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Operational (Short-Term) Earthquake Loss Forecasting in Italy

by Iunio Iervolino, Eugenio Chioccarelli, Massimiliano Giorgio, Warner Marzocchi,
Giulio Zuccaro, Mauro Dolce, and Gaetano Manfredi

Abstract The seismological community is currently developing operational earthquake forecasting (OEF) systems that aim to estimate the seismicity in an area of interest, based on continuous ground-motion recording by seismic networks; the seismicity 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 possibly may be 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 article reports on the feasibility of short-term risk assessment, or operational earthquake loss forecasting (OELF), in Italy. The approach is that of performance-based earthquake engineering, in which 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; the exposure is represented 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 of the methodology currently used for OEF in Italy on short-term risk assessment.

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 used 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 $\{A_1, A_2, \ldots A_i, \ldots A_n\}$, which includes the option of no action, and the expected value of the loss associated to each of them $\{E[L|A_1], E[L|A_2], \ldots E[L|A_i], \ldots E[L|A_n]\}$, which includes the cost to undertake the action, a criterion for the optional decision (D) is to undertake the action $A^* \in \{A_1, A_2, \ldots, A_n\}$ such that the estimated expected loss is minimized (Benjamin and Cornell, 1970):

$$D(A^*) \text{ is optimal} \overset{\text{def}}{\Leftrightarrow} E[L|A^*] \leq E[L|A_i] \forall i = 0, 1, \ldots, n. \quad (1)$$

On these premises, the present article focuses on the Italian case to discuss 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. 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 (i.e., 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 (PBEE; 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 of the seismological model used to carry out OEF, was coded in a prototypal operational earthquake loss forecasting (OELF) system, MANTIS-K, which is currently undergoing testing 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.

Although the developed study intentionally does not present any specific advancement in the seismological and earthquake engineering models employed, which all reflect published methodologies, it is deemed innovative because, to date and to the knowledge of the authors, it represents 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 that require accounting for spatial correlation of ground motion) are briefly addressed. The Methodology 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: (a) before the swarm, (b) during the swarm just before the largest magnitude earthquake, (c) during the swarm after the largest magnitude event, and (d) post-swarm. At each of the four instants, the expected losses for a one-week time-horizon are computed for an area within 70 km from a point identified as the center of the swarm. Also shown is a comparison of the loss assessment carried out based on OEF with the one computed for the same area using the seismicity rates that were used for the long-term hazard mapping of the country.

Methodology

Given a region monitored by a seismic sensor network, OEF models may provide the estimated expected number of earthquakes above a magnitude of interest per unit time (e.g., one week) for each elementary area in which the territory is divided and identified by a pair of coordinates $\{x, y\}$. Such a rate, $\lambda[t, x, y|H(t)]$, 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 (e.g., 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 a certain MS level, or exceedance of an IM threshold. 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 MS intensity level, ms, (i.e., $\lambda_{\mathrm{MS=ms}}[t, w, z|H(t)]$) is obtained by filtering $\lambda[t, x, y|H(t)]$; 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, $P[\mathrm{MS} = \mathrm{ms}|R(x, y, w, z)]$:

$$\begin{aligned}\lambda_{\mathrm{MS=ms}}[t, w, z|H(t)] &= \lambda[t, x, z|H(t)] \\ &\quad \cdot P[\mathrm{MS} = \mathrm{ms}|R(x, y, w, z)] \\ &= \lambda[t, x, z|H(t)] \\ &\quad \cdot \int_m P[\mathrm{MS} = \mathrm{ms}|m, R(x, y, w, z)] \\ &\quad \cdot f_M(m) \cdot dm. \end{aligned} \tag{2}$$

In the equation, $P[\mathrm{MS} = \mathrm{ms}|m, R(x, y, w, z)]$ 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; for example, 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, 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.

$$\lambda_{\mathrm{MS=ms}}[t,w,z|H(t)]=\int_x\int_y\lambda[t,x,z|H(t)]\cdot\int_m P[\mathrm{MS}=\mathrm{ms}|m,R(x,y,w,z)]\cdot f_M(m)\cdot dm\cdot dy\cdot dx \tag{3}$$

An extension of equation (3), including a vulnerability term, allows computation of the rate of events causing some damage state (ds) to a building of a given structural typology (k). This is given in equation (4), in which $P[\mathrm{DS}^{(k)}=\mathrm{ds}|\mathrm{ms}]$ is the damage probability for the structural typology of interest given *ms*, that is, a DPM:

$$\lambda_{\mathrm{DS}^{(k)}=\mathrm{ds}}[t,w,z|H(t)]=\int_x\int_y\lambda[t,x,z|H(t)]\cdot\sum_{\mathrm{ms}}P[\mathrm{DS}^{(k)}=\mathrm{ds}|\mathrm{ms}]\cdot\int_m P[\mathrm{MS}=\mathrm{ms}|m,R(x,y,w,z)]\cdot f_M(m)\cdot dm\cdot dy\cdot dx. \tag{4}$$

