Featured Article (Research Paper)

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From Earthquake Geophysical Measures to Insurance Premium: A Generalised Method for the Evaluation of Seismic Risk, with Application to Italy's Housing Stock

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Abstract: Following the increasing necessity of quantitative measures for the impact of natural catastrophes, this paper proposes a new technique for a probabilistic assessment of seismic risk by using publicly available data on the earthquakes that have occurred in Italy. We implement an insurance-oriented methodology to produce a new map of the seismic risk and to evaluate, under various hypotheses, the costs of insuring all the Italian housing units against it. The model is compared with two main privately developed models, well known in the reinsurance industry, providing fairly similar results.

Keywords: earthquakes, seismic risk, exceedance loss, insurance pricing

JEL codes: G22

1 Introduction

The growing impact of natural catastrophes (so called NAT CAT) all over the world has generated a research effort to shift from purely qualitative evaluations of these events to quantitative and probabilistic approaches. The international agencies engaged in supporting the communities affected by these events have increasingly sponsored this line of research (UNIDSR 2015).

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Within this framework, our paper proposes a model to measure the seismic risk of Italy and to analyse how insurance can protect its housing stock from it. The relevance of these issues arises from the intensity of the seismic risk affecting Italy as well as from the high share of households' wealth invested in real estate.

The final aim of a catastrophe model is to estimate the probability distribution of the losses caused by a natural event on a portfolio of housing units. According to an approach pioneered by Friedman in 1984 (see also Mitchell-Wallace et al. 2017), three main factors contribute to jointly determine the amount of the losses: hazard, exposure, and vulnerability. Hazard is the physical event generating the risk with a certain distribution of probability, intensity and location; exposure is the set of assets that could be affected by a hazard; vulnerability represents the damaging effect (from 0 to 100%) of different hazards over different kinds of exposure. Hazard modelling is clearly a key element and it could be implemented by two main approaches: through a stochastic scenario generating module in which physical phenomena are modelled and simulated to create a large scale event database, or through a historical estimation of some key hazard measures. We follow the latter approach, but we remark that all the models present a margin of error because the natural phenomena modelled are very complex, highly interconnected and rapidly evolving. Moreover, some kinds of hazards, like floods and storms, are also affected by the climate change (Charpentier 2008; Kunreuther and Michel-Kerjan 2007; Poljanšek et al. 2017, p. 45).

Compared to the existing models, our main contribution is to propose a new evaluation method of the seismic-risk probability, based on publicly available datasets and suitable for insurance purposes. We apply such a method to compute the main indicators of comprehensive insurance coverage for all the Italian housing units, obtaining results in line with the main industry proprietary CAT models.

The paper is organised as follows. The second section describes Italy's seismic risk and the third presents a general overview of the under-insurance for natural risk, with a focus on how this problem affects Italy. Since the paper concentrates on seismic risk, the fourth section briefly reports the main measures of earthquake strength and the fifth summarises the approach to seismic risk assessment used by the Italian National Institute of Geophysics and Vulcanology (the government agency providing the official measures of seismic and volcanic risks for all the Italian territory). The sixth section proposes a new method for a probabilistic assessment of Italy's seismic risk and describes two applications for it: (1) a probabilistic geographical representation of risk, (2) an evaluation of the insurance coverage of all the Italian housing units. The seventh and last section concludes.

2 The Seismic Risk of Italy

The simulation models put Italy in the first place in Europe and the eighth on a worldwide scale, as for the possible size of the economic losses generated by earthquakes. The damages caused by a seismic event with a 250-year return period (i.e. which occurs on average every 250 years) would amount to 50 billion euros (3% of the Italian GDP's value for the year 2016, SwissRe 2015). This, of course, could not translate in a similar amount of insurance losses, due to the structural under-insurance of the Italian market, as discussed in the next paragraph. By comparison, the exposure to flood risk is deemed to be lower, in the sense that for a similar return period, the potential economic damage is about one third of earthquake damage (SwissRe 2016). According to the Italian Insurance Industry Association, ANIA (2011), a yearly average loss of 0.006% of the total value of the Italian building stock is caused by floods, as opposed to 0.067% from earthquakes. Historically (since 1950), earthquake victims (around 5000, of which 97% as an aftermath of the worst five seismic events, Figure 1) have been 4 times higher than those caused by floods (1100). The share of the Italian population exposed to high or very high seismic risk amounts to 40.6%, whereas that exposed to medium or high flood risk is 5.3% (Table 1). In perspective, however, because of the climate change, the flood risk is going to be adversely affected.

Seismic risk is intense along the Apennine range, where both frequency and severity of earthquakes have been historically high and remain potentially dangerous, because of the geologic activity of the area caused by the constant shift of the underlying faults and the likely ongoing subduction of the Euro-Asiatic plate under the African one (Lovett 2011).

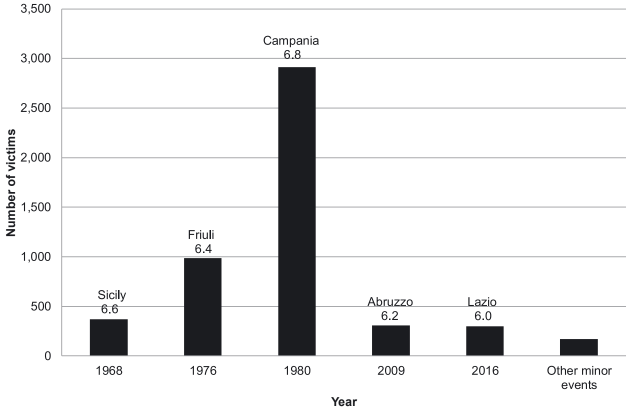

Figure 1: Intensity (Mw) and the number of victims of the major earthquakes occurred in Italy since 1950(a).
(a) See Section 4 for the definition of Mw.

Table 1: Exposure of Italian municipalities and population to different levels of seismic and flood risk, 2017.

Seismic risk level[b]	Flood risk level[a]									
	Absent		Low		Medium		High		Total	
	Municipalities[c] (units, %)									
Low	2536	31.8%	521	6.5%	52	0.7%	2	0.0%	**3111**	**39.0%**
Medium	1493	18.7%	350	4.4%	141	1.8%	11	0.1%	**1995**	**25.0%**
High	2054	25.7%	83	1.0%	32	0.4%	2	0.0%	**2171**	**27.2%**
Very high	688	8.6%	13	0.2%	0	0.0%	0	0.0%	**701**	**8.8%**
Total	**6771**	**84.9%**	**967**	**12.1%**	**225**	**2.8%**	**15**	**0.2%**	**7978**	**100.0%**
	Population[c] (million, %)									
Low	14.7	24.3%	3.0	4.9%	0.3	0.6%	0.0	0.0%	**18.0**	**29.8%**
Medium	11.1	18.3%	4.6	7.7%	2.1	3.4%	0.1	0.2%	**17.9**	**29.6%**
High	19.8	32.7%	1.2	2.0%	0.7	1.1%	0.0	0.0%	**21.8**	**35.9%**
Very high	2.7	4.5%	0.1	0.2%	0.0	0.0%	0.0	0.0%	**2.9**	**4.7%**
Total	**48.4**	**79.8%**	**9.0**	**14.9%**	**3.1**	**5.1%**	**0.1**	**0.2%**	**60.6**	**100.0%**

[a]Source: Italian Institute for Environmental Protection and Research (ISPRA), 2016. [b]Italian Civil Protection Department (2017). [c]Italian National Statistical Institute (Istat), 2017.

The fragility of the buildings magnifies the effect of natural perils, also for the unlawful practices followed in their localisation and construction. In the years 2004–2016, an index of illegality (expressed as the ratio between numbers of new unauthorised buildings and new authorised ones) rose from 13 to 19.6% (Istat, 2017), with peaks above 60% in some regions of southern Italy, where on average it amounts to 48.2% (higher than the level of 47.8% registered in 2015). Seismic risk is also magnified by the shoddy state of preservation of buildings, widespread in most of southern Italy (especially in Sicily).

3 The Under-insurance of Natural Risks

3.1 An Overview

The issue of under-insurance against natural risks has been widely analysed in the US, with reference to the damages caused by floods and hurricanes. In a recent paper, Nguyen and Noy (2020) presents a counterfactual assessment of the insurance reimbursements to homeowners in California and in Japan, had they been struck by a seismic event as damaging as the ones that actually took place in New Zealand in 2010–11. Japanese and Californian homeowners would receive only 19.4 and 11.3% of the amount effectively paid to New Zealand's policyholders. This is clear evidence of the large under-insurance for the earthquake peril in California and Japan, as opposed to New Zealand where the coverage protects almost all the residential buildings.

