Operational (short-term) earthquake loss forecasting in Italy

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Abstract

The seismological community is currently developing operational earthquake forecasting (OEF) systems that aim to estimate, based on continuous ground motion recording by seismic networks, the seismicity in an area of interest; the latter may be expressed, for example, in terms of rates of events exceeding a certain magnitude threshold in a short-period of time (days to weeks). OEF may be possibly used for short-term seismic risk management in regions affected by seismic swarms only if its results may be the input to compute, in a probabilistically sound manner, consequence-based risk metrics.

The present paper reports about feasibility of short-term risk assessment, or operational earthquake loss forecasting (OELF), in Italy. The approach is that of performance-based earthquake engineering, where the loss rates are computed by means of hazard, vulnerability, and exposure. The risk is expressed in terms of individual and regional measures, which are based on short-term macroseismic intensity (or ground motion intensity) hazard. The vulnerability of the built environment relies on damage probability matrices empirically calibrated for Italian structural classes, and exposure data in terms of buildings per vulnerability class and occupants per building typology. All vulnerability and exposure data are at the municipality scale.

The developed procedure, which is virtually independent of the seismological model used, is implemented in an experimental OELF system that continuously processes OEF information to produce nationwide risk maps applying to the week after the OEF data release. This is illustrated by a retrospective application to the 2012 Pollino (southern Italy) seismic sequence, which provides insights on the capabilities of the system and on the impact, on short-term risk assessment, of the methodology currently used for OEF in Italy.

Introduction

Short-term risk assessment (i.e., during seismic swarms) is emerging as a topic of increasing importance because of its broad impact in terms of affected communities. A great deal of research in the geophysical community is currently devoted to operational earthquake forecasting (OEF; e.g., Jordan et al., 2011), represented by the bulk of models and methods to constantly update estimates of seismicity on the basis of continuous earthquake activity monitoring. On the other hand, seismic risk management requires consequence-based measures of the earthquake potential. Indeed, loss forecasting allows cost/benefit analysis to compare different options for risk mitigation and then to optimally allocate resources. In fact, given a set of possible risk mitigation actions $\{A_1, A_2, ...A_i, ...A_n\}$, which includes the option of no-action, and the expected value of the loss associated to each of them $\{E[L|A_1], E[L|A_2], ...E[L|A_i], ...E[L|A_n]\}$, which includes the cost to undertake the action, a criterion for the optional decision (D) is to undertake the action $A^* \in \{A_1, A_2, ..., A_n\}$ such that the estimated expected loss is minimized (Benjamin and Cornell, 1970); Equation (1).

$$D\left(A^*\right) \text{ is optimal} \overset{def}{\Longleftrightarrow} E\left[L \mid A^*\right] \leq E\left[L \mid A_i\right] \;\; \forall i = 0,1,...,n. \tag{1}$$

On these premises, the present study discusses, focusing on the Italian case, the feasibility of probabilistic seismic loss assessment, when seismicity rates based on OEF represent the input. For Italy, these rates are continuously provided by an experimental OEF system (see Marzocchi et al., 2014, and references therein for discussions about the use of OEF models during seismic swarms).

The OEF output provides the basis for a short-term adaption of probabilistic seismic hazard analysis (PSHA; e.g., McGuire, 2004). Indeed, short-term PSHA may be derived from OEF rates if the probability to observe a given macroseismic (*MS*) intensity level in one earthquake, or alternatively, to exceed a ground motion intensity measure (*IM*) threshold, is available (to follow). In fact, the risk assessment also needs models for the vulnerability of the built environment conditional to any earthquake intensity level. Finally, probabilistic measures of loss (e.g., casualties) conditional to damage, that is exposure models, are also required.

Starting from these risk components, a procedure was set-up to compute a number of site-specific and regional (i.e., referring to a number of sites in the same area) loss measures, consistent with the performance-based earthquake engineering approach (Cornell and Krawinkler, 2000). The risk metrics considered include: damaged or collapsed buildings, displaced residents, injuries and fatalities.

The procedure developed, which is virtually independent on the seismological model used to carry out OEF, was coded in a prototypal operational earthquake loss forecasting (OELF) system, namely MANTIS-K, which is currently under experimentation for potential civil protection purposes. The system continuously receives daily input from OEF procedures and carries out OELF for the whole country immediately after each update of seismicity rates. The loss forecasting refers to one week after the OEF data release.

Even if, intentionally, the developed study does not present any specific advancement in the seismological and earthquake engineering models employed, which all reflect published methodologies, the developed study is deemed innovative as it represent, to date and to the knowledge of the authors, the first prototype of a, continuously operating, nationwide seismic risk estimation system, virtually enabling real-time risk management.

In the following, the stochastic framework developed to pass from OEF-based seismicity rates to short-term loss forecasting is presented first. The illustration of the procedure starts from short-term seismic hazard, expressed in terms of *MS* and *IM*, based on a source cell to which a seismicity rate is assigned by OEF. Then, building damage and casualty rates for a site exposed to multiple source cells in an area (e.g., the area of a seismic swarm) are formalized, and the stochastic hypotheses to pass from the weekly number of casualty-producing events at a site, to regional expected losses in an area of interest, are discussed. Subsequently, regional hazard and risk measures (i.e., those requiring to account for spatial correlation of ground motion) are briefly addressed. The second section describes the exposure and vulnerability models considered, based on national census and empirically-calibrated damage probability matrices (DPM) for Italy, respectively. Finally, to illustrate how the implemented experimental OELF system operates, the 2012 Pollino (southern Italy) sequence, which featured a magnitude 5 event (the largest in the sequence), is analyzed. Four days are taken as representative of the evolution of the swarm, in terms of forecasted seismicity: (i) before the swarm, (ii) during the swarm just before the largest magnitude earthquake, (iii) during the swarm after the largest magnitude event, and (iv) post-swarm. At each of the four instants the expected losses, in one-week time-horizon, are computed for an area within 70 km from a point identified as the center of the swarm. A comparison of the loss assessment carried out based on OEF with the one computed using, for the same area, the seismicity rates used for the long term hazard mapping of the country, is also shown.

Methodology

Given a region monitored by a seismic sensor network, OEF models may provide, for each elementary area in which the territory is divided and identified by a pair of coordinates $\{x, y\}$, the estimated expected number of earthquakes above a magnitude of interest per unit time (for example one week). Such a rate, $\lambda\left(t, x, y \,|\, H(t)\right)$, depends on the recorded seismicity history, $H(t)$, and consequently varies with time, *t*. In this context, if the grid is sufficiently small, the point of coordinates $\{x, y\}$ may be treated as a point-like seismic source; i.e., the centroid of a cell representing an elementary seismic source zone.

Considering a site of coordinates $\{w, z\}$, in which there is exposure to seismic risk, for example one or more residential buildings, it is possible to transform the rate above into the expected number of events that, at the $\{w, z\}$ location, will cause the occurrence of certain *MS* level, or exceedance of an *IM* threshold. In the following equations are written in terms of *MS*, yet an equivalent procedure can be set up in terms of *IM*, as illustrated in the subsequent section.