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 (e.g., 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 using equation (5). This equation assumes 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 $\{w,z\}$ on the left is dropped for simplicity in this equation and in those derived from it.)

$$P[\mathrm{DS}^{(k)}_{(t,t+\Delta t)}=\mathrm{ds}|H(t)]\approx\lambda_{\mathrm{DS}^{(k)}=\mathrm{ds}}[t,w,z|H(t)]\cdot\Delta t \tag{5}$$

If the number of buildings of the kth 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.

$$E[N^{(k)}_{\mathrm{ds},(t,t+\Delta t)}|H(t)]=N_B^{(k)}\cdot P[\mathrm{DS}^{(k)}_{(t,t+\Delta t)}=\mathrm{ds}|H(t)] \tag{6}$$

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

$$\lambda_{\mathrm{Cas}^{(k)}}[t,w,z|H(t)]=\int_x\int_y\lambda[t,x,y|H(t)]\cdot\sum_{ds}P[\mathrm{Cas}^{(k)}|\mathrm{ds}]\cdot\sum_{\mathrm{ms}}P[\mathrm{DS}^{(k)}=\mathrm{ds}|\mathrm{ms}]\cdot\int_m P[\mathrm{MS}=\mathrm{ms}|m,R(x,y,w,z)]\cdot f_M(m)\cdot dm\cdot dx\cdot dy. \tag{7}$$

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 kth typology at the $\{w,z\}$ site. It also allows computation of expected values of ultimate earthquake consequences because, in the same hypotheses of equation (5), the probability of observing an event determining casualties $P[\mathrm{Cas}^{(k)}_{(t,t+\Delta t)}|H(t)]$ may be obtained using equation (8). Then, the expected number of casualties in the time interval of interest $E[N^{(k)}_{\mathrm{Cas},(t,t+\Delta t)}|H(t)]$ can be computed through equation (9), if the number of residents $N_P^{(k)}$ in buildings of the kth typology at $\{w,z\}$ is available:

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

$$E[N^{(k)}_{\mathrm{Cas},(t,t+\Delta t)}|H(t)]=N_P^{(k)}\cdot P[\mathrm{Cas}^{(k)}_{(t,t+\Delta t)}|H(t)]. \tag{9}$$

The expected losses as per equations (6) and (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 MANTIS-K System and An Illustrative 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 $\lambda_{\mathrm{IM>im}}$ that cause the exceedance of an IM threshold (im) at the $\{w,z\}$ site. Such a rate is given in equation (10), in which the $P[\mathrm{IM}>\mathrm{im}|m,R(x,y,w,z)]$ term is from a ground-motion prediction equation (GMPE; e.g., Ambraseys *et al.*, 1996). (In contrast to MS intensity prediction equations, GMPEs require geological information about the $\{w,z\}$ site.)

$$\lambda_{\mathrm{IM>im}}[t,w,z|H(t)]=\int_x\int_y\lambda[t,x,y|H(t)]\cdot\int_m P[\mathrm{IM}>\mathrm{im}|m,R(x,y,w,z)]\cdot f_M(m)\cdot dm\cdot dx\cdot dy \tag{10}$$

Consequent to equation (10), the rate of events causing some DS = ds to a building of typology k may be computed using equation (11), in which the term $P[\mathrm{DS}^{(k)} = \mathrm{ds}|\mathrm{im}]$ is the fragility curve for the building (note that one fragility is required for each DS level).

$$\lambda_{\mathrm{DS}^{(k)}=\mathrm{ds}}[t, w, z|H(t)] = \int_x \int_y \lambda[t, x, y|H(t)] \cdot \int_{\mathrm{im}} P[\mathrm{DS}^{(k)} = \mathrm{ds}|\mathrm{im}] \cdot \int_M f_{\mathrm{IM}|M,R}[\mathrm{im}|\mathrm{m}, R(x, y, w, z)] \cdot f_M(m) \cdot dm \cdot d(\mathrm{im}) \cdot dy \cdot dx \quad (11)$$

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

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

Along the same line, the rate of events causing casualty may be computed with equation (13), with variables as defined previously. At this point, these rates can be used to compute the individual risk metrics in equations (8) and (9). 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 semiempirical models used in both approaches, differences may be expected:

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

Because the IMs or MSs at different sites in a given earthquake are stochastically dependent, the losses (i.e., building damage and casualties) also are dependent. Therefore, in general, it is 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, for example, if one wants to compute the probability that at least one building of the region will be in some damaged state in the forthcoming week, then all the sites have to be treated jointly. In fact, this issue primarily arises from the hazard, because, for example, equation (14) is required to compute the rate of earthquakes in the region, which will cause exceedance of an IM threshold at least at one of the $\{1, 2, \ldots, i, \ldots, n\}$ sites, $\lambda_{\{\exists i:\mathrm{IM}_i>\mathrm{im}\}}$. Equation (14) may be referred to as a regional hazard integral (e.g., Esposito and Iervolino, 2011):

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

In the equation, the

$$P\left[\bigcap_{i=1}^{n} \mathrm{IM}_i \le \mathrm{im}|m, \mathbf{R}(x, y, \mathbf{w}, \mathbf{z})\right]$$

term is the joint probability of the IMs at the n sites (in the equation, $\mathbf{w}$ and $\mathbf{z}$ 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: (1) the considered sites share the same event features (i.e., earthquake magnitude and location) and (2) intraevent residuals of IMs, with respect to a GMPE, are (in principle) spatially correlated (e.g., Esposito and Iervolino, 2012).

The rates in equation (14) may be used to approximate probabilities of interest, in analogy with equation (5). From this perspective, 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 RV. Moreover, it may also be required to account for spatial correlation of building damage given the intensity, or spatial correlation of casualties. This is not discussed further here, 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.