From the behavioural point of view, Meyer and Kunreuther (2017) identify six systematic biases affecting individual disaster risk perception and decision making system: myopia, amnesia, optimism, inertia, simplification and herding. All these elements lead to downplaying low-frequency high-impact risks, such as those of natural catastrophes. Underestimation of the probabilities and overestimation of the costs are, in fact, important explanations of the lack of households nat-cat insurance demand (Kunreuther and Pauly 2004; Kunreuther, Pauly, and McMorrow, 2013). The emotional surge following a natural catastrophe might temporarily increase the propensity to buy insurance cover (Botzen, Kunreuther, and Michel-Kerjan, 2015; Gallagher 2014), but this effect tends to fade away soon (Atreya, Ferreira, and Michel-Kerjan 2015).

According to empirical studies carried out on US households, multi-year insurance contracts and multi-risk policies may increase their willingness to buy insurance cover against natural risks. Multi-risk covers are very suitable for some areas of the US, exposed at the same time to risks from typhoons, floods, windstorms, and earthquakes, since they increase the probability of getting reimbursement for losses and hence decrease the economic agent's mistrust towards these insurance instruments. The benefits of these covers might justify some forms of public support to households and firms to reduce the burden of the insurance premium (Kunreuther and Michel-Kerjan 2013).

3.2 The Italian Under-Insurance

In the international comparisons of natural catastrophe management systems, Italy stands out for its almost exclusive reliance on *ex-post* public intervention. This factor, together with the structurally low propensity to buy insurance cover against natural risk (IVASS 2016, p. 86; SwissRe 2015), explains the scarce diffusion of such a cover in the country, despite being largely available as a non-compulsory extension of the policy against fire for the housing units. The insurance protection for natural disasters is more common among industrial and commercial buildings, albeit its diffusion is low in international rankings. In the first months of 2017 IVASS (the Italian Insurance Supervisory Authority) carried out a survey on all the insurance policies against fire covering the Italian housing units and on the presence of additional covers for earthquake and flood perils. The survey shows that, at the end of September 2016, the basic protection against fire covered around 35.4% of the housing units and the cover for seismic risk protected only 1.7% of houses, i.e. 567.000 units (of which 299.000 also against flood risk, Table 2).

We now briefly describe the main measurements of earthquake destructive power, in order to clarify the developments that follow.

4 Measuring Earthquake Power

4.1 Evaluating Macro-Seismic Intensity

The first measurement of earthquake strength introduced in the literature is an empirical assessment of the total damages caused to population and buildings. The measurement uses an ordinal scale, known as the Mercalli Scale (1908), with eleven values labelled with the Roman numbers from I to XI. A slightly modified scale, with twelve levels from I to XII, is now in use, developed by Cancani and Sieberg (abbreviated with MCS in Europe). The English-speaking countries use a version of this scale with small variations, commonly indicated as MMI (*Modified Mercalli Intensity*).

Table 2: Italian housing units' insurance protection for different levels of earthquake and flood risk, 2016 (thousands of units, % in the last column).

Housing units[a]		Insured housing units[d]	
Seismic risk level[b]		**Insurance only for seismic risk**	
Very high	1469	1	0.1
High	12,249	31	0.3
Medium	14,703	185	1.3
Low	6368	50	0.8
Total	**34,788**	**268**	**0.8**
Flood risk level[c]		**Insurance only for flood risk**	
High	451	3	0.7
Medium	1064	5	0.5
Low	30,718	252	0.8
Absent	2555	9	0.3
Total	**34,788**	**269**	**0.8**
Seismic and flood risk levels		**Insurance for both seismic and flood risk**	
Medium to very high seismic risk, medium to high flood risk	1516	12	0.8
Medium to very high seismic risk, absent to low flood risk	26,913	232	0.9
Low seismic risk, absent to low flood risk	6359	55	0.9
Total	**34,788**	**299**	**0.9**
		Total housing units insured for natural risk	
Total	**34,788**	**836**	**2.4**

Sources: [a]Italian Ministry of Economy and finance for the number of housing units. [b]Italian Civil Protection Department for seismic risk level. [c]Authors' estimates based on data from the Italian Institute for Environmental Protection and Research (ISPRA) for flood risk level. [d]Italian Agency for Insurance Supervision (IVASS) for the number of insured housing units.

4.2 Evaluating the Local Magnitude of Seismic Events

The second earthquake measurement proposed is the Richter scale (abbreviated with M_L), introduced in 1935 by C. Richter. It measures on a logarithmic scale the maximum amplitude of seismic waves as they reach seismographs. Thus, an earthquake measuring 7.0 on the Richter scale would be twice as large as an earthquake measuring 6.7 and 10 times as large as one measuring 6.0 (which releases the same energy as the Hiroshima nuclear bomb). In the 1970s Kanamori proposed to modify this scale by measuring the moment magnitude (known under the abbreviation Mw of Mechanical work), which also takes into account the fault areas, as well as the soil resiliency and thus allows to estimate the total energy released by the earthquake.

4.3 Local Evaluations of Ground Shaking

An available quantity is the measurement of ground shaking in different micro-areas, as the peak ground acceleration (PGA), often used together with the peak ground velocity (PGV). PGA is expressed in decimal or percentages of g (the acceleration due to Earth's gravity, amounting to 9.81 meters per second squared, m/s^2), whereas PGV is measured in meters per second (m/s). PGA and PGV tend to be strongly correlated, but both of them can be weakly correlated with the macro-seismic intensity measures[1].

5 Italy's Seismic Risk according to the National Institute of Geophysics and Vulcanology

We now introduce the measures of seismic risk produced by the Italian National Institute of Geophysics and Vulcanology (INGV), which civil engineers use to compute buildings' resilience to seismic events. The INGV divides Italy's surface into areas with uniform seismic hazard by using 16,852 points forming an evenly

1 In this paper, because of the limits of publicly available data, we use simple PGA and PGV earthquake measures to estimate the seismic intensity in the classical MCS scale. A more refined analysis should include measure of spectral acceleration and seismic wave amplitude attenuation, considering the local structure of the crust and building characteristics. PGA is essentially spectral acceleration at the ground level. In general, the ground-motion amplitude increases with earthquake magnitude and decreases as the epi/hypocentre distance increases. However, local spectral attenuation (SA) equations are not available to describe the ground-motion for different response spectral periods.

spaced grid, with each square having 0.02 degrees of longitude and latitude. For every point, nine values for PGA are locally estimated, $\mathrm{PGA}_{z,50,\alpha}$ one for each of the nine exceedance probabilities $j \in \{2\%, 5\%, 10\%, 22\%, 30\%, 39\%, 50\%, 63\%, 81\%\}$ over a 50-year observation period. Moreover, for every exceedance probability $\alpha_{z,50,\mathrm{PGA}}$ (representing the probability of having in 50 years at least one event with PGA equal or higher than the assigned PGA), there is a corresponding count $\lambda_{z,50,\mathrm{PGA}}$ of the average yearly number of events with PGA higher or equal than the assigned PGA (Figure 2a). If the events follow Poisson's law, the relation between