The sought rate for an arbitrary macroseismic intensity level, *ms*, that is $\lambda_{MS=ms}\left(t, w, z \middle| H(t)\right)$, is obtained filtering $\lambda\left(t, x, y \,|\, H(t)\right)$, that is multiplying it by the probability that an earthquake generated in $\{x, y\}$, with known distance from $\{w, z\}$, $R(x, y, w, z)$, causes the considered effect in terms of *MS*, $P\left[MS = ms \middle| R(x, y, w, z)\right]$; Equation (2).

$$\lambda_{MS=ms}\left(t,w,z\left|H\left(t\right)\right.\right)=\lambda\left(t,x,y\left|H\left(t\right)\right.\right)\cdot P\left[MS=ms\left|R\left(x,y,w,z\right)\right.\right]= \\ =\lambda\left(t,x,y\left|H\left(t\right)\right.\right)\cdot\int_{m}P\left[MS=ms\left|m,R\left(x,y,w,z\right)\right.\right]\cdot f_{M}\left(m\right)\cdot dm \tag{2}$$

In the equation $P\left[MS=ms\left|m,R\left(x,y,w,z\right)\right.\right]$ is the probability of observing *ms* at $\{w,z\}$ given an earthquake of magnitude *m* at $\{x,y\}$, and emphasizes that attenuation models (i.e., prediction equations) providing such probabilities are dependent not only on the distance, but also (at least) on a random variable (RV) accounting for the earthquake intensity at the source; e.g., the earthquake magnitude, *M*. Indeed, $f_M(m)$ is the magnitude distribution of earthquakes at the $\{x,y\}$ seismic source. (Some models for *MS* use an equivalent of magnitude instead; it is called the expected intensity at the epicenter or I_E ; e.g., Pasolini et al., 2008.)

If the $\{w,z\}$ site is subjected to several point sources, the total rate is given in Equation (3), as the summation of terms in Equation (2) over the source area. This equation is not different from a classical seismic hazard integral, except that the rate of events is time-variant, which is not the common assumption in PSHA.

$$\lambda_{MS=ms}\left(t,w,z\left|H\left(t\right)\right.\right)=\int_{x}\int_{y}\lambda\left(t,x,y\left|H\left(t\right)\right.\right)\cdot\int_{m}P\left[MS=ms\left|m,R\left(x,y,w,z\right)\right.\right]\cdot f_{M}\left(m\right)\cdot dm\cdot dy\cdot dx \tag{3}$$

An extension of Equation (3), including a vulnerability term, allows to compute the rate of events causing some damage state (ds) to a building of a given structural typology (k). This is given in Equation (4), where $P\left[DS^{(k)}=ds\left|ms\right.\right]$ is the damage probability for the structural typology of interest given *ms*; i.e., a DPM (to follow).

$$\lambda_{DS^{(k)}=ds}\left(t,w,z\left|H\left(t\right)\right.\right)=\int_{x}\int_{y}\lambda\left(t,x,y\left|H\left(t\right)\right.\right)\cdot \\ \sum_{ms}P\left[DS^{(k)}=ds\left|ms\right.\right]\cdot\int_{m}P\left[MS=ms\left|m,R\left(x,y,w,z\right)\right.\right]\cdot f_{M}\left(m\right)\cdot dm\cdot dy\cdot dx \tag{4}$$

Even if it was just mentioned that these rates may not be constant over wide time intervals, such a hypothesis may be acceptable in the short-term (for example unless an update of seismicity from OEF is available). Thus, in the (small) time interval $(t,t+\Delta t)$, the probability of observing one event producing a damage state equal to ds to a building of the structural typology k, can be computed through Equation (5). This equation assumes that the stochastic process of events causing damage to the building at the site is locally (in time) approximated by a (homogeneous) Poisson process. (Note that dependence on $\{w,z\}$ at the left hand side is dropped for simplicity in this equation and in those derived from it.)

$$P\left[DS_{(t,t+\Delta t)}^{(k)} = ds \middle| H(t)\right] \approx \lambda_{DS^{(k)}=ds}\left(t,w,z\middle|H(t)\right)\cdot\Delta t \qquad (5)$$

If number of buildings of the k-th structural typology, ${N_B}^{(k)}$, is known for the $\{w,z\}$ site (i.e., a measure of the exposure), then the expected number of buildings in damage state ds in $(t,t+\Delta t)$ can be computed via Equation (6). It is worth noting that cumulated damages due to subsequent events, which can eventually lead to building failure, are neglected, even if this issue can virtually be accounted for in the considered methodology.

$$E\left[N_{ds,(t,t+\Delta t)}^{(k)} \middle| H(t)\right] = {N_B}^{(k)} \cdot P\left[DS_{(t,t+\Delta t)}^{(k)} = ds \middle| H(t)\right] \qquad (6)$$

In fact, Equation (4) may be further extended in the direction of earthquake consequences if for the *k-th* structural typology, and conditional to damage, the probability of an occupant to suffer casualties, $P\left[Cas^{(k)}\middle|ds\right]$, is available. Then, it is possible to compute the rate of events producing the considered loss, $\lambda_{Cas^{(k)}}\left(t,w,z\middle|H(t)\right)$, as in Equation (7).

$$\begin{aligned}\lambda_{Cas^{(k)}}\left(t,w,z\middle|H(t)\right) = \int_x\int_y \lambda\left(t,x,y\middle|H(t)\right)\cdot\sum_{ds} P\left[Cas^{(k)}\middle|ds\right]\cdot \\ \sum_{ms} P\left[DS^{(k)}=ds\middle|ms\right]\cdot\int_m P\left[MS=ms\middle|m,R(x,y,w,z)\right]\cdot f_M(m)\cdot dm\cdot dx\cdot dy\end{aligned} \qquad (7)$$

The latter equation, formally equivalent to the PBEE framing equation (Cornell and Krawinkler, 2000), is the one of interest and it provides the rate of events producing casualties (e.g., fatality, injury, or shelter need) for an occupant of a building of the k-th typology at the $\{w,z\}$ site. It also allows to compute of expected values of ultimate earthquake consequences because, in the same hypotheses of Equation (5), the probability of observing an event determining casualties, $P\left[Cas_{(t,t+\Delta t)}^{(k)}\middle|H(t)\right]$, may be obtained via Equation (8). Then, the expected number of casualties in the time interval of interest,

$E\left[N_{Cas,(t,t+\Delta t)}^{(k)} \middle| H(t)\right]$, can be computed through Equation (9), if the number of residents, $N_P{}^{(k)}$, in buildings of the *k*-th typology at $\{w,z\}$ is available.

$$P\left[Cas_{(t,t+\Delta t)}^{(k)} \middle| H(t)\right] \approx \lambda_{Cas^{(k)}}\left(t,w,z \middle| H(t)\right)\cdot \Delta t \tag{8}$$

$$E\left[N_{Cas,(t,t+\Delta t)}^{(k)} \middle| H(t)\right] = N_P{}^{(k)} \cdot P\left[Cas_{(t,t+\Delta t)}^{(k)} \middle| H(t)\right] \tag{9}$$

Note that the expected losses as per Equation (6) and Equation (9) may be considered as site-specific risk measures; however, it is probabilistically rigorous to sum them up over all the exposed sites of interest to compute the expected number of casualties in the area (see also the application section).

Site-specific and regional risk assessment based on ground motion intensity

In the same underlying hypotheses of Equation (3), it is possible to compute the average number per unit-time of events, $\lambda_{IM>im}$, that cause the exceedance of an *IM* threshold, *im*, at the $\{w,z\}$ site. Such a rate is given in Equation (10), where the $P\left[IM > im \mid m, R(x,y,w,z)\right]$ term is from a ground motion prediction equation, or GMPE (e.g., Ambraseys et al., 1996). (Note that, GMPEs, differently from macroseismic intensity prediction equations, require geological information about the $\{w,z\}$ site.)

$$\begin{aligned}&\lambda_{IM>im}\left(t,w,z \mid H(t)\right) = \\ &= \int_x\int_y \lambda\left(t,x,y \middle| H(t)\right)\cdot \int_m P\left[IM > im \mid m, R(x,y,w,z)\right]\cdot f_M(m)\cdot dm\cdot dx\cdot dy\end{aligned} \tag{10}$$

Consequent to Equation (10), the rate of events causing some $DS = ds$ to a building of typology *k*, may be computed via Equation (11), where the term $P\left[DS^{(k)} = ds \middle| im\right]$ is the fragility curve for the building (note that one fragility is required for each *DS* level).

$$\begin{aligned}&\lambda_{DS^{(k)}=ds}\left(t,w,z \middle| H(t)\right) = \int_x\int_y \lambda\left(t,x,y \middle| H(t)\right)\cdot \\ &\int_{im} P\left[DS^{(k)} = ds \middle| im\right]\cdot \int_m f_{IM|M,R}\left(im, R(x,y,w,z)\right)\cdot f_M(m)\cdot dm\cdot d(im)\cdot dy\cdot dx\end{aligned} \tag{11}$$