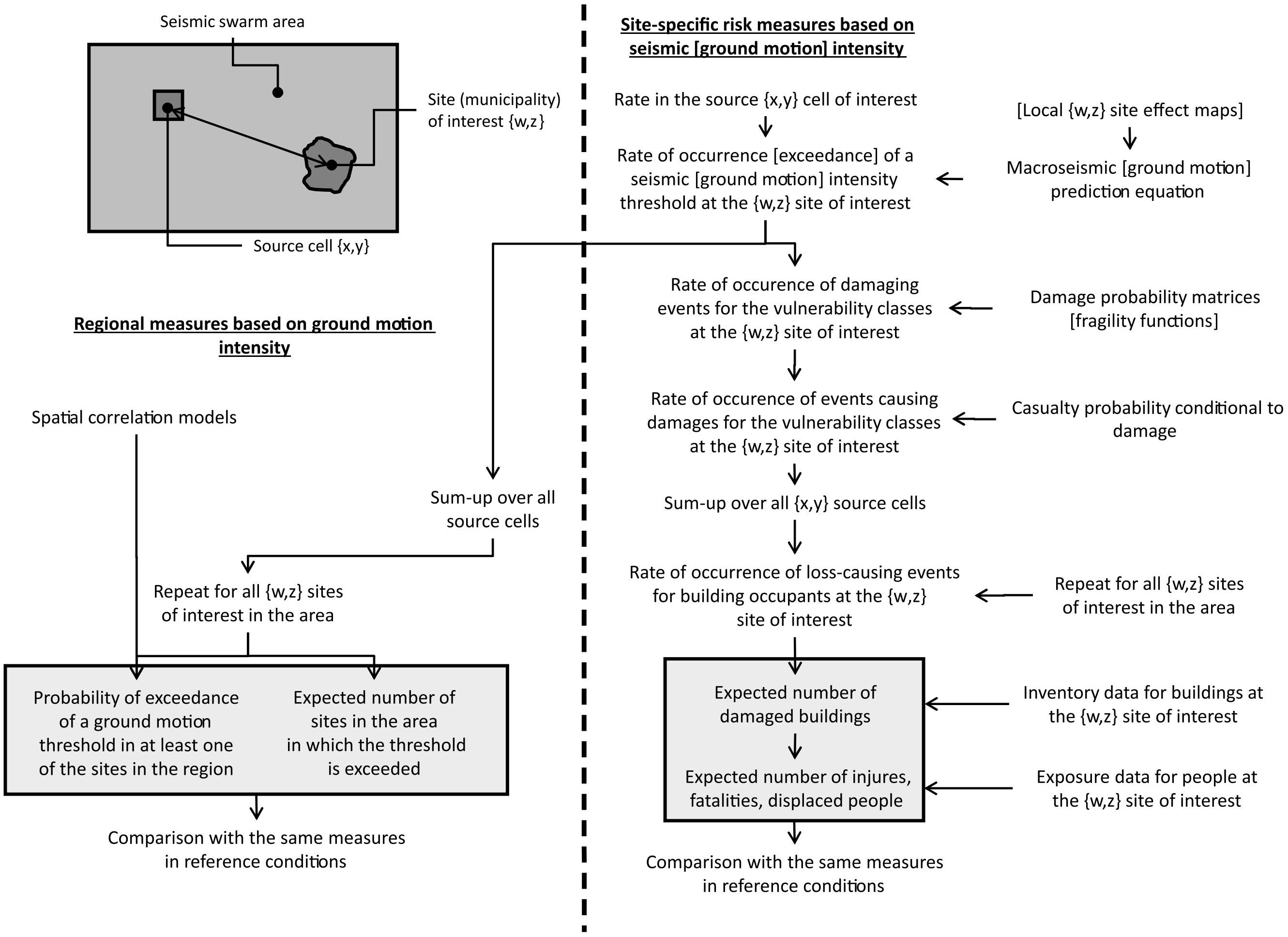

Figure 1. Summary of the short-term risk assessment procedure.

Models and Data for OELF in Italy

Seismicity Rates

Seismicity rates from OEF, $\lambda[t, x, y|H(t)]$, are provided by the OEF-Italy system of the Italian National Institute of Geophysics and Volcanology (INGV) for a grid space of about 0.1° and covering the whole national area and some sea. They are obtained based on the seismicity recorded by the countrywide seismic network of INGV and are updated daily or after an M 3.5+ (local magnitude scale is used) event in the monitored area. The time unit for rates is one week, and refers to events with local magnitude equal to or larger than 4 (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 1. This relationship does not change with the point source referred to by a specific rate value (i.e., it is spatially invariant).

It is not the focus of this work to scientifically discuss OEF models, and it has to be emphasized 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 MS intensity is that of Pasolini *et al.* (2008), which is also adopted by INGV for the assessment of MS 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 [0 km, 220 km] interval of the R_{epi}, and between 5 and 12 of the I_E. (Cardinal numbers are used for MS, in lieu of ordinals, consistent with the cited study.)

Pasolini *et al.* (2008) also provide a semiempirical model relating I_E and moment magnitude M_{w}, from which the distribution of I_E conditional to M_{w}, $f_{I_E|M_{\mathrm{w}}}(i_E|m)$, 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.

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

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

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 150 km 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 $P[0 \leq \text{ms} \leq 12] = 1$. The considered model applies for M_w up to about 7; therefore, the magnitude distribution of the sources was truncated to M_w 7, and the consequences of such an assumption were verified for tolerability. In the loss assessment, the check was carried out considering magnitudes up to 10 and extrapolating the models up to this magnitude. It was verified that the weekly expected losses did change (in the worst case) on the order of 10% with respect to the truncation to M_w 7.

Vulnerability

For each vulnerability class (k) and conditional to MS, models of structural vulnerability provide the $P[\text{DS}^{(k)} = \text{ds}|\text{ms}]$ 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 DPM.

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 (D0, no damage; D1, slight damage; D2, moderate damage; D3, heavy damage; D4, very heavy damage; and D5, collapse). Vulnerability classes, damage levels, and MS are defined in accordance with the European Macroseismic Scale 1998 (EMS-98; Grünthal, 1998). In fact, in this article, DPM are applied to the hazard assessment in term of MCS. Moreover, it is worthwhile to note that, due to the lack of Italian observational data, DPM values for MS ≥ 11 are based on extrapolation.

Table 2
Casualty Probabilities Conditional to Structural Damage and Typology

Loss	Vulnerability Class	D0	D1	D2	D3	D4	D5
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

Casualty probabilities conditional to a given structural damage and vulnerability class, $P[\mathrm{Cas}^{(k)}|\mathrm{ds}]$, 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 with damage levels equal to or lower than D3, whereas for D4 and D5 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 D4 or D5 is 1, whereas it is 0.5 for buildings in D3, and 0 for lower damage levels.

Exposure

For exposure, municipalities are the elementary units into 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. In about 1.5 hrs on an ordinary modern personal computer, the system computes the probabilities, for each vulnerability class (and on a municipality basis), that in one week after the OEF release the following will occur:

- a building becomes unusable for seismic causes;
- a building collapses for seismic causes;
- the occupant of a building is injured for seismic causes; and
- the occupant of a building dies for seismic causes.

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

- collapsed buildings,
- displaced residents,
- injuries, and
- 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 is the risk for the most hazardous area according to the current OEF estimate (as also illustrated in the The 2012 Pollino Sequence section).