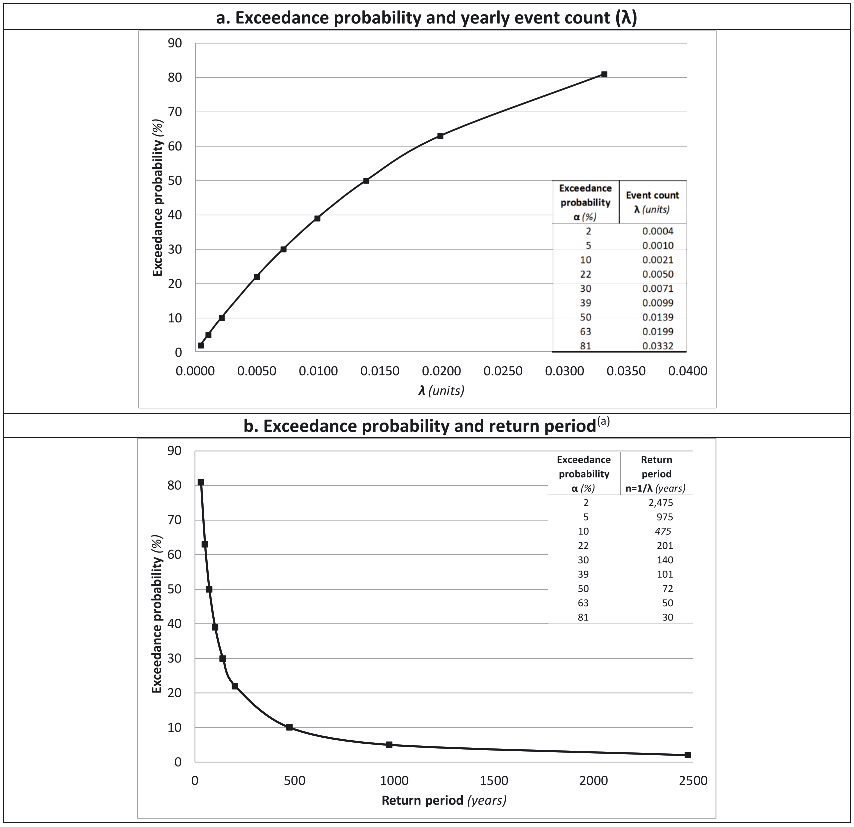

Figure 2: Exceedance probability and return period over 50 years according to the Poisson's law.
Source: Italian National Institute of Geophysics and Vulcanology (INGV).
[a] The return periods for the exceedance probabilities 2 and 5% are generally rounded to 2500 and 1000 years.

the two parameters is:

$$\lambda_{z,50,\text{PGA}} = -\frac{\ln(1 - \alpha_{z,50,\text{PGA}})}{50}$$

Finally, the return period $n_{z,50,\text{PGA}} = \frac{1}{\lambda_{z,50,\text{PGA}}}$ is the average number of years between two consecutive events with PGA higher or equal than the assigned PGA (Figure 2b).

For every exceedance probability and every point of the grid, the methodology of INGV (INGV 2004) derives sixteen geographical distributions for the PGA, each obtained by combining all the levels of three factors: (a) different degree of completeness of the historical catalogues of earthquakes used (2 levels), (b) different methods of determining seismic intensity (2 levels), (c) different measurements of earth-shaking attenuation (4 levels). Each geographical distribution is assigned a weight, representing the degree of trust in the specific method. From the sixteen possible values obtained for each point of the map, the weighted 16th, 50th and 84th percentiles are finally determined. The median is the central evaluation, with the 16th and 84th percentiles respectively representing an optimistic and a pessimistic assessment of the local seismic risk.

Let $I_{\text{PGA}_{z,t} > \text{PGA}_z}$ denote a dummy variable that is equal to one in the case of occurrence of the event $\text{PGA}_{z,t} > \text{PGA}_z$, zero otherwise ($z$ and t indicate respectively a point of the grid and a year). The INGV provides a PGA value for the point z, corresponding to the exceedance probability α_{50} in 50 years, formally expressed as Eq. (1):

$$\text{PGA}_{z,50,10\%} = \max\left\{\text{PGA}_z \colon \text{Prob}\left(\left[\sum_{t=1}^{50} I_{\text{PGA}_{z,t} > \text{PGA}_z}\right] \geq 1\right) = 10\%\right\} \tag{1}$$

$\text{PGA}_{z,50,10\%}$ is therefore the value exceeded with 10% probability over 50 years by at least one ground shaking.

Three maps (available for the three percentiles 16th, 50th, 84th) represent $\text{PGA}_{z,50,10\%}$ by using a 13-class categorization, with a different colour associated with each class (Figure 3).

This quantification of seismic risk is useful for civil engineering projects, because, for each zone, it provides the maximum PGA (occurring in 50 years with 10% probability) the buildings have to withstand. However, it is unsuitable for insurance pricing, for which the main interest is estimating the probability of a seismic event greater than a given intensity over a time horizon usually shorter than 50 years (e.g. 5 or 10 years).

The following section shows how to obtain such probability and presents its possible applications. Note that the proposed methodology is independent of the

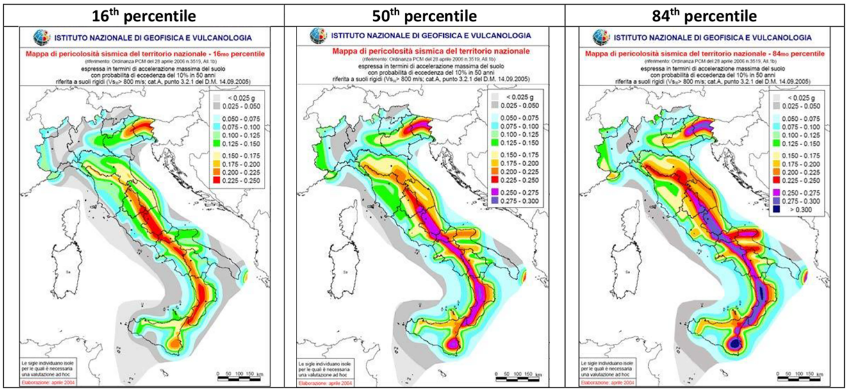

Figure 3: Maps of Italy's seismic risk (10% exceedance probability over 50 years). Source: Italian National Institute of Geophysics and Vulcanology (INGV).

particular data source (INGV in our case) and could be applied to other (e.g. more severe) earthquake scenarios as well.

6 An Alternative Measurement of Seismic Risk for Insurance Purposes

6.1 The Insurance Viewpoint

The pure premium's evaluation of an insurance cover for seismic risk in a zone z requires the knowledge of the probability distribution for the following event: at least one seismic episode with intensity greater than $\overline{\mathrm{MCS}}$ occurring over m years.

We can formally express this probability as:

$$\alpha_{z,m}\left(\overline{\mathrm{MCS}}\right) = \mathrm{Prob}\left(\left[\sum_{t=1}^{m} I_{\mathrm{MCS}_{z,t}>\overline{\mathrm{MCS}}}\right] \geq 1\right) \tag{2}$$

We aim to obtain such probability from the INGV's geographical distributions of this event: at least one seismic episode[2] with a PGA

2 Note that a single major earthquake is composed of many seismic episodes of varying magnitude. For example, the disastrous earthquake that struck l'Aquila on April 6th 2009 had an episode with peak magnitude of 5.8 M_L, preceded by two minor ones and followed by scores of lesser ground movements in the same day.

level greater than the assigned PGA*, occurring with probability $\alpha \in \{2\%, 5\%, 10\%, 22\%, 30\%, 39\%, 50\%, 63\%, 81\%\}$ over 50 years.

This event can mathematically be expressed as:

$$\{\mathrm{PGA}^*\,(z, 50, \alpha) : \mathrm{prob}\left(\left[\sum_{t=1}^{50} I_{\mathrm{PGA}_{z,t} > \mathrm{PGA}^*(z,50,\alpha)}\right] \geq 1\right) = \alpha\}$$

6.2 Model Development

Our first step is estimating the MCS corresponding to the assigned PGA for all the points of the INGV grid. To do this, we rely on the model used by the INGV to produce an evaluation of MCS for a seismic episode, based on the instrumental measurement of PGA and PGV (Faenza and Michelini 2010).[3]

This model requires a preliminary estimate of PGV values for the grid points. We obtain them by running an ordinary least squares (OLS) regression model of PGV over PGA for a collection of seismic events that occurred in Italy during the years 2009–2017, for which the INGV *ShakeMaps* provide both measures. We use the 9 major earth tremors from 2009 to 2017, together with 6 other minor seismic episodes. We introduce the latter to provide variability to the estimation dataset and to limit the excessive influence of the strongest ground movements. The following log-linear model is estimated over $T = 907{,}515$ time-space observations (Table 3)[4]:

$$\ln(\mathrm{PGV}_k) = \gamma_0 + \gamma_1 \ln(\mathrm{PGA}_k) + \varepsilon_k \tag{3}$$

The range of the regression residuals is (−1.9558, 2.4327) and a graphic plot does not show relevant outliers. The residuals do not pass the standard normality tests, since even small deviations from normality lead to the rejection of the null hypothesis with the huge number of observation available in our case. We however take into account of the risk of heteroscedasticity by using White's correction in computing the standard errors for the coefficients (Verbeek 2008). The high

3 The INGV produces a *ShakeMap* for any seismic event occurring in Italy or in the surrounding areas. These maps are downloadable from the webpage: http://shakemap.rm.ingv.it/shake/archive/. They collect the M_L, a map of the geographical diffusion of the MCS/MMI and a complete list of PGA and PGV for all the points of the INGV grid covering all the Italian territory, with an MCS/MMI estimate obtained with the orthogonal regression of Faenza and Michelini (2010). The *ShakeMap* is available within a few hours after the seismic event.