It is also possible to use the IM-based rates in Equation (10) to compute $\lambda_{DS^{(k)}=ds}$ employing DPMs in terms of macroseismic intensity; i.e., Equation (12). Of course this requires a probabilistic relationship (e.g., a semi-empirical model) between *IM* and *MS*, that is the $P\left[MS = ms|im\right]$ term. This kind of models exists, also calibrated on Italian data; e.g., Faenza and Michelini (2010).

$$\lambda_{DS^{(k)}=ds}\left(t,w,z|H(t)\right)=\int_x\int_y \lambda\left(t,x,y|H(t)\right)\cdot \sum_{ms} P\left[DS^{(k)}=ds|ms\right]\cdot\int_{im} P\left[MS=ms|im\right]\cdot\int_m f_{IM|M,R}\left(im,R(x,y,w,z)\right)\cdot f_M(m)\cdot dm\cdot d(im)\cdot dy\cdot dx \tag{12}$$

Along the same line, the rate of events causing casualty, may be computed in Equation (13), with obvious meaning of the symbols. At this point these rates can be used to compute the individual risk metrics in Equation (8) and Equation (9). Note that in principle, this should lead to the same results as if the expected losses are computed using *MS* as the hazard-related measure, even if, because of the semi-empirical models used in both approaches, differences may be expected.

$$\lambda_{Cas^{(k)}}\left(t,w,z|H(t)\right)=\int_x\int_y \lambda\left(t,x,y|H(t)\right)\cdot\sum_{ds} P\left[Cas^{(k)}|ds\right]\cdot\int_{im} P\left[DS^{(k)}=ds|im\right]\cdot\int_m f_{IM|M,R}\left(im,R(x,y,w,z)\right)\cdot f_M(m)\cdot dm\cdot d(im)\cdot dy\cdot dx \tag{13}$$

Because the *IMs* or *MS'* at different sites in a given earthquake are stochastically dependent, also the losses (i.e., building damage and casualties) are dependent. Therefore, in general, it not easy to compute the probability of observing a certain value of the loss over a region (i.e., the distribution of the total regional loss). Nonetheless, the expected number of damaged buildings, or casualties at each site, may be summed up over a region of interest to obtain global averages, which justifies equations derived in the previous section. This is because the expected value is not affected by stochastic dependency of the added RVs.

Conversely, if one wants, for example, to compute the probability that at least one building of the region will get in some damage state in the forthcoming week, then all the sites have to be treated jointly. In fact, this issue primarily raises from the hazard, because to compute, for example, the rate of earthquakes in the region, which will cause exceedance of an *IM* threshold at least at one of the $\{1,2,...,i,...,n\}$ sites, $\lambda_{\{\exists\, i:IM_i>im\}}$, Equation (14) is required, which may be referred to as a regional hazard integral; e.g., Esposito and Iervolino (2011).

$$\lambda_{\{\exists i:IM_i>im\}} = \int_x \int_y \lambda\left(t,x,y\middle|H(t)\right)\cdot\left\{1-\int_m P\left[\bigcap_{i=1}^{n} IM_i \le im \mid M, \underline{R}\left(x,y,\underline{w},\underline{z}\right)\right]\cdot f_M(m)\cdot dm\right\}\cdot dx\cdot dy \quad (14)$$

In the equation the $P\left[\bigcap_{i=1}^{n} IM_i \le im \mid M, R\left(x,y,\underline{w},\underline{z}\right)\right]$ term is the joint probability of the *IMs* at the *n* sites (note that in the equation *w* and *z* are vectors in this case). This distribution has to be used to properly account for intraevent correlation that exists among *IMs* in different sites. This correlation arises because of two factors: (i) the considered sites share the same event features (i.e., earthquake magnitude and location); (ii) intraevent residuals of *IMs*, with respect to a GMPE, are (in principle) spatially correlated (e.g., Esposito and Iervolino, 2012).

That said, the rates in Equation (14) may be used to approximate probabilities of interest, in analogy with Equation (5). For example, the probability of events causing at least one damaged building (or casualty), or the probability of observing a certain number of damaged buildings (or casualties), in the region, may be computed. However, this may imply large computational effort due to the likely required Monte Carlo simulation of random fields of losses at all sites. Indeed, an individual building location is virtually a site with an associated *IM* random variable. Moreover, it may also be required to account for spatial correlation of building damage given intensity or of casualty given damage. This is not discussed here further, as the developed system primarily works in terms of expected losses.

The flowchart in Figure 1 recaps the described procedure to compute the discussed site-specific and regional short-term risk measures, starting from time-variant seismicity estimations from OEF. The following section describes the models and data for hazard, vulnerability, and exposure employed for OELF in Italy.

Models and data for OELF in Italy

Seismicity rates

Seismicity rates from OEF, $\lambda\left(t,x,y\middle|H(t)\right)$, are provided by the OEF-Italy system of the (Italian) national institute of geophysics and volcanology (INGV) for a grid spaced of about 0.1° and covering the whole national area and some sea. They are obtained based on the seismicity recorded by the country-wide seismic network of INGV and are updated daily or after a *M* 3.5+ (local magnitude scale is used) event in the monitored area. The time unit for rates is one week and they refer to events with local magnitude equal or larger than four (Marzocchi et al., 2014). The magnitude of these events is supposed, herein, to be distributed according to a Gutenberg-Richter-type relationship (Gutenberg and Richter, 1994), with unbounded maximum magnitude and *b*-value equal to one. This relationship does not change with the point source a specific rate value refers to; i.e., it is spatially-invariant.

It is not the focus of this work to scientifically discuss OEF models, and it has to be underlined that the risk assessment procedure is practically independent of how input data (i.e., seismicity rates for point-like cells discretizing the territory) are computed; therefore, the reader is referred to Marzocchi et al (2014) for further details.

Earthquake intensity

The chosen prediction equation for macroseismic intensity is that of Pasolini et al. (2008), which is also adopted by INGV for the assessment of macroseismic national hazard (Gómez Capera et al., 2007). Intensity is defined by the Mercalli-Cancani-Sieberg (MCS) scale (Sieberg, 1931) and the explanatory variables of the model are epicentral distance, R_{epi}, and I_E (epicentral intensity). The model applies to the [0km,220km] interval of the former, and between 5 and 12 of the latter. (Cardinal numbers are used for MS, in lieu of ordinals, consistent with the cited study.)

Pasolini et al. (2008) also provide a semi-empirical model relating epicentral intensity, I_E, and the moment magnitude, M_w, from which the distribution of epicentral intensity conditional to moment magnitude, $f_{I_E|M_w}\left(i_E\middle|m\right)$, may be obtained. Thus for each point source, the I_E distribution, $f_{I_E}(i_E)$, may be obtained through the marginalization in Equation (15). These distributions are conditional to the earthquake occurrence at the specific point-like source.

$$f_{I_E}(i_E) = \int_m f_{I_E|M_w}(i_E|m) \cdot f_{M_w}(m) \cdot dm \tag{15}$$

According to the adopted model for *MS* attenuation, in the equations above the I_E RV and its distribution, $f_{I_E}(i_E)$, have to replace *M* and $f_M(m)$, respectively.

In the loss assessment, contributions from sources with epicentral distance larger than 150km are neglected. Moreover, in order to convert the continuous model of *MS* provided by Pasolini et al. (2008) into a discrete model, mass probabilities associated to integer values of *ms* between 0 and 12 are computed. Then, conditional to the occurrence of the earthquake, the resulting *ms* distribution for each site is scaled such that $P[0 \le ms \le 12] = 1$. It is to finally note that the considered model applies for M_w up to about 7; therefore, the magnitude distribution of the sources has been truncated to M_w 7; consequences of such an assumption were verified for tolerability. The check was carried out considering, in the loss assessment, magnitudes up to ten and extrapolating the models up to this magnitude. It was verified that the weekly expected losses did change (in the worst case) in the order of 10% with respect to the truncation to magnitude seven.