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

In principle, the losses computed via this system can be compared, in the framework of equation (1), with the expected losses when 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 that 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 an M_w 5 event in October 2012, which was the largest magnitude observed. Four OEF outputs are considered here for the risk assessment, they are based on OEF rates released at 00:00 (UTC) on the following days: (a) 1 January 2010, (b) 25 October 2012, (c) 26 October 2012, and (d) 21 July 2013. Release (a) is considered representative of conditions

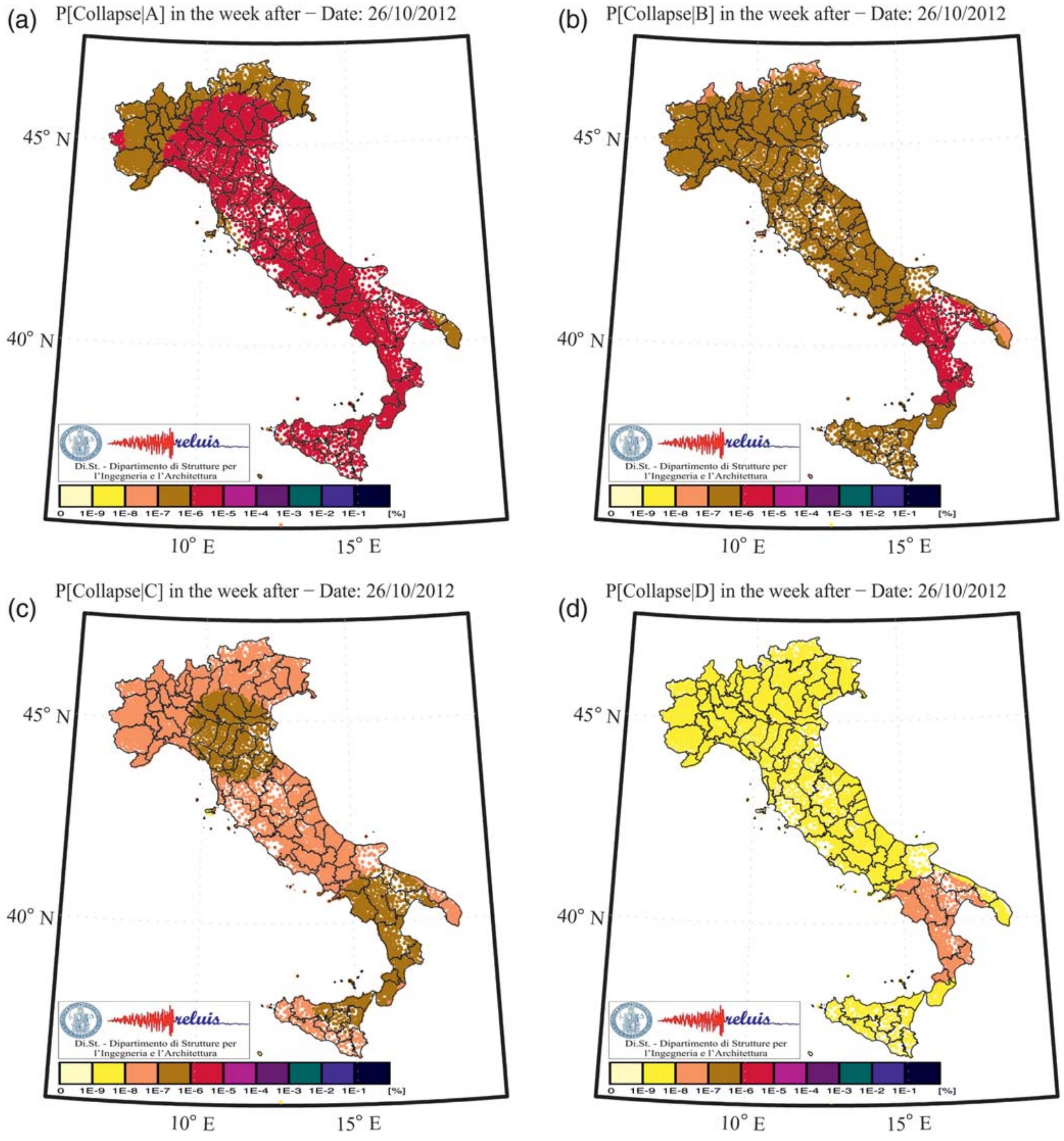

Figure 2. Weekly collapse probability per building vulnerability class after 26 October 2012.

before the start of the seismic sequence, whereas those for (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 $\lambda[t, x, y|H(t)]$ for the whole national area. From these rates, represented in Figure 4a–d, it can be noted that the Pollino area is the most hazardous in Italy only on 26 October 2012 (i.e., 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 are at the grid point of coordinates latitude 39.85° and longitude 16.05°, which is hereafter identified as the center of the Pollino sequence. The expected number of $M \geq 4$ events in the week following instant (c) is equal to 0.0615000 (events/week). Rates estimated by INGV at the same point for the instants are (a) 0.0000727 (events/week),