4 The datasets distributed with the *ShakeMaps* contain a number of points greater than that of the INGV grid. The values for the points outside the grid are estimated in order to minimize the misrepresentation of the ground motion pattern due to data gaps (for further details, we refer to the webpage: http://shakemap.rm.ingv.it/shake/about.html).

Table 3: Linear model for the association between PGV and PGA, 2009–2017[a, b].

Dependent variable: PGV (ln)		
Covariate	**Coefficient**	**Pr > |*t*|**
Intercept	−0.2560	<0.0001
PGA (ln)	0.9956	<0.0001
***R*-square**	***F* value**	**Pr > *F***
0.9291	1.19E+07	<0.0001
Number of observations		907,515

[a]The 9 most destructive seismic episodes in the years 2009–2017, occurred in the five major earthquakes of the period, are considered, to which 6 minor episodes are then added, recorded in other minor events. The total number of observations in the 9 + 6 = 15 episodes amounts to 907,515 (60.501 in each episode, see footnote 3). [b]Significance of the coefficient computed with White's correction for heteroscedasticity.

value of the model *R*-square (0.9291) makes the model coefficient suitable for out-of-sample prediction.

With the two estimates $\{\hat{\gamma}_0, \hat{\gamma}_1\}$, the estimate of $\mathrm{PGV}_{z,50,\alpha_{50}}$ for each $\mathrm{PGA}_{z,50,\alpha_{50}}$ of the grid is written as:

$$\widehat{\mathrm{PGV}}_{z,50,\alpha_{50}} = \hat{c}e^{\hat{\gamma}_0+\hat{\gamma}_1 \ \ln(\mathrm{PGA}_{z,50,\alpha_{50}})} \tag{4}$$

where $\hat{c} = \frac{\frac{1}{T}\sum_{k=1}^{T}\mathrm{PGV}_k}{\frac{1}{T}\sum_{k=1}^{T}e^{\hat{\gamma}_0+\hat{\gamma}_1 \ \ln(\mathrm{PGA}_k)}}$ is a correction factor that eliminates the bias generated by modelling the natural logarithm of a dependent variable.

We accordingly produce a matrix of 16,852 × 9 PGV estimates, with the nine estimates for every grid point corresponding to the available exceedance probabilities.

We can now exploit the parameters of the model MCS = f (PGA, PGV) currently used by the INGV (Faenza and Michelini 2010) to produce an estimate for MCS whenever a seismic event occurs. The model uses two equations estimated by orthogonal regression (Boggs and Rogers 1989):

$$\mathrm{MCS}_{\mathrm{PGA}} = (1.68 \pm 0.22) + (2.58 \pm 0.14)\log_{10}(\mathrm{PGA}), \quad \sigma = 0.35 \tag{5.1}$$

$$\mathrm{MCS}_{\mathrm{PGV}} = (5.11 \pm 0.07) + (2.35 \pm 0.09)\log_{10}(\mathrm{PGA}), \quad \sigma = 0.26 \tag{5.2}$$

For every value of PGA, Eq. (5.1) computes a symmetric interval $\left[\mathrm{MCS}_{\mathrm{PGA}}^{(\mathrm{INF})}, \mathrm{MCS}_{\mathrm{PGA}}^{(\mathrm{SUP})}\right]$ around the predicted value $\mathrm{MCS}_{\mathrm{PGA}}$. Similarly, Eq. (5.2) produces a symmetric interval $\left[\mathrm{MCS}_{\mathrm{PGV}}^{(\mathrm{INF})}, \mathrm{MCS}_{\mathrm{PGV}}^{(\mathrm{SUP})}\right]$ for the predicted value $\mathrm{MCS}_{\mathrm{PGV}}$ of

MCS. The best fit is obtained with the rule:

$$\mathrm{MCS} = \begin{cases} \mathrm{MCS_{PGA}} & \text{if MCS} \leq 6 \\ \mathrm{MCS_{PGV}} & \text{if MCS} > 6 \end{cases}$$

We adapt this model to our case, for which a true value for MCS, to be compared with the two predictions $\{\mathrm{MCS_{PGA}}, \mathrm{MCS_{PGV}}\}$, is not available. We use a decision rule based on the threshold value of 6 for MCS. The rule is based on the fact that it is always $\mathrm{MCS_{PGA}} < \mathrm{MCS_{PGV}}$ when Eqs. (5.1) and (5.2) are applied to the T observations in Eq. (3). Between the two predictions, we choose the one more distant from the threshold-value of 6. The distance takes the role of a credibility measure and the rule is formally expressed Eq. (6) as[5]:

$$\mathrm{MCS} = \begin{cases} \mathrm{MCS_{PGA}} & \text{if } 6 - \mathrm{MCS_{PGA}} > \mathrm{MCS_{PGV}} - 6 \\ \mathrm{MCS_{PGV}} & \text{if } 6 - \mathrm{MCS_{PGA}} < \mathrm{MCS_{PGV}} - 6 \end{cases} \tag{6}$$

We now have three values for MCS (lower and upper limits and central value) for all the 16,852 points and the 9 available exceedance probabilities.

Let us indicate with $\mathrm{MCS}_{z,j}$ the central value of the interval, where z and j respectively denote the generic point and the jth generic exceedance probability among the nine available. Under the Poisson's law, we have the following Eq. (7) for the exceedance probability $\alpha_{z,50}$ and the yearly event frequency $\lambda_{z,j}$:

$$\alpha_{z,50} = \mathrm{Prob}\,(N\,(50) > 0) = 1 - \mathrm{Prob}\,(N\,(50) = 0) = 1 - \mathrm{e}^{-50\lambda_{z,j}} \tag{7}$$

Therefore, in order to obtain $\alpha_{z,m}$ we firstly model $\lambda_{z,j}$ on $\mathrm{MCS}_{z,j}$. The best-fitting model is log-linear [Eq. (8)], with separate intercepts $\beta_{1,z}$ for every point and a common intercept β_0:

$$\ln\left(\lambda_{z,j}\right) = \beta_0 + \beta_{1,z} + \beta_2 \mathrm{MCS}_{z,j} + \varepsilon_{z,j} \tag{8}$$

The high number of intercepts is computed by estimating the model like a fixed-effect panel, with repeated measurements for each point of the grid over the nine exceedances (Table 4).

The range of the regression residuals is (−3.1095, 10.6294) and extreme outliers do not emerge from the graphic analysis. As for the case of the regression

5 In Eq. (6), the threshold of 6 is the value proposed by Faenza and Michelini (2010) in order to choose between the two equations modelling MCS. The equation with PGA as covariate is preferred to the one having PGV as covariate for values of MCS not higher than 6. In our case, we do not have the true MCS value and we interpret the authors' rule as an indication that, between the two available estimates $\mathrm{MCS} = f(\mathrm{PGA})$, $\mathrm{MCS} = f(\mathrm{PGV})$, where it is always $f(\mathrm{PGA}) < f(\mathrm{PGV})$ on our dataset, we should prefer the one more distant from the value of 6.

Table 4: Fixed-effect panel linear model for the association between λ and MCS.

	Dependent variable: λ (ln)	
Covariate	**Coefficient**	**Pr > |t|**
Intercept	5.5691	<0.0001
MCS	−1.6603	<0.0001
***R*-square**		**Number of units**
Within	0.7942	16,852
Between	0.0034	Number of measurements per unit
Overall	0.2404	9
Standard deviation of residuals		Total number of observations
	$\sigma_\varepsilon = 0.6553$	$16{,}852 \times 9 = 151{,}663$

in Eq. (3), the residuals fail to pass the standard normality test because of the large number of observations available. The asymmetry of the range around zero makes the presence of heteroscedasticity more likely in this case, which, however, does not prevent the estimates from being unbiased, even though not minimum-variance.

For an m-year horizon, from Eqs. (7) and (8) we obtain Eq. (9), given a generic $\overline{\mathrm{MCS}}$, the following expression for the local exceedance:

$$\alpha_{z,m}\left(\overline{\mathrm{MCS}}\right) = 1 - \mathrm{e}^{-m\left(\hat{f}\mathrm{e}^{\hat{\beta}_0+\hat{\beta}_{1,z}+\hat{\beta}_2\overline{\mathrm{MCS}}}\right)} \tag{9}$$

where $\hat{f}$ is a correction factor computed as in Eq. (4).