Vulnerability

For each vulnerability class (k) and conditional to *MS*, models of structural vulnerability provide the $P\left[DS^{(k)} = ds|ms\right]$ terms, which are usually computed based on empirical data. These probabilities are traditionally arranged in the form of a matrix with the number of rows equal to number of structural classes considered times the possible *MS* intensities, whereas the number of columns is the number of considered damage states. The resulting matrix is referred to as a damage probability matrix.

The DPM considered in this study (Iervolino et al, 2014) is based on Italian observational data (Zuccaro and Cacace, 2009). The DPM, reported in Table 1, accounts for four different vulnerability classes from A to D, and six damage levels (*D*0 – no damage, *D*1 – slight damage, *D*2 – moderate damage, *D*3 – heavy damage, *D*4 – very heavy damage, *D*5 collapse). Vulnerability classes, damage levels and *MS* are defined in accordance with the European macroseismic scale or EMS 98 (Grünthal, 1998). In fact, in this paper, DPM are applied to the hazard assessment in term of MCS. Moreover it is worth to note that, due to the lack of Italian observational data, DPM values for $MS \geq 11$ are based on extrapolation.

Casualty probabilities conditional to a given structural damage and vulnerability class, $P\left[Cas^{(k)} \middle| ds\right]$, are those of Zuccaro and Cacace (2011), in which fatalities and injuries are considered (someone requiring hospital treatment is defined as injured); Table 2. Zero probability is associated to damage levels equal to or lower than *D*3, whereas for *D*4 and *D*5 casualty probabilities are provided for each vulnerability class from A to D. The probability of being displaced for a resident in a building in damage level *D*4 or *D*5 is one, while is 0.5 for buildings in *D*3, and zero for lower damage levels.

Exposure

For exposure, municipalities are the elementary units in which the Italian territory is divided. Data regarding the number of buildings and the number of residents (both grouped by vulnerability class) are derived from the National census of 2001 (Zuccaro et al., 2012).

According to Zuccaro et al. (2012), casualty and injury assessment may be carried out considering that 65% of the total population is exposed at the time of occurrence of the earthquake, that is the term $N_P^{(k)}$ in Equation (9) is multiplied by 0.65. (In fact, Zuccaro and Cacace (2011) provide hourly occupancy ratios, which are, however, neglected herein.)

The MANTIS-K system and an illustrative application

The described procedure and data have been implemented in an automatic system, currently under experimentation that receives the output of the OEF-Italy system in real-time. The system computes, in about 1.5 hours on a today's ordinary personal computer, for each vulnerability class, on a municipality basis, the probabilities that in one week after the OEF release:

- a building becomes unusable for seismic causes;
- a building collapses for seismic causes;

- the occupant of a building is injured for seismic causes;
- the occupant of a building dies for seismic causes.

As an example, panels a-d of Figure 2 report the countrywide probability of collapse of buildings given the vulnerability class in the week after October 26th 2012. In the same week, panels a-d of Figure 3 report the probability of a generic building to collapse, as well as of being unusable. The figure also reports the injury and fatality probability for the whole country. Actually, for an arbitrary area in the country, MANTIS-K can compute the weekly total expected number of:

- collapsed buildings;
- displaced residents;
- injuries;
- fatalities.

In fact, the system, at each release of the OEF rates, automatically identifies the location in Italy for which the rate from the OEF-Italy system is the largest. For an area of 140 km in diameter around this point, which is defined as the one with the largest current seismicity, the system computes the expected losses in terms of total expected number of collapsed buildings, displaced residents, injuries and fatalities. This should automatically provide the risk for the most hazardous area according to the current OEF estimate (as also illustrated in the next subsection).

The discussed risk metrics are expressed in terms of probabilities for the week after the release of OEF rates primarily because the OEF-Italy system of INGV releases weekly rates; however, it also believed that one week is a time-span sufficient also to put in place risk reduction actions, if needed; therefore this time-frame was kept for the loss assessment. It is also to note that, because the OEF rates are released by INGV at least daily, the weekly probabilities are updated at each OEF rates release; therefore, at least daily as well.

In principle, the losses computed via this system can be compared, in the framework of Equation (1), to the expected losses in the case some risk reduction action is hypothetically put in place in a region affected by a seismic swarm. This may aid decision making with respect to taking the decision which minimizes the expected loss.

The 2012 Pollino sequence

In this section OELF is applied to the Pollino (southern Italy) seismic sequence, which lasted several months and featured a M_w 5 event in October 2012, which was the largest magnitude observed. Four OEF outputs are here considered for the risk assessment, they are based on OEF rates released at 00:00 (UTC) of the following days: (a) 01/01/2010; (b) 25/10/2012; (c) 26/10/2012; (d) 21/07/2013. Release (a) is considered representative of conditions before the start of the seismic sequence, whereas (b) and (c) are before and after the largest magnitude event, respectively. Finally, (d) is several months after the largest magnitude event.

For each of these instants, INGV provided $\lambda\left(t,x,y\,|\,H\left(t\right)\right)$ for the whole national area. From these rates, represented in panels a-d of Figure 4, it can be noted that only on 10/26/2012 the Pollino area is the most hazardous in Italy (that is right after the largest magnitude event; this is a specific feature of the OEF models used as an input herein). More specifically, maximum values of seismicity is at the grid point of coordinates lat. 39.85° and long. 16.05°, which is hereafter identified as the center of the Pollino sequence. The expected number of $M_w \geq 4$ events in the week following instant (c) is equal to 0.0615000 [events/week]. Rates estimated by INGV at the same point for instants (a), (b), and (d), are 0.0000727 [events/week], 0.002260 [events/week], and 0.000672 [events/week], respectively. For the risk assessment, all municipalities within a radius of 70 km from the center of the sequence are considered; in Figure 5 these municipality are plotted with a color-scale reflecting the expected number of fatalities in the week after 26/10/2012.

The centroid of each municipality area is considered for computing the distance from each point-like seismic source, $R\left(x,y,w,z\right)$, which is required by the attenuation model. Clearly, there are two implicit assumptions behind this choice: the first is that it is possible to concentrate in a single point the whole vulnerability and exposure of each municipality; the second is that such a point is the geometrical canter of each municipality.

Applying Equation (6) and Equation (9), the expected number of: (i) collapsed buildings (i.e., buildings damage levels *D*4 and *D*5), (ii) displaced, (iii) injured, and (iv) dead residents, in the week following each of the four considered instants was computed for each municipality. In Table 3, results are summed up per bin of distance from the center of the Pollino area. In the same table, risk indices are normalized with respect to the total number of buildings or residents in each distance bin.

These results allow to point out that risk measures are sensitive to the short-term seismicity variations inferred by OEF. On the other hand, if absolute values of indices are considered, the largest computed risk (at time 3) is about one expected fatality over more than $4 \cdot 10^5$ residents within a radius of 50 km from the center of the sequence (note that, according to the information available to the authors, no casualties were recorded in the Pollino sequence).

The largest evaluated risk is just after the largest shock observed. This feature stems from the OEF models used in the OEF-Italy system, which yield an expected seismicity rate that is proportional to the seismic moment already released.

Comparison with losses based on long-term hazard

Further insights regarding from these results may be obtained by comparing them with the weekly loss computed using the seismic source model of Meletti et al. (2008), with rates from Barani et al. (2009), which lie at the basis of the national hazard map for Italy (Stucchi et al., 2011), used for structural design. This model considers areal source zones and no background seismicity. The rates associated to each source zone are annual and were scaled to one week, for the purposes of this study, using a 7/365 conversion factor. Because the Barani et al. (2009) study provides rates for earthquakes with minimum magnitude equal to 4.3 (for all zones, but zone named 936, which is has a minimum magnitude of 3.7), these rates have been adjusted herein to include earthquakes with magnitude between 4 and 4.3. This was to be consistent with the minimum magnitude from the OEF-Italy system, and such an adjustment was carried out via a Gutenberg-Richter relationship with a *b*-value equal to one. The resulting rates for Italy are given in Figure 6 along with the seismic source zones.