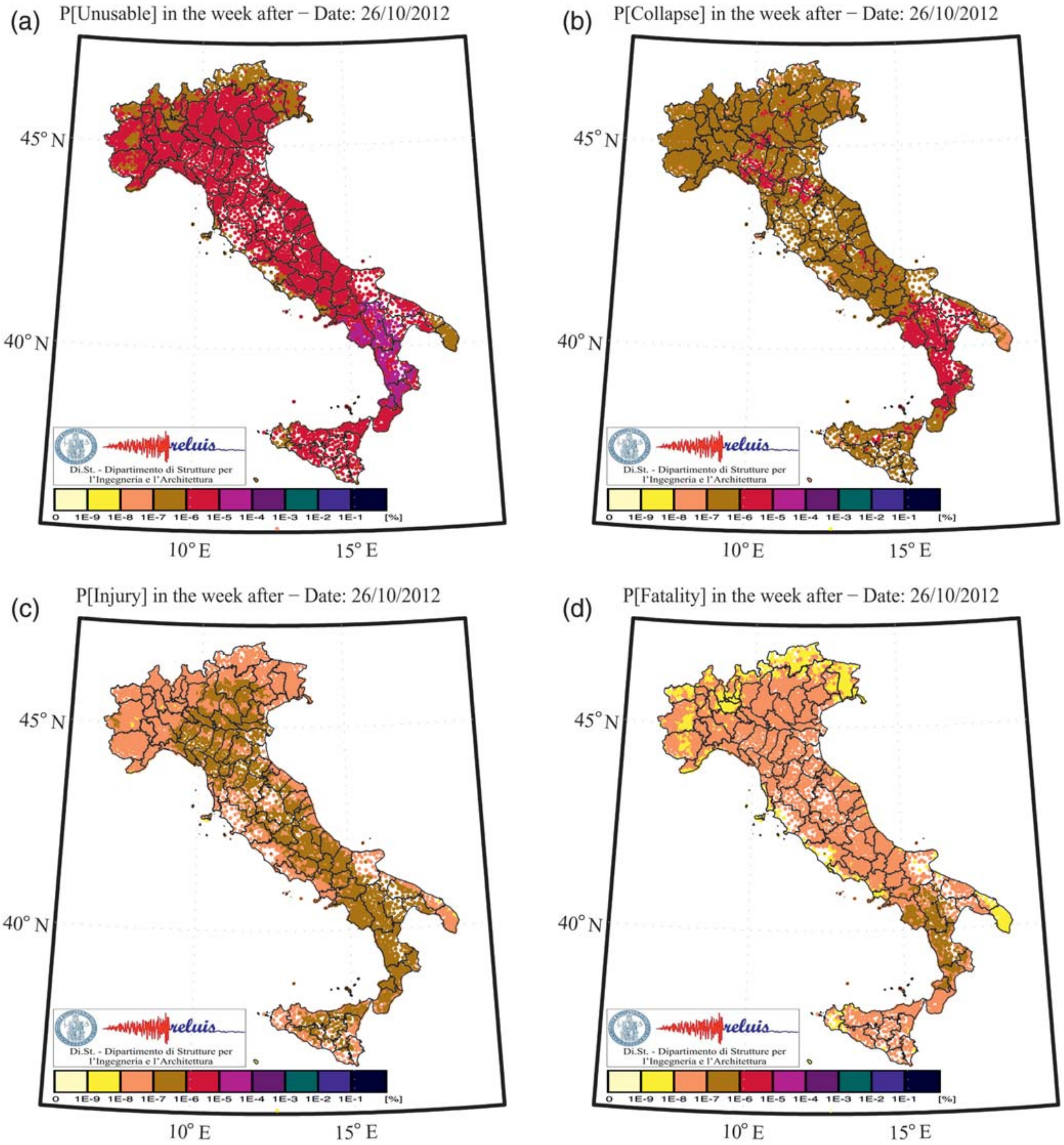

Figure 3. Weekly probabilities of (a) unusable buildings, (b) collapsed buildings, (c) injury occurrence, and (d) fatalities after 26 October 2012.

(b) 0.002260 (events/week), and (d) 0.000672 (events/week). For the risk assessment, all municipalities within a radius of 70 km from the center of the sequence are considered; in Figure 5, these municipalities are plotted with a color-scale reflecting the expected number of fatalities in the week after 26 October 2012.