A synthetic representation of the model (Figure 4a–d) can be obtained by plotting over a 50-year horizon, for the 9 exceedances used by the INGV (each indexed by j): (a) the average $\mathrm{MCS}_{z,j}$ (Eq. (6)) against the average PGA, (b) the average $\mathrm{MCS}_{z,j}$ against the average yearly frequency $\lambda_{z,j}$ (Eq. (8)), (c) the average exceedance $\alpha_{z,m}\left(\overline{\mathrm{MCS}}\right)$ (Eq. (9)) against the average yearly frequency $\lambda_{z,j}$, (d) the average exceedance $\alpha_{z,m}\left(\overline{\mathrm{MCS}}\right)$ against the average PGA.

Each of the 4 previous plots can be read for a specific exceedance. For example in Figure 4b, $j = 22\%$ corresponds to an average frequency equal to 0.004969 (with a return period of 201 years) and to an average intensity equal to or higher than 6.6 MCS. This MCS level might seem not very high, but it is only an overall average: the space-level fixed effects estimated in Eq. (8) reveal that, for 25% of Italy's surface,

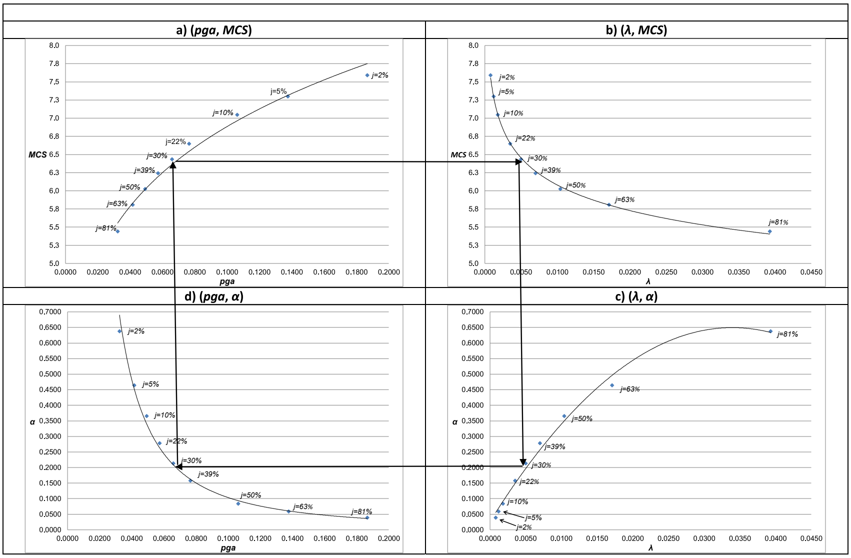

Figure 4: Average predictions of the model over a 50-year horizon.

the lower bound for the average level rises up to 8.0 MCS, increasing respectively to 8.7 and 8.9 MCS for 5 and 1% of Italy's surface.

The uncertainty of the previous estimates is obtained by plotting the lower, central, and upper values of $\overline{\alpha}_m\left(\overline{\mathrm{MCS}}\right) = \frac{1}{Z}\sum_{z=1}^{Z}(1 - \mathrm{e}^{-m\left(\hat{f}\mathrm{e}^{\hat{\beta}_0+\hat{\beta}_{1,z}+\hat{\beta}_2\overline{\mathrm{MCS}}}\right)})$ (average probability over all the $Z = 16{,}852$ grid points):

(1) with respect to MCS for a given horizon m,

(2) with respect to the horizon m for an assigned MCS.

Figure 5 shows the two plots for $m = 10$ and MCS $= 9$.

Finally, the seismic risk of every Italian municipality can be measured by matching its centroid[6] with the nearest point of the INGV grid, using the Euclidean distance. The number of inhabitants exposed to a given level of seismic risk can be also derived.

6 The coordinates of Italian municipalities' centroids are at the link: http://clisun.casaccia.enea.it/Comuni/Comuni.xls.

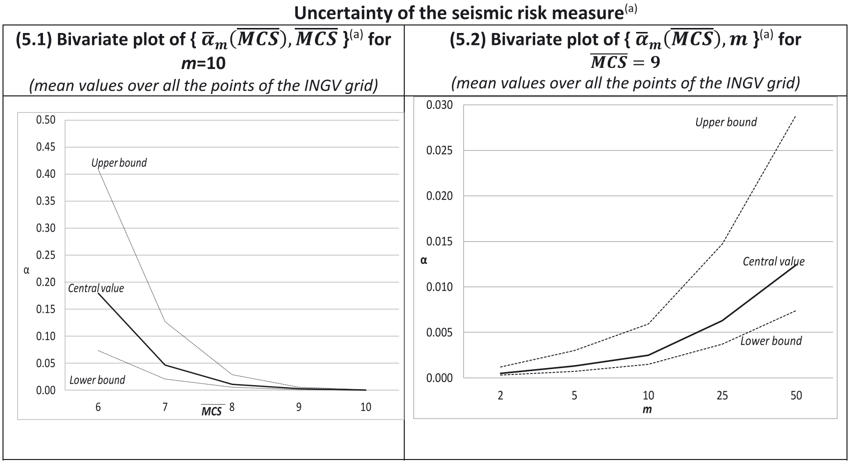

Figure 5: Uncertainty of the seismic risk measure[(a)].
Source: Italian National Institute of Geophysics and Vulcanology (INGV).
[(a)] $\overline{\alpha}_m\left(\overline{\text{MCS}}\right)$ is the mean probability of at least a seismic event of intensity equal or greater than $\overline{\text{MCS}}$ over an m-year observation period.

6.3 Understanding Seismic Risk's Geographical Diffusion

We choose the ten-year time horizon $m = 10$. The $\alpha_{z,m=10}\left(\overline{\text{MCS}}\right)$ values Eq. (2) can be categorized and represented on a map (Figure 6a–d), for $\overline{\text{MCS}} \in \{6, 7, 8, 9\}$ (the intensities lower than 6 are not represented because they correspond to almost negligible damages). The population at risk is also tabulated beside each map.

We report below the meaning of the four $\overline{\text{MCS}}$ values represented.[7]

$\overline{\text{MCS}} = 6$. Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight.
$\overline{\text{MCS}} = 7$. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken.
$\overline{\text{MCS}} = 8$. Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned.
$\overline{\text{MCS}} = 9$. Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations. Liquefaction.

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7 See https://en.wikipedia.org/wiki/Modified_Mercalli_intensity_scale for further details.

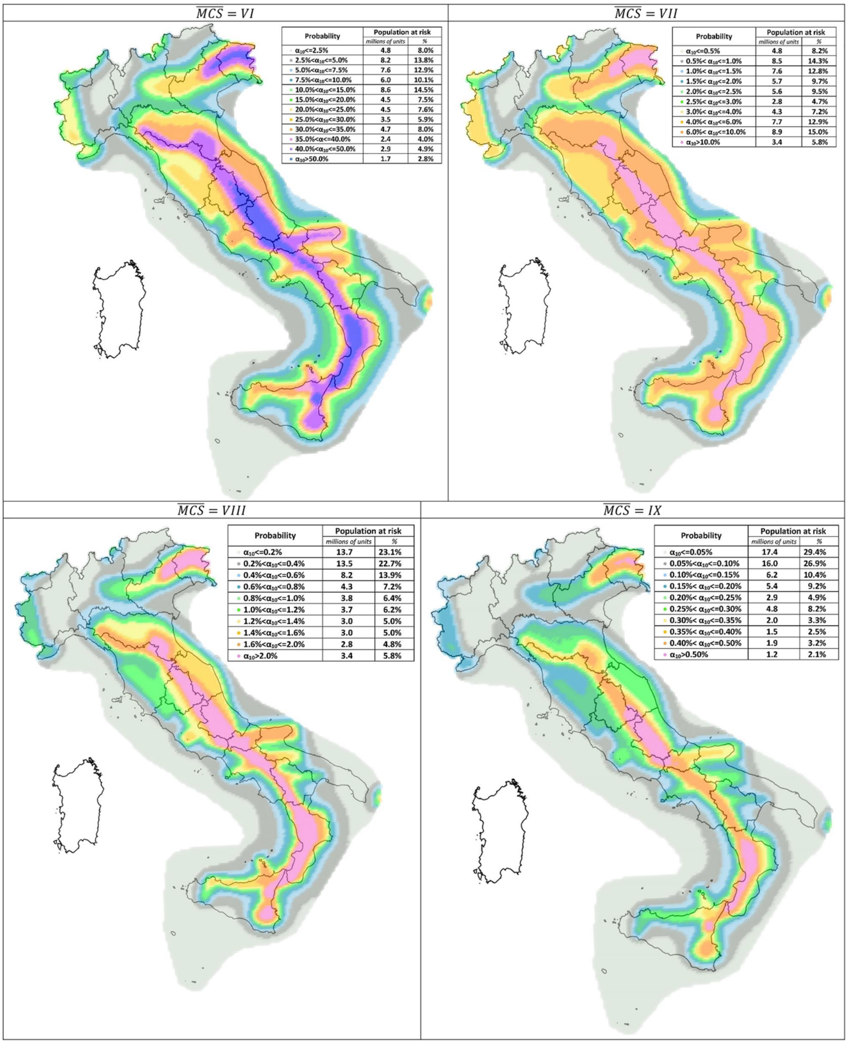

Figure 6: Risk levels of seismic events with MCS intensity equal to or greater than $\overline{\mathrm{MCS}} \in \{VI, VII, VIII, IX\}$.
Geographical distribution of risk and population under different risk levels for a 10-year horizon.