Weekly expected losses with this source model were computed for the Pollino area. In risk analysis, except of the rates, all others models and assumptions being the same as those based on OEF; i.e., those discussed above. Results, are reported in Table 4, which shows a good agreement with those computed for day (a) and day (d) of the Pollino sequence. This was somewhat expected as (a) and (d) were identified as a pre-swarm and post-swarm instants, and therefore the risk associated to them should grossly reconcile (i.e., same order of magnitude) with loss assessment based on long-term hazard. To better understand this comparison of losses based on OEF with respect to those from the assessment based on long-term seismicity rates, Table 5 reports the ratios of the losses computed during the Pollino sequence (Table 3) divided by those of Table 4.

Conclusions

The study discussed, focusing on the Italian case, the feasibility of probabilistic short-term seismic loss (risk) assessment, when the input is represented by the seismicity rates given by the operational earthquake forecasting procedures.

Given data available in terms of vulnerability and exposure for Italy, and the seismicity data provided daily by the OEF-Italy system of the Italian national institute of geophysics and volcanology, an experimental system for continuous nationwide short-term seismic risk assessment, MANTIS-K, was set-up. According to the output of OEF, the forecasted consequence statistics are for one-week time-horizon after the time of the analysis. Risk metrics are the expected number of collapsed buildings, fatalities, injuries, and displaced residents. In fact, an illustrative application, which does not discuss the scientific merit of input seismicity data and vulnerability/exposure models employed, was developed. It refers to the 2012 Pollino (southern Italy) sequence.

The main conclusions from this feasibility study are that: (i) probabilistically-consistent continuous short-term seismic risk assessment in Italy appears to be feasible; (ii) the approach is probabilistically rigorous and it is virtually independent of the OEF and vulnerability/exposure models employed, while results, obviously, are not; (iii) the risk measures considered seem to be sensitive to the short-term seismicity variations inferred by OEF, that is, orders of magnitude variations of seismicity rates are reflected in orders of magnitude variations of casualty rates; (iv) because of the intrinsic feature of the OEF model employed, the largest risk is observed after the largest-magnitude event observed in the sequence, indicating the moment in which a worse earthquake is more likely.

Data and resources

OEF rates from the OEF-Italy system of INGV were provided by Warner Marzocchi. Damage probability matrices and exposure information were provided by Giulio Zuccaro. The rest of data is from the listed references.

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Table 1. Considered damage probability matrix.

Class	MS	$P[D0\|ms]$	$P[D1\|ms]$	$P[D2\|ms]$	$P[D3\|ms]$	$P[D4\|ms]$	$P[D5\|ms]$
A	5	0.3487	0.4089	0.1919	0.0450	0.0053	0.0002
B	5	0.5277	0.3598	0.0981	0.0134	0.0009	0.0000
C	5	0.6591	0.2866	0.0498	0.0043	0.0002	0.0000
D	5	0.8587	0.1328	0.0082	0.0003	0.0000	0.0000
A	6	0.2887	0.4072	0.2297	0.0648	0.0091	0.0005
B	6	0.4437	0.3915	0.1382	0.0244	0.0022	0.0001
C	6	0.5905	0.3281	0.0729	0.0081	0.0005	0.0000
D	6	0.7738	0.2036	0.0214	0.0011	0.0000	0.0000
A	7	0.1935	0.3762	0.2926	0.1138	0.0221	0.0017
B	7	0.3487	0.4089	0.1919	0.0450	0.0053	0.0002
C	7	0.5277	0.3598	0.0981	0.0134	0.0009	0.0000
D	7	0.6591	0.2866	0.0498	0.0043	0.0002	0.0000
A	8	0.0656	0.2376	0.3442	0.2492	0.0902	0.0131
B	8	0.2219	0.3898	0.2739	0.0962	0.0169	0.0012
C	8	0.4182	0.3983	0.1517	0.0289	0.0028	0.0001
D	8	0.5584	0.3451	0.0853	0.0105	0.0007	0.0000
A	9	0.0102	0.0768	0.2304	0.3456	0.2592	0.0778
B	9	0.1074	0.3020	0.3397	0.1911	0.0537	0.0060
C	9	0.3077	0.4090	0.2174	0.0578	0.0077	0.0004
D	9	0.4437	0.3915	0.1382	0.0244	0.0022	0.0001
A	10	0.0017	0.0221	0.1138	0.2926	0.3762	0.1935
B	10	0.0313	0.1563	0.3125	0.3125	0.1563	0.0313
C	10	0.2219	0.3898	0.2739	0.0962	0.0169	0.0012
D	10	0.2887	0.4072	0.2297	0.0648	0.0091	0.0005
A	11	0.0002	0.0043	0.0392	0.1786	0.4069	0.3707
B	11	0.0024	0.0284	0.1323	0.3087	0.3602	0.1681
C	11	0.0380	0.1755	0.3240	0.2990	0.1380	0.0255
D	11	0.0459	0.1956	0.3332	0.2838	0.1209	0.0206
A	12	0.0000	0.0000	0.0000	0.0010	0.0480	0.9510
B	12	0.0000	0.0000	0.0006	0.0142	0.1699	0.8154
C	12	0.0000	0.0001	0.0019	0.0299	0.2342	0.7339
D	12	0.0000	0.0002	0.0043	0.0498	0.2866	0.6591

Table 2. Casualty probabilities conditional structural damage and structural typology.

Loss	Vulnerability Class	*D*0	*D*1	*D*2	*D*3	*D*4	*D*5
Fatality	A or B or C	0	0	0	0	0.04	0.15
Fatality	D	0	0	0	0	0.08	0.3
Injury	A or B or C	0	0	0	0	0.14	0.7
Injury	D	0	0	0	0	0.12	0.5

Table 3. Indices of seismic risk across the swarm.

Date	Dist.	Total build.	Total res.	Coll.	Disp.	Injuries	Fatalities	Coll. [%]	Disp. [%]	Injuries [%]	Fatalities [%]
01/01/2010	≤ 10km	4281	12567	2.85E-02	2.92E-01	1.16E-02	3.00E-03	6.65E-04	2.32E-03	9.25E-05	2.39E-05
	≤ 30km	66243	188538	2.34E-01	2.74E+00	1.03E-01	2.69E-02	3.53E-04	1.45E-03	5.45E-05	1.43E-05
	≤ 50km	149733	438990	5.21E-01	6.14E+00	2.29E-01	5.98E-02	3.48E-04	1.40E-03	5.21E-05	1.36E-05
	≤ 70km	256281	878432	9.07E-01	1.16E+01	4.35E-01	1.14E-01	3.54E-04	1.32E-03	4.96E-05	1.30E-05
25/10/2012	Dist.	Total build.	Total res.	Coll.	Disp.	Injuries	Fatalities	Coll. [%]	Disp. [%]	Injuries [%]	Fatalities [%]
	≤ 10km	4281	12567	1.22E-01	1.05E+00	5.64E-02	1.43E-02	2.85E-03	8.35E-03	4.49E-04	1.14E-04
	≤ 30km	66243	188538	6.17E-01	6.43E+00	2.81E-01	7.27E-02	9.32E-04	3.41E-03	1.49E-04	3.86E-05
	≤ 50km	149733	438990	1.07E+00	1.17E+01	4.77E-01	1.24E-01	7.15E-04	2.66E-03	1.09E-04	2.82E-05
	≤ 70km	256281	878432	1.55E+00	1.85E+01	7.27E-01	1.90E-01	6.05E-04	2.10E-03	8.27E-05	2.16E-05
26/10/2012	Dist.	Total build.	Total res.	Coll.	Disp.	Injuries	Fatalities	Coll. [%]	Disp. [%]	Injuries [%]	Fatalities [%]
	≤ 10km	4281	12567	1.87E+00	1.52E+01	8.88E-01	2.24E-01	4.37E-02	1.21E-01	7.06E-03	1.78E-03
	≤ 30km	66243	188538	7.46E+00	7.18E+01	3.47E+00	8.90E-01	1.13E-02	3.81E-02	1.84E-03	4.72E-04
	≤ 50km	149733	438990	1.07E+01	1.08E+02	4.83E+00	1.24E+00	7.13E-03	2.46E-02	1.10E-03	2.84E-04
	≤ 70km	256281	878432	1.28E+01	1.38E+02	5.84E+00	1.51E+00	4.98E-03	1.57E-02	6.65E-04	1.72E-04
21/07/2013	Dist.	Total build.	Total res.	Coll.	Disp.	Injuries	Fatalities	Coll. [%]	Disp. [%]	Injuries [%]	Fatalities [%]
	≤ 10km	4281	12567	5.77E-02	5.33E-01	2.54E-02	6.49E-03	1.35E-03	4.24E-03	2.02E-04	5.17E-05
	≤ 30km	66243	188538	3.68E-01	4.06E+00	1.67E-01	4.34E-02	5.55E-04	2.15E-03	8.85E-05	2.30E-05
	≤ 50km	149733	438990	7.27E-01	8.25E+00	3.25E-01	8.47E-02	4.86E-04	1.88E-03	7.39E-05	1.93E-05
	≤ 70km	256281	878432	1.17E+00	1.45E+01	5.60E-01	1.47E-01	4.55E-04	1.65E-03	6.37E-05	1.67E-05