The centroid of each municipality area is considered for computing the distance from each point-like seismic source $R(x, y, w, z)$, 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

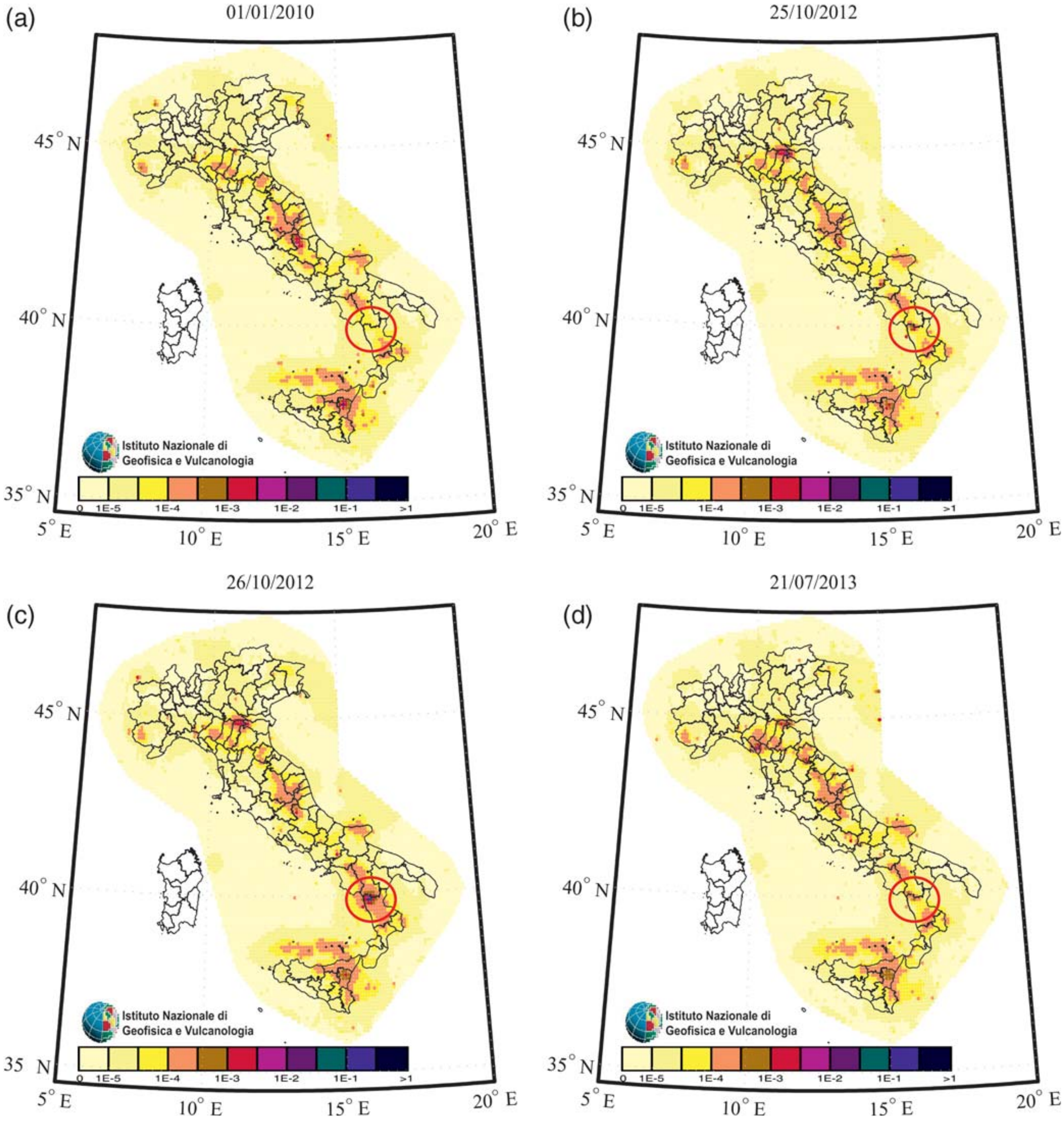

Figure 4. Seismic rates in terms of expected number of M 4+ events per week estimated through operational earthquake forecasting (OEF) at the four considered instants of the Pollino (2012) sequence: (a) 1 January 2010, (b) 25 October 2012, (c) 26 October 2012, and (d) 21 July 2013.

municipality, and the second is that such a point is the geometrical center of each municipality.

Applying equations (6) and (9), the expected number of (1) collapsed buildings (i.e., buildings damage levels D4 and D5) and (2) displaced, (3) injured, and (4) 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 indexes are normalized with respect to the total number of buildings or residents in each distance bin.