The maps highlight that higher levels of risk affect increasingly smaller areas. High-risk areas are widespread along the south-central Apennines with some offshoots in the Friuli Venezia-Giulia region. These patterns are consistent with the original INGV maps. As for the risk for the population, 11.7 million inhabitants

(19.7% of the whole Italian population) would experience a quake with an intensity equal or greater than 6 MCS degrees with a probability at least of 30% (Figure 6a): the seismic events at the bottom of the intensity interval could damage only very deteriorated buildings.

The dangerous MCS intensities affect relatively small groups of residents: for example, a seismic event with an intensity equal or greater than 8 MCS degrees would be perceived by 3.4 million people with a probability at least of 2% (Figure 6c), whereas only 1.2 million people face the risk of destructive earthquakes with an intensity equal or greater than 9 MCS degrees with a probability higher than 0.5% (Figure 6d).

6.4 Assessing the Insurance Risk of a Portfolio of Housing Units

A common approach to measure the consequences of natural risk (Poljanšek et al. 2017, cap. 2) combines the probability distribution of events (hazard), the exposure value, and a vulnerability measure. Hazard has been extensively discussed in the previous sections.

In order to introduce exposure and vulnerability, we define:

$v_{c,l,p}$: value of the housing units for municipality c, building structure type l and state of preservation p;

$\overline{d}_{\overline{\text{MCS}},l,p} \in [0,1]$: average damage (expressed as a share of the value) for a housing unit with type of building structure l and preservation state p as the aftermath of a seismic event with $\overline{\text{MCS}}$ intensity;

$\lambda^{\circ}_{c,1,\overline{\text{MCS}}}$: yearly frequency of seismic events with intensity equal to $\overline{\text{MCS}}$. It can be approximately derived from the yearly frequency of seismic events with an intensity equal to or greater than $\overline{\text{MCS}}$ ($\lambda_{c,1,\overline{\text{MCS}}}$) as follows:

$$\lambda^{\circ}_{c,1,\overline{\text{MCS}}} \cong \lambda_{c,1,\overline{\text{MCS}}} - \lambda_{c,1,\overline{\text{MCS}}+1}$$

We obtain $v_{c,l,p}$ by multiplying the total value V_c of the municipality's residential units by the share of the buildings with type of structure equal to l and state of preservation equal to p.

Let $n^{\circ}_{c,1,\overline{\text{MCS}}}$ be the stochastic number of seismic events with an intensity equal to $\overline{\text{MCS}}$ occurring in one year in municipality c. The buildings with type of structure l and state of preservation p suffer damages amounting to a random share $d_{\overline{\text{MCS}},l,p}$ of their value. By hypothesis, $n^{\circ}_{c,1,\overline{\text{MCS}}}$ (conditional frequency) and $d_{\overline{\text{MCS}},l,p}$ (conditional severity) are respectively generated by a Poisson distribution with frequency parameter $\lambda^{\circ}_{c,1,\overline{\text{MCS}}}$ and by an independent beta distribution with alpha = 1 and mean = $\overline{d}_{\overline{\text{MCS}},l,p}$ (the beta parameter is beta = alpha $*$ $(1-\overline{d})/\overline{d}$). The stochastic models of natural catastrophes apply extensively these distributions (Mitchell-Wallace et al. 2017).

For a given return period n, the Aggregate Exceedance Loss is the minimum value that the total damages in a year exceed with $\frac{1}{n}$ probability. It is formally expressed Eq. (10) as:

$$\mathrm{AEL}\,(n) \equiv \min\left\{L\colon 1 - F_A(L) = \frac{1}{n}\right\} \tag{10}$$

where the aggregate loss $\tilde{A}$

$$\tilde{A} \equiv \sum_c \sum_{\overline{\mathrm{MCS}}} \sum_l \sum_p v_{c,l,p} d_{\overline{\mathrm{MCS}},l,p} n^{\circ}_{c,1,\overline{\mathrm{MCS}}} \tag{11}$$

has the probability distribution F_A.

The average annual loss (AAL) is expressed as:

$$\mathrm{AAL} = \sum_c \sum_{\overline{\mathrm{MCS}}} \sum_l \sum_p v_{c,l,p} \bar{d}_{\overline{\mathrm{MCS}},l,p} \lambda^{\circ}_{c,1,\overline{\mathrm{MCS}}} \tag{12}$$

and it can be regarded as a yearly pure premium for the risk. We remark that, by Poisson's law, $\alpha^{\circ}_{c,1}\left(\overline{\mathrm{MCS}}\right) = 1 - \mathrm{e}^{-\lambda^{\circ}_{c,1,\overline{\mathrm{MCS}}}} \cong \lambda^{\circ}_{c,1,\overline{\mathrm{MCS}}}$ is the yearly probability of at least a seismic event with intensity equal to or greater than $\overline{\mathrm{MCS}}$.

Under general conditions, the Hoeffding formula expresses, for any random variable X, the mean $E\,(X)$ as the integral of the distribution function (X): $E\,(X) \equiv \int_0^{+\infty} u\mathrm{d}F\,(u) = \int_0^{+\infty} (1 - F\,(u))\,\mathrm{d}u$.

If we define:

$$n(L) \equiv \min\left\{n\colon 1 - F_A(L) = \frac{1}{n}\right\}$$

from the Hoeffding formula we obtain:

$$\mathrm{AAL} = \int_0^{\infty} \frac{1}{n(L)}\mathrm{d}L = \int_0^{\infty} \lambda\,(L)\,\mathrm{d}L \tag{13}$$

Under the absolute continuity of F_A, the property of the integral of invertible functions can be applied, obtaining AAL Eq. (14) as the integral of $\mathrm{AEL}\,(n)$ over all the possible n as:

$$\mathrm{AAL} = \int_1^{\infty} \mathrm{AEL}\,(n)\,\mathrm{d}n \tag{14}$$

Modelling natural catastrophes often requires an assessment of the maximum damage that an event causes to the insured portfolio and of the minimum value such maximum exceeds with a given probability (Occurrence Exceedance Loss, OEL). If our portfolio is the set of all Italian municipalities, we can write Eq. (15):

$$\mathrm{OEL}\,(n) = \min\left\{L\colon \mathrm{Prob}\left(\max\left\{v_{c,l,p} d_{\overline{\mathrm{MCS}},l,p} n_{c,1,\overline{\mathrm{MCS}}}\right\} > L\right) = \frac{1}{n}\right\} \tag{15}$$

6.5 Insuring the Whole Italian Housing Stock Against Seismic Risk

Italian residential buildings are largely underinsured against natural risks. A simulation exercise evaluating the coverage of all the Italian housing units against seismic risk is very informative since such peril is one of the most dangerous ones affecting the country. We carry out the simulation by using the previously described model.

6.5.1 Main Features of the Simulation Exercise

The number of housing units for each municipality is provided by the Italian Revenue Agency and it totals 34.8 million in 2015, for a global value of 5510 billion euros (Bank of Italy 2015).

The distribution of the housing units' value at the municipality level is derived from an IVASS survey carried out in the first months of 2017, covering the Italian housing units insured for natural risks as of September 2016. From the survey, we obtain the housing unit's average value for each municipality c as: $\frac{\sum_{i\in c} c_{i,c}}{n_c}$, where $c_{i,c}$ is the insured value for the ith insured housing units and n_c is the total number of insured housing units. For every municipality c with no housing insured (it happens for some small municipalities), we replace $\frac{\sum_{i\in c} v_{i,c}}{n_c}$ with $\frac{\sum_{i\in c_P} v_{i,c_P}}{n_{c_P}}$, computed over all the n_{c_P} insured housing units of the province c_P to which municipality c belongs.