Dist. means distance; Build. means buildings; Res. means residents; Coll. means collapsed buildings; disp. means displaced residents.

Table 4. Indices of seismic risk derived from seismogenic zones and seismic rates from Barani et al. (2009).

Distance	Total buildings	Total residents	Coll.	Disp.	Injuries	Fatalities	Coll. [%]	Disp. [%]	Injuries [%]	Fatalities [%]
≤ 10km	4281	12567	3.74E-02	3.56E-01	1.60E-02	4.09E-03	8.74E-04	2.84E-03	1.27E-04	3.25E-05
≤ 30km	66243	188538	2.85E-01	3.19E+00	1.33E-01	3.44E-02	4.30E-04	1.69E-03	7.04E-05	1.82E-05
≤ 50km	149733	438990	6.04E-01	6.91E+00	2.82E-01	7.33E-02	4.04E-04	1.57E-03	6.41E-05	1.67E-05
≤ 70km	256281	878432	1.01E+00	1.27E+01	5.13E-01	1.34E-01	3.93E-04	1.44E-03	5.84E-05	1.53E-05

Coll. means collapsed buildings; disp. means displaced residents.

Table 5. Ratio of losses during the Pollino sequence with respect to long term risk estimates (i.e., ratios of the cells in the columns coll., disp., injuries and fatalities of Table 3 divided by the corresponding values of Table 4).

	Distance	Coll.	Disp.	Injuries	Fatalities
01/01/2010	≤ 10km	0.76	0.82	0.73	0.73
	≤ 30km	0.82	0.86	0.78	0.78
	≤ 50km	0.86	0.89	0.81	0.82
	< 70km	0.90	0.92	0.85	0.85
25/10/2012	Distance	Coll.	Disp.	Injuries	Fatalities
	≤ 10km	3.26	2.95	3.53	3.50
	≤ 30km	2.16	2.02	2.12	2.11
	≤ 50km	1.77	1.69	1.69	1.69
	< 70km	1.54	1.46	1.42	1.41
26/10/2012	Distance	Coll.	Disp.	Injuries	Fatalities
	≤ 10km	49.99	42.56	55.59	54.79
	≤ 30km	26.16	22.54	26.14	25.89
	≤ 50km	17.67	15.60	17.14	16.99
	< 70km	12.68	10.90	11.39	11.25
21/07/2013	Distance	Coll.	Disp.	Injuries	Fatalities
	≤ 10km	1.54	1.50	1.59	1.59
	≤ 30km	1.29	1.27	1.26	1.26
	≤ 50km	1.20	1.19	1.15	1.16
	< 70km	1.16	1.14	1.09	1.09

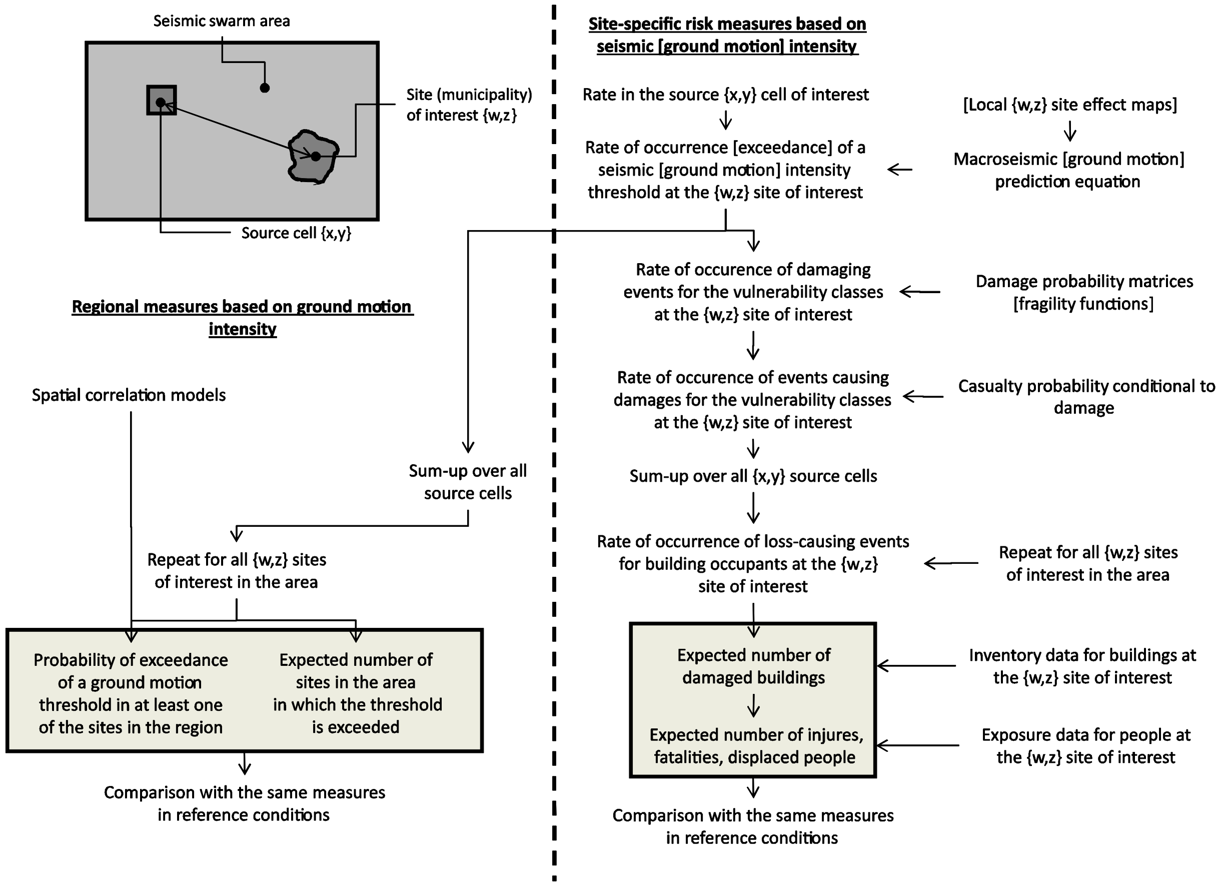

Figure 1. Sketch of the short-term risk assessment procedure.

