Onida, M. Lopez, D. Polli, F. Meroni, R. Pinho, A comparison of seismic risk maps for Italy, *Bullettin of Earthquake Engineering*, **7(1)**, 149–180, 2009.

[20] M. Rota, A. Penna, C. Strobbia, G. Magenes, Typological seismic risk maps for Italy, *Earthquake Spectra*, **27(3)**, 907–926, 2011.

[21] D. Asprone, F. Jalayer, S. Simonelli, A. Acconcia, A. Prota, G. Manfredi, Seismic insurance model for the Italian residential building stock, *Structural Safety*, **44**, 70–79, 2013.

[22] V. Silva, H. Crowley, M. Pagani, D. Monelli, R. Pinho, Development of the OpenQuake engine, the Global Earthquake Model's open-source software for seismic risk assessment, *Natural Hazards*, **72**, 1409–1427, 2012.

[23] V. Silva, H. Crowley, H. Varum, R. Pinho, Seismic risk assessment for mainland Portugal, *Bulletin of Earthquake Engineering*, **13**, 429–457, 2015.

[24] H. Chaulagain, H. Rodrigues, V. Silva, E. Spacone, H. Varum, Seismic risk assessment and hazard mapping in Nepal, *Natural Hazards*, **78**, 583–602, 2012.

[25] V. Silva, H. Crowley, M. Pagani, R. Pinho, D. Monelli, Development and Application of OpenQuake, an Open Source Software for Seismic Risk Assessment, *Proceedings of 15th World Conference on Earthquake Engineering - WCEE*, Lisbon, Portugal, September 24-28 2012.

[26] M.A. Zanini, L. Hofer, F. Faleschini, C. Pellegrino, The influence of record selection in assessing uncertainty of failure rates, *Ingegneria Sismica*, **34 (4)**, pp. 30-40, 2017.

[27] L. Hofer, P. Zampieri, M.A. Zanini, F. Faleschini, C. Pellegrino, Seismic damage survey and empirical fragility curves for churches after the August 24, 2016 Central Italy earthquake, *Soil Dynamics and Earthquake Engineering*, **111**, 98-109, 2018

[28] F. Faleschini, J. Gonzalez-Libreros, M.A. Zanini, L. Hofer, L. Sneed, C. Pellegrino, Repair of severely-damaged RC exterior beam-column joints with FRP and FRCM composites, *Composite Structures*, **207**, pp. 352-363, 2019.

[29] L. Hofer, M.A. Zanini, F. Faleschini, C. Pellegrino, Profitability Analysis for Assessing the Optimal Seismic Retrofit Strategy of Industrial Productive Processes with Business-Interruption Consequences, *Journal of Structural Engineering (United States)*, **144(2)**, 4017205, 2018.

[30] M.A. Zanini, C. Vianello, F. Faleschini, L. Hofer, G. Maschio, A framework for probabilistic seismic risk assessment of NG distribution networks, *Chemical Engineering Transactions*, **53**, pp. 163-168, 2016

[31] M.A. Zanini, L. Hofer, F. Faleschini, P. Franchetti, C. Pellegrino, Maintenance and seismic retrofit cost assessment of existing bridges, Maintenance, *Monitoring, Safety, Risk and Resilience of Bridges and Bridge Networks - Proceedings of the 8th Interna-*

tional Conference on Bridge Maintenance, Safety and Management, IABMAS 2016, pp. 1106-1112, 2016.

[32] M.A. Zanini, L. Hofer, F. Faleschini, C. Pellegrino, Building damage assessment after the Riviera del Brenta tornado, northeast Italy, *Natural Hazards*, **86(3)**, pp. 1247-1273, 2017

[33] C. Meletti, F. Galadini, G. Valensise, M. Stucchi, R. Basili, S. Barba, G. Vannucci, E. Boschi, A seismic source zone model for the seismic hazard assessment of the Italian territory, *Tectonophysics*, **450**, 85–108, 2008

[34] S. Barani, D. Spallarossa, P. Bazzurro, Disaggregation of probabilistic ground-motion hazard in Italy, *Bull. Seismol. Soc. Am.*, **99 (5)**, 2638–2661, 2009.

[35] D. Bindi, F. Pacor, L. Luzi, R. Puglia, M. Massa, G. Ameri, R. Paolucci, Ground motion prediction equations derived from the Italian strong motion database, *Bulletin of Earthquake Engineering*, **9(6)**, 1899–1920, 2011.

[36] T.I. Allen, D.J. Wald, Topographic slope as a proxy for global seismic site conditions (v_{s30}) and amplification around the globe: U.S. Geological Survey Open-File Report2007-1357, 69 pp.

[37] M.A. Zanini, l. Hofer, C. Pellegrino, A framework for assessing the seismic risk map of Italy and developing a sustainable risk reduction program, *International Journal of Disaster Risk Reduction*, **33**, 74–93, 2019.

[38] M. Kostov, E. Vaseva, A. Kaneva, N. Koleva, G. Verbanov, D. Stefanov, E. Darvarova, D. Salakov, S. Simeonova, L. Cristoskov, Application to Sofia. RISK-UE, WP13, 2004.

[39] ECS-IT; 2015: Evoluzione della Classificazione Sismica in Italia. Retreived online at www.reluis.it/index.php?option=com_content&view=article&id=399&Itemid=185&lang=it

[40] N. Ahmad, H. Crowley, R. Pinho, Analytical fragility functions for reinforced concrete and masonry buildings aggregates of Euro-Mediterranean regions – UPAV methodology. Internal report, Syner-G Project, 2009/2012, 2011.

[41] Istituto Nazionale di Statistica, 15-esimo Censimento Generale della popolazione e delle abitazioni, 2011. Postel Editore, Roma (in Italian), 2011.

[42] M. Dolce, G. Manfredi, Libro bianco sulla ricostruzione privata fuori dai centri storici nei comuni colpiti dal sisma dell’Abruzzo del 6 aprile 2009. Doppiavoce Edizioni, pp.224 (in Italian), 2015.

[43] M.A. Zanini, L. Hofer, F. Faleschini, K. Toska, C. Pellegrino, Municipal expected annual loss as an indicator to develop seismic risk maps in Italy, *Bollettino di Geofisica Teorica ed Applicata*, DOI 10.4430/bgta0262, Accepted.