For municipality c, if N_c is the total number of housing units, an estimate v_c of the housing stock's value is:

$$v_c = kN_c \frac{\sum_{i\in c} c_{i,c}}{n_c}$$

where k is a scaling factor to obtain $\sum_{c\in C} v_c = 5510$ billion euros.

We consider the two hypotheses of damages completely reimbursed and of partial reimbursement with deductibles and limits. Damages as a share of property value depend on seismic intensity as well as on the type of building structure and maintenance conditions.

We consider the following sets of four building structures and four maintenance conditions:

Building structure $\in$ {masonry, reinforced concrete, other}

Maintenance condition $\in$ {very bad, bad, good, very good}

These two classifications are based on actually available data, collected by the National Statistical Institute in the latest 2011 census at the municipality level. Clearly, more refined evaluations would provide better results. We remark, however, that the commercially available catastrophe models, in their simulations, consider very similar sets of stylized building structures.

Note also that in the simulation analysis of the following paragraph, the actual building scenario will be compared with two alternative extremes (all masonry and all reinforced concrete, both with the census distribution of the maintenance conditions) essentially for three reasons. One reason is to assess the sensitivity of our results to this parameter, which reflects qualitative assessments and is therefore subject to some fuzziness. Secondly, this help us to compare our results with those of two commercial catastrophe models which use similar extremes, very fragile and very resistant buildings, whereas the actual structures (based on census data) can be matched to an intermediate stylization. Thirdly, our analysis could give to the various stakeholders some insights to evaluate the benefits of a restructuring plan aimed at ameliorate the robustness of existing dwellings.

Finally, damages are assessed through vulnerability curves[8] providing the share of property value damaged by different seismic intensities (measured with the MCS scale) for all the building structures and maintenance conditions considered.

6.5.2 Simulation Results

The AAL (Eq. (12)), divided by the total value of the Italian housing stock and multiplied by 100,000 euros, is an evaluation of the pure-risk premium for an insurance policy covering 100,000 euros of exposure, supposing that all the Italian house buildings are insured against seismic risk.[9] It is a standardized measure used to compare the price of different insurance contracts protecting the same asset against the same risk.

We represent (Table 5) the geographical variation of this measure by dividing Italy's territory into CRESTA areas, a well-established classification for assessing natural perils caused by earthquakes, storms, and floods. The classification divides a broad geographical area into smaller areas defined by sub-national

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8 We use the damage curves normally employed for the construction of residential buildings in Italy, expressing the damage as a share of the value of the building.

9 We compute AAL by using the expression of Eq. (12). We also approximated by simulation the alternative expressions of AAL from Eqs. (13) and (14), obtaining similar results.

Table 5: Pure premium for the Italian house buildings' seismic risk[a] (per 100,000 € of exposure, €).

CRESTA zone[b]		Building structure								
Level of CRESTA zone	**Name of CRESTA zone**	**All unreinforced masonry[c]**			**Actual structure[c,d]**			**All reinforced concrete[c]**		
1	Piemonte, Valle d'Aosta, Liguria	35.0	31.7		32.6	29.6		25.9	23.7	
2	Torino	26.4			24.8			20.1		
1	Lombardi, Emilia-Romagna	56.1	48.6		52.9	46.0		43.4	37.8	
2	Milano	13.5			12.8			10.7		
2	Bologna	105.4			100.1			83.2		
1	Veneto,Trentino-A.A., Friuli-V.G.	56.9	74.5		63.0	70.2		51.4	57.3	
2	Udine e Pordenone	145.8			1375			112.5		
Northern Italy				**50.4**			**47.5**			**38.8**
1	Toscana, Lazio	95.8	88.3		90.0	82.9		73.0	67.2	
2	Roma	77.8			73.2			59.3		
1	Marche, Umbria, Abruzzo, Molise	134.8	144.0		1265	135.1		102.0	108.8	
2	L'Aquila	226.3			211.7			169.6		
Central Italy				**105.0**			**98.6**			**79.7**
1	Puglia	344	52.2		32.0	48.4		25.3	37.8	
2	Foggia	132.9			122.6			94.5		
1	Campania, Basilicata, Calabria	132.2	148.1		121.4	135.3		92.2	101.3	
2	Napoli	114.4			103.7			76.1		
2	Benevento e Avellino	180.2			1675			131.6		
2	Potenza	169.3			155.9			119.5		
2	Catanzaro e Reggio Calabria	250.0			2265			165.5		
1	Sicilia	70.4	122.0		642	111.1		47.8	825	
2	Messina e Catania	202.8			183.8			134.6		

Table 5: (continued)

CRESTA zone[b]		Building structure								
Level of CRESTA zone	**Name of CRESTA zone**	**All unreinforced masonry[c]**			**Actual structure[c,d]**			**All reinforced concrete[c]**		
2	Siracusa e Ragusa	123.2			114.0			88.4		
1	Sardegna[e]	–	–		–	–		–	–	
Southern Italy and major islands				**109.5**			**100.0**			**75.0**
Range		236.5	116.4	54.6	213.7	105.7	51.1	159.0	85.2	41.0
Coefficient of variation		56.9	47.3	35.1	56.2	46.7	35.0	54.7	45.1	34.6
Total for Italy				**76.8**			**71.5**			**56.5**

[a]Complete compensation of damages. [b]The acronym CRESTA stands for Catastrophe Risk Evaluation and Standardizing Target Accumulations. It is a geographical classification of the world according to the different levels of the main natural risks (earthquakes, floods, storm), commonly used in the insurance industry. [c]For each of the three building structures we have three columns: the first one reports the pure premium for the level-1 and level-2 CRESTA zones (for the level-1 CRESTA, the area considered do not include those of the level-2 CRESTA zones nested within it). The second column shows the pure premium for the whole level-1 CRESTA zones. The third column displays the pure premium at the macro area level. [d]Distribution of buildings by type of structure available at the municipality level (Istat, 2011 census). [e]Sardegna is not considered, since it is virtually free of seismic risk.

administrative boundaries. The CRESTA classification for Italy creates areas where the earthquake risk is qualitatively similar.

For the whole Italy, this measure amounts on average to 76.8 euros (Table 5), under the scenario of all the houses built of unreinforced masonry (the least resistant structure). This amount decreases respectively to 71.5 euros, by introducing the actual building structures, and to 56.5 euros, if all the building structures are made of reinforced concrete.

Whatever the type of building structure, using a less granular partition of Italy's territory to calculate the average pure premium per 100,000 euros decreases its variability, as shown by the reduction in both the range and the variation coefficient. In this way, the premiums become more evenly distributed among policyholders residing in areas of different seismic risk. This is evidence of the mutuality effect, realised through similar average premiums, which do not place too heavy a financial burden on house-owners in high-risk areas.[10]

We then introduce the possibility of limiting the risk exposure of insurance companies by using deductibles and limits estimated from the IVASS survey described in Section 3.2.[11] On average, the pure premium for 100,000 euros decreases by around 30% (Figure 7).

According to our data, the average value of an Italian housing unit is 159,000 euros, so that the pure-risk premium for an insurance policy covering the average Italian housing unit ranges between a minimum of 63 euros and a maximum of 122 euros.

We finally generate 100,000 independent replications from the model, to generate a distribution that allows us to compute the AEL also for extreme return periods (Table 6).[12]

10 A number of countries (like New Zealand, Norway, UK and Turkey) apply some solidarity rating model. If the insurance scheme is not compulsory, the adverse selection effect must be taken into account to avoid affordable but unsustainable prices. New Zealand's compulsory scheme offers a partial insurance, which can be supplemented by buying an additional coverage, with the possibility of deductibles.