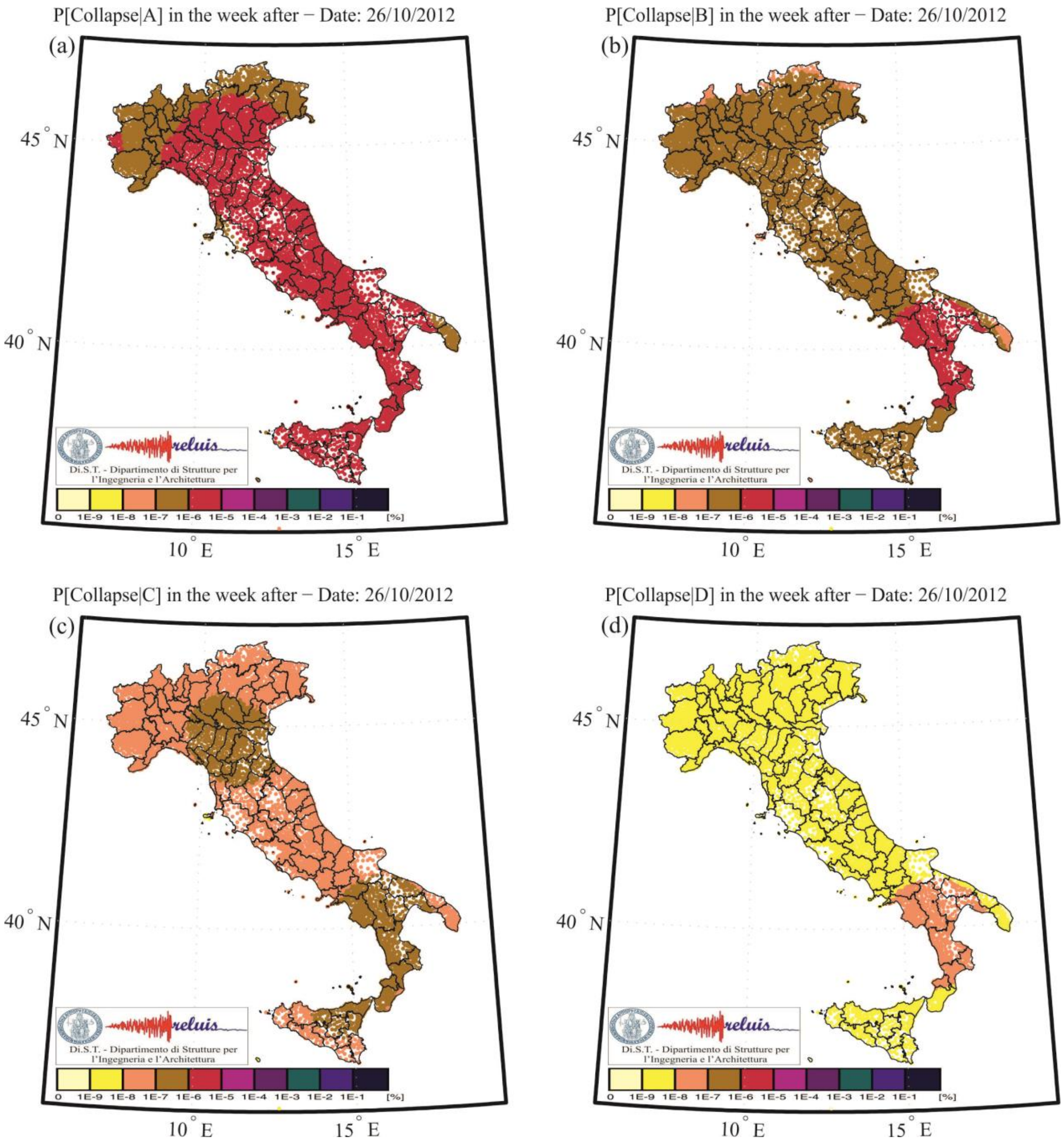

Figure 2. Weekly collapse probability per building vulnerability class after October 26th 2012.

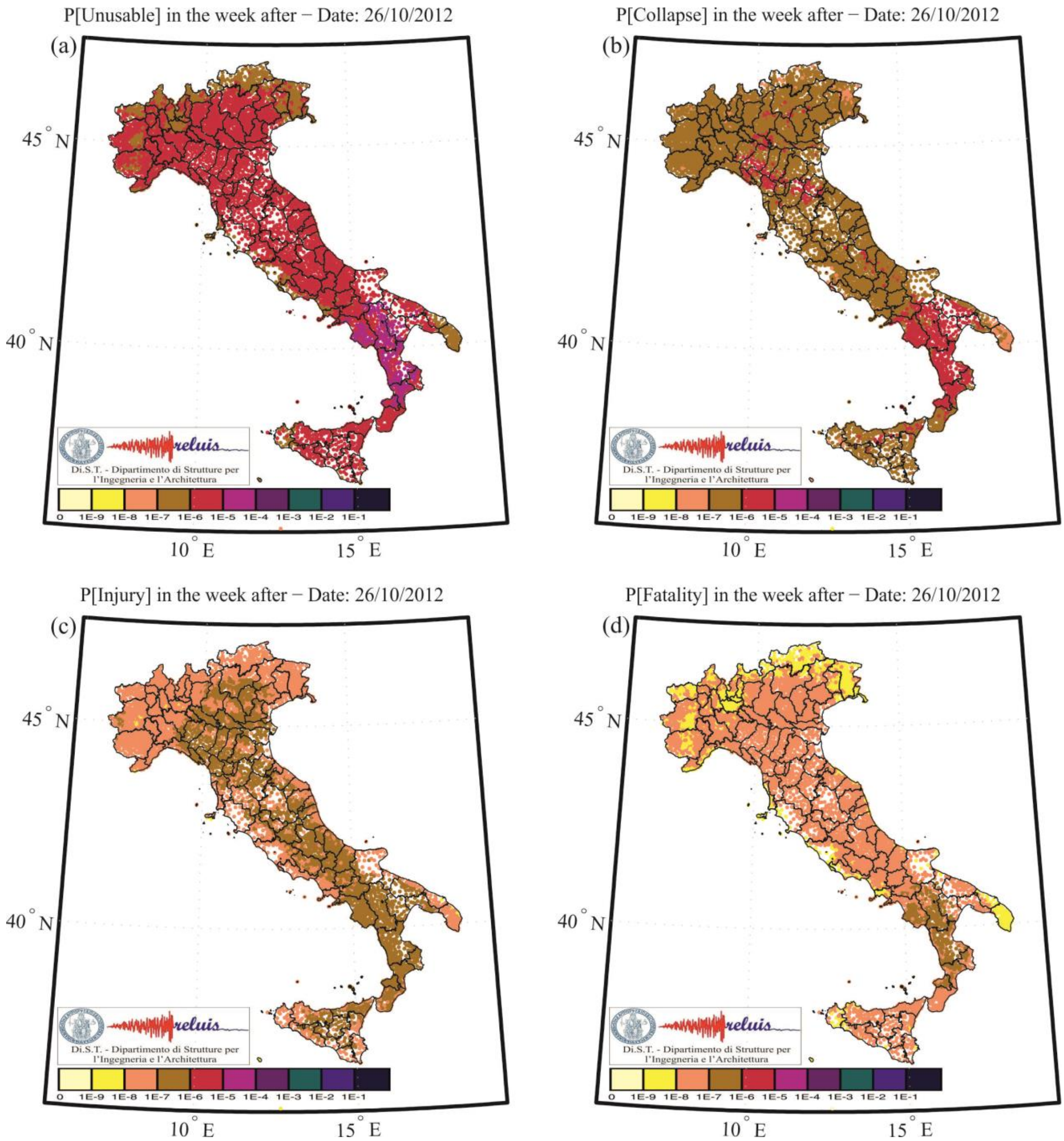

Figure 3. Weekly displaced, collapse, injury, and fatality probability after October 26th 2012.