11 We use the average values: 65.3% for the limit and 6.2% for the deductible.

12 Each replication is obtained by summing up the separate simulated values of the damage for every municipality. The municipality damage is the sum of several separate damages, each corresponding to a combination of all the possible earthquake intensities (five values, from 6 to 10 MCS), levels of maintenance conditions (four levels) and types of building structure (a unique type is considered for the two theoretical scenarios of structures entirely composed of unreinforced masonry or reinforced concrete, three types for the actual scenario). For each combination, the loss is the product between: (1) a yearly number of seismic events; (2) a value of the damage. The number of events in (1) is an extraction from a Poisson distribution, whereas the value of the damage in (2) is the product between: (a) the damaged share of the value of the buildings, drawn from a beta distribution with parameters alpha = 1 and

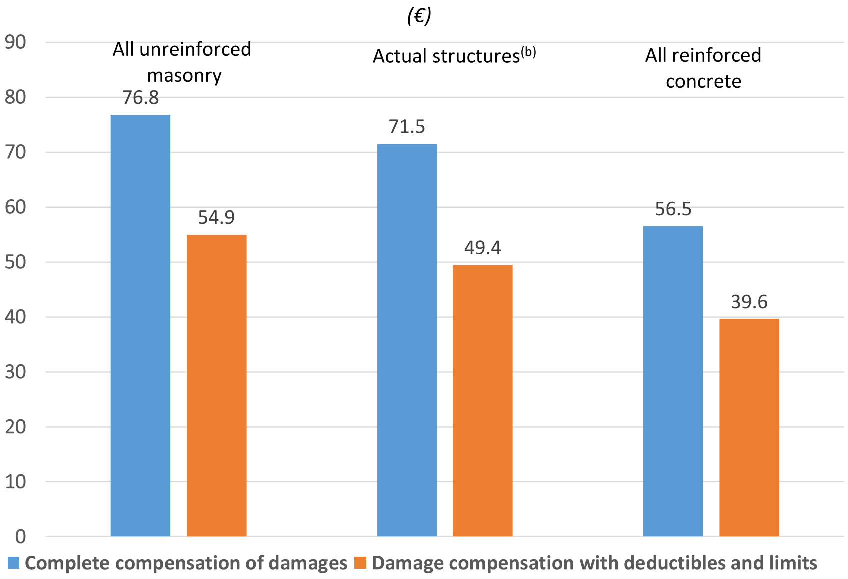

Figure 7: Average pure premium per 100,000 euros for the Italian house buildings' seismic risk[(a)] with total or partial compensation of damages and different building structures.
[(a)] Deductibles and limits collected in a large-scale survey carried out by IVASS in 2017 on the insurance coverages against natural risks for the Italian house buildings. [(b)] Distribution of buildings by type of structure available at the single-municipality level (Istat, 2011 census).

The most destructive scenario is the minimum aggregate exceedance loss for seismic events occurring on average every 10,000 years. The comparison of the losses obtained with different building structures helps compute the savings derived from using technical solutions more resilient to earthquakes. An exam of all the return periods reported in the table shows that using only reinforced concrete entails a loss decrease between 23 and 31%, compared to structures wholly composed of unreinforced masonry.

In comparison with two well-known proprietary models, by RMS and *Swiss Re*, our AEL estimations are very similar for return periods up to 50 years and perform half-way between RMS and *Swiss Re* for higher return periods.

beta = alpha$*(1-\overline{d})/\overline{d}$, where $\overline{d}$ is the average; (b) the value of the building. The λ parameter of the Poisson distribution is the predicted value from the model of Eq. (8), multiplied by a perturbation factor $e^{k*\sigma_\varepsilon}$. σ_ε indicates the standard deviation of the model residuals (Table 4) k is comprised in the interval $[-3.1, +3.1]$, with the lower bound -3.1 used as starting value, and k progressively increasing, by the constant step required to obtain 100,000 iterations, until it reaches the upper bound $+3.1$. The interval $[-3.1, +3.1]$ covers 99.81% of the probability mass of the standard normal distribution.

Table 6: Aggregate exceedance loss (AEL) and average annual loss (AAL) (€ millions).

Return period	**Compensation of damages**					
	Complete compensation			**Compensation with deductibles and limits**[a]		
	Type of building structure					
	Unreinforced masonry	**Actual structures**[b]	**Reinforced concrete**	**Unreinforced masonry**	**Actual structures**[b]	**Reinforced concrete**
	AEL					
10,000	144,142	107,497	103,737	89,753	83,571	68,919
5000	124,731	89,589	88,487	81,432	74,156	60,830
1000	74,220	61,760	51,152	52,368	45,651	38,806
500	58,677	49,235	41,414	42,062	35,565	31,156
250	47,619	41,056	34,340	33,541	29,252	24,768
200	44,544	39,122	32,523	31,563	27,702	23,134
100	37,413	33,536	27344	26,357	23,670	19,383
50	32,295	29,242	23,807	22,681	20,489	16,711
25	28,066	25,549	20,594	19,610	17,840	14,412
10	21,478	19,638	15,809	15,051	13,659	11,041
5	14,158	12,944	10,398	9918	9099	7312
2	4040	3713	2968	2813	2569	2066
AAL *Average*	4236	3944	3118	3032	2728	2185
Stand. dev.	*3146*	*2805*	*2592*	*2258*	*2092*	*2283*

[a]Deductibles and limits collected in a large-scale survey carried out by IVASS in 2017 on the insurance coverages against natural risks for house buildings. [b]Distribution of buildings by type of structure available at municipality level (Istat, 2011 census).

The AAL at the bottom of Table 6 can be regarded as the total yearly pure premium that all the Italian homeowners need to pay to protect themselves against seismic risk. It varies from a minimum of 2.2 billion (with the most resistant building structure and compensation capped by deductibles and limits) to a maximum of 4.2 billion (with the worst possible building structure and complete damage compensation).[13]

7 Concluding Remarks

According to the European guidelines (European Commission, 2016) developed within the *Sendai Framework for Disaster Risk Reduction*, there are three pillars to implement effective policies of natural catastrophe reduction:

(1) a thorough scientific understanding of the natural mechanisms underlying risk,
(2) consistent communication of risk,
(3) an optimal disaster risk management (DRM).

The third pillar comprises four risk-management steps:

(a) mitigation and prevention of risk (Roubault 1970)[14], in order to decrease exposure and vulnerability to it and prevent natural hazards from becoming natural disasters. Risk prevention can be realised through structural reinforcements as well as suitable building codes and construction limits;
(b) enhancing the preparedness to adverse events;
(c) planning an effective reaction both in the immediate aftermath of the natural catastrophe and in the medium term;

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13 We have compared the results of our model with two models widely used in the insurance sector, developed by RMS (*Risklink v16*) and *Swiss Re*, the first one being a proprietary modelling firm and the second one a reinsurer. Their inputs (risk portfolio at the municipality level, composed of all the Italian housing units) are the same as those used by our model. In particular, RMS and *Swiss Re* consider four building structures for the Italian housing units: {unreinforced masonry, 50% unreinforced masonry + 50% steel, 50% unreinforced masonry + 50% reinforced masonry, 50% unreinforced masonry + 50% reinforced concrete}. In particular, the results of our model's worst scenario are compared with those obtained under the unreinforced-masonry hypothesis; our intermediate scenario is set against that of 50% unreinforced masonry + 50% steel and finally, the outputs from our model's best scenario are measured against those produced by the scenario of 50% unreinforced masonry + 50% reinforced concrete. In summary, our results in terms of AEL are intermediate between those of RMS (lower) and *Swiss Re* (higher).

14 Risk prevention is different from risk forecasting, pioneered by Marcel Roubault's classical work (Roubault 1970), but it is still in an early development phase. One recent research field is exploring the changing chemical composition of underground waters as a possible predictor of seismic events (Barberio et al. 2017)

(d) implementing structural, economic, and social post-disaster recovery.

This general framework is also applicable to seismic risk; an effective policy of risk management through insurance products falls into points (c) and (d).

Italy's peculiarity is that earthquake damages have been reimbursed by the Government in the course of the years, with very limited diffusion of insurance covers.

Increasing the utilisation of insurance for the seismic risk of Italian housing units would benefit the state finances, which could become less exposed to the outlays required to help the communities damaged by natural disasters (Poljanšek et al. 2017). In fact, economic agents' reliance on state intervention after natural disasters is not a feature shared by all the democratic systems, in which politicians have to satisfy their constituency's requests in order to be re-elected. For example, Japan, Germany, the United Kingdom, and Portugal concentrate post-disaster state aids to re-activate public infrastructures, without necessarily compensating private housing's damages (Crichton 2008).

Our simulation illustrates that an insurance policy covering all the Italian housing stock would require a pure-risk premium slightly higher than one hundred euros for the average housing unit, which decreases well below this threshold with the introduction of deductibles and limits to cap the policyholder's compensation. Another system to achieve the reduction of pure premiums is the utilisation of earthquake-resistant structures for the construction of new buildings and the improvement of existing ones.

We have also shown that the mutuality effect decreases the geographical variability of premiums since those paid by high-risk policyholders, typically in the Center-South of Italy, are subsidised by lower-risk ones, who pay a rate slightly higher than a risk-based one.

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