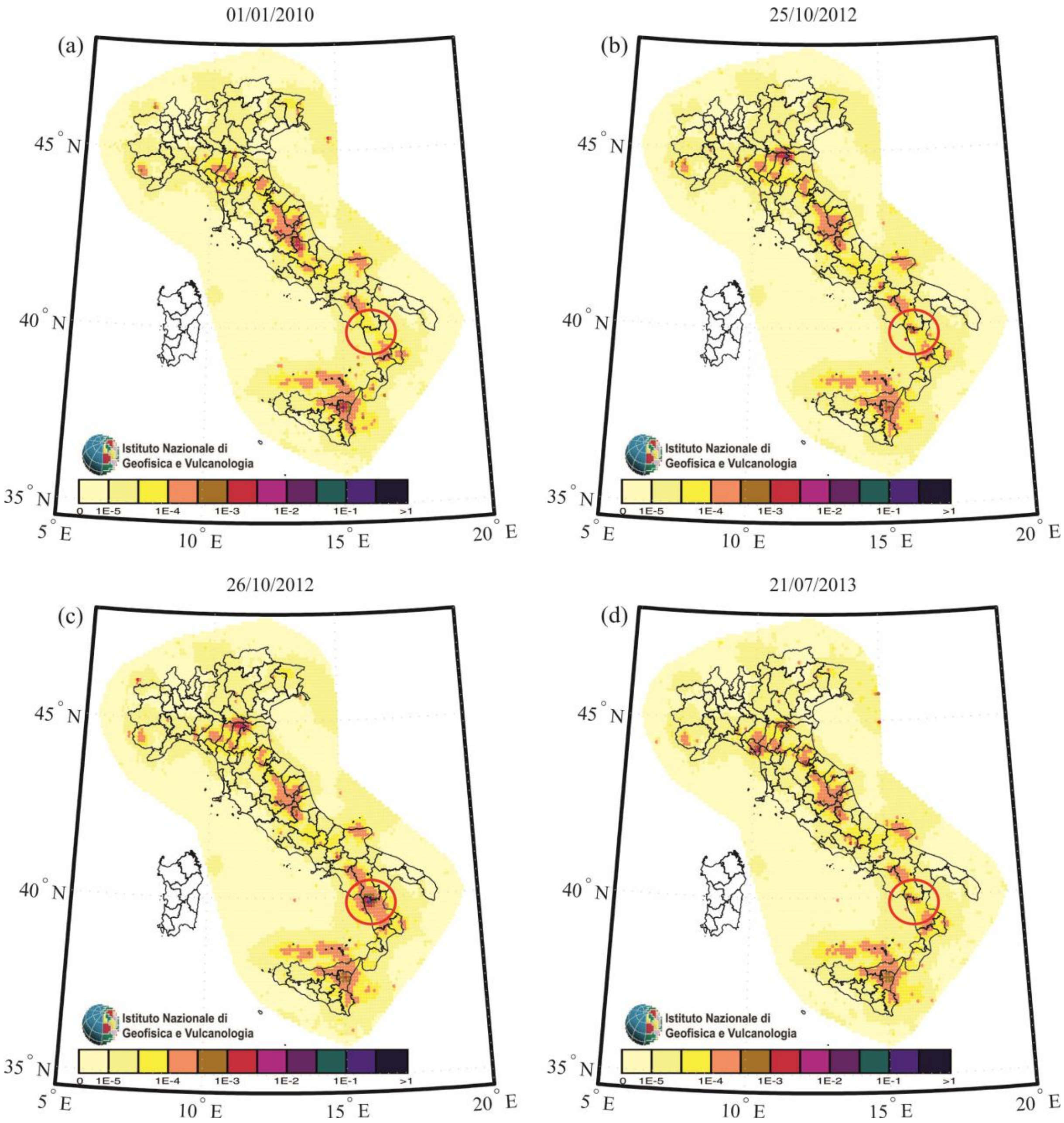

Figure 4. Seismic rates in terms of expected number of M4+ events per week estimated through OEF at the four considered instants of the Pollino (2012) sequence.

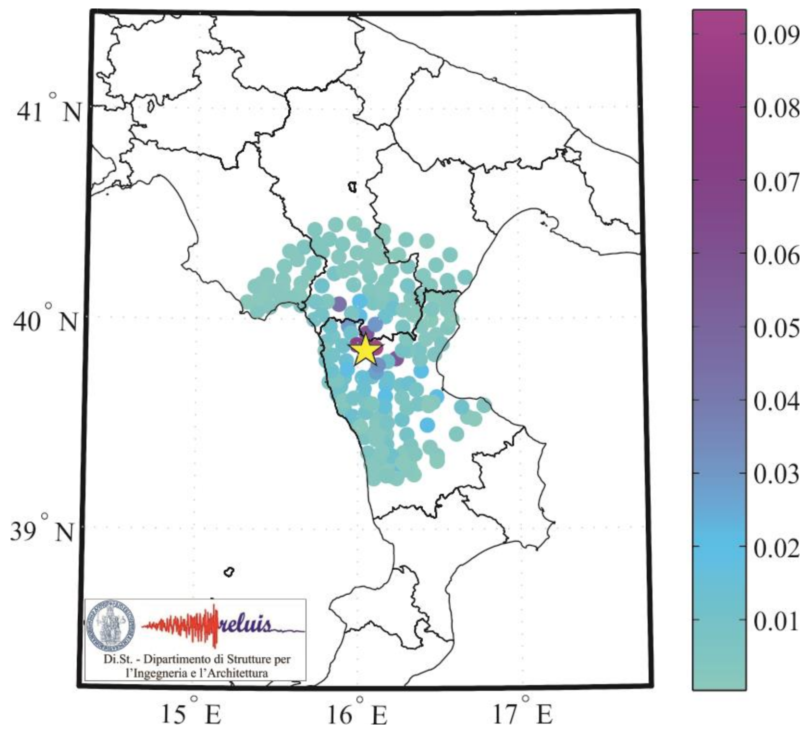

Figure 5. Considered municipalities within 70km (in radius) from the center of the Pollino sequence (star). The color of points is proportional to the expected number of fatalities, per municipality, in the week after 26/10/2012.

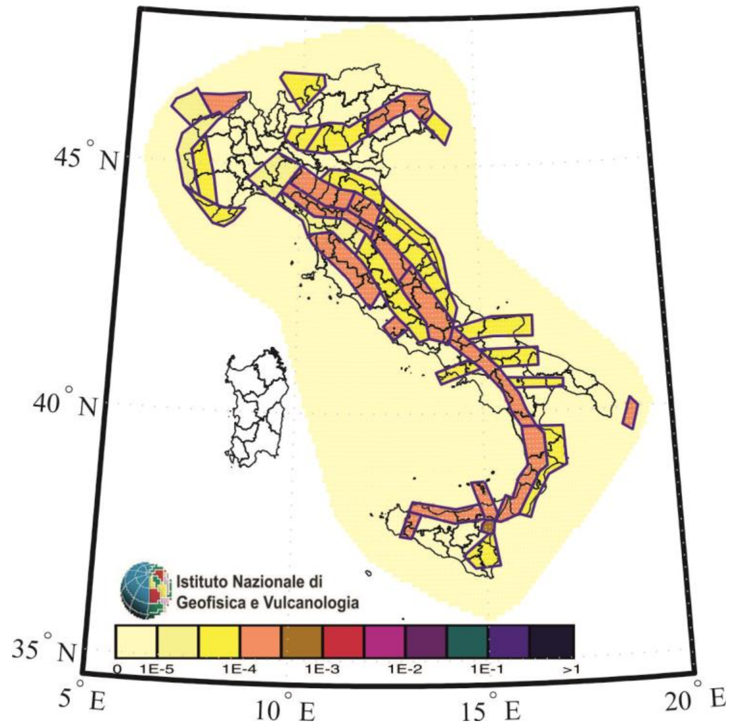

Figure 6. Weekly rates of M4+ events in one week adjusted from Barani et al. (2009) and seismic source model of Meletti et al. (2008).