These results illustrate that risk measures are sensitive to the short-term seismicity variations inferred by OEF. On the other hand, if absolute values of indexes are considered, the largest computed risk (at instant c) is about one expected fatality over more than 4×10^5 residents within a radius

Table 3
Indexes of Seismic Risk across the Swarm

Date (yyyy/mm/dd)	Distance (km)	Total Buildings	Total Residents	Collapsed Buildings	Displaced Residents	Injuries	Fatalities	Collapsed Buildings (%)	Displaced Residents (%)	Injuries (%)	Fatalities (%)
2010/01/01	≤10	4281	12,567	2.85×10^{-2}	2.92×10^{-1}	1.16×10^{-2}	3.00×10^{-3}	6.65×10^{-4}	2.32×10^{-3}	9.25×10^{-5}	2.39×10^{-5}
	≤30	66,243	188,538	2.34×10^{-1}	2.74×10^{0}	1.03×10^{-1}	2.69×10^{-2}	3.53×10^{-4}	1.45×10^{-3}	5.45×10^{-5}	1.43×10^{-5}
	≤50	149,733	438,990	5.21×10^{-1}	6.14×10^{0}	2.29×10^{-1}	5.98×10^{-2}	3.48×10^{-4}	1.40×10^{-3}	5.21×10^{-5}	1.36×10^{-5}
	≤70	256,281	878,432	9.07×10^{-1}	1.16×10^{1}	4.35×10^{-1}	1.14×10^{-1}	3.54×10^{-4}	1.32×10^{-3}	4.96×10^{-5}	1.30×10^{-5}
2012/10/25	≤10	4281	12,567	1.22×10^{-1}	1.05×10^{0}	5.64×10^{-2}	1.43×10^{-2}	2.85×10^{-3}	8.35×10^{-3}	4.49×10^{-4}	1.14×10^{-4}
	≤30	66,243	188,538	6.17×10^{-1}	6.43×10^{0}	2.81×10^{-1}	7.27×10^{-2}	9.32×10^{-4}	3.41×10^{-3}	1.49×10^{-4}	3.86×10^{-5}
	≤50	149,733	438,990	1.07×10^{0}	1.17×10^{1}	4.77×10^{-1}	1.24×10^{-1}	7.15×10^{-4}	2.66×10^{-3}	1.09×10^{-4}	2.82×10^{-5}
	≤70	256,281	878,432	1.55×10^{0}	1.85×10^{1}	7.27×10^{-1}	1.90×10^{-1}	6.05×10^{-4}	2.10×10^{-3}	8.27×10^{-5}	2.16×10^{-5}
2012/10/26	≤10	4281	12,567	1.87×10^{0}	1.52×10^{1}	8.88×10^{-1}	2.24×10^{-1}	4.37×10^{-2}	1.21×10^{-1}	7.06×10^{-3}	1.78×10^{-3}
	≤30	66,243	188,538	7.46×10^{0}	7.18×10^{1}	3.47×10^{0}	8.90×10^{-1}	1.13×10^{-2}	3.81×10^{-2}	1.84×10^{-3}	4.72×10^{-4}
	≤50	149,733	438,990	1.07×10^{1}	1.08×10^{2}	4.83×10^{0}	1.24×10^{0}	7.13×10^{-3}	2.46×10^{-2}	1.10×10^{-3}	2.84×10^{-4}
	≤70	256,281	878,432	1.28×10^{1}	1.38×10^{2}	5.84×10^{0}	1.51×10^{0}	4.98×10^{-3}	1.57×10^{-2}	6.65×10^{-4}	1.72×10^{-4}
2013/07/21	≤10	4281	12,567	5.77×10^{-2}	5.33×10^{-1}	2.54×10^{-2}	6.49×10^{-3}	1.35×10^{-3}	4.24×10^{-3}	2.02×10^{-4}	5.17×10^{-5}
	≤30	66,243	188,538	3.68×10^{-1}	4.06×10^{0}	1.67×10^{-1}	4.34×10^{-2}	5.55×10^{-4}	2.15×10^{-3}	8.85×10^{-5}	2.30×10^{-5}
	≤50	149,733	438,990	7.27×10^{-1}	8.25×10^{0}	3.25×10^{-1}	8.47×10^{-2}	4.86×10^{-4}	1.88×10^{-3}	7.39×10^{-5}	1.93×10^{-5}
	≤70	256,281	878,432	1.17×10^{0}	1.45×10^{1}	5.60×10^{-1}	1.47×10^{-1}	4.55×10^{-4}	1.65×10^{-3}	6.37×10^{-5}	1.67×10^{-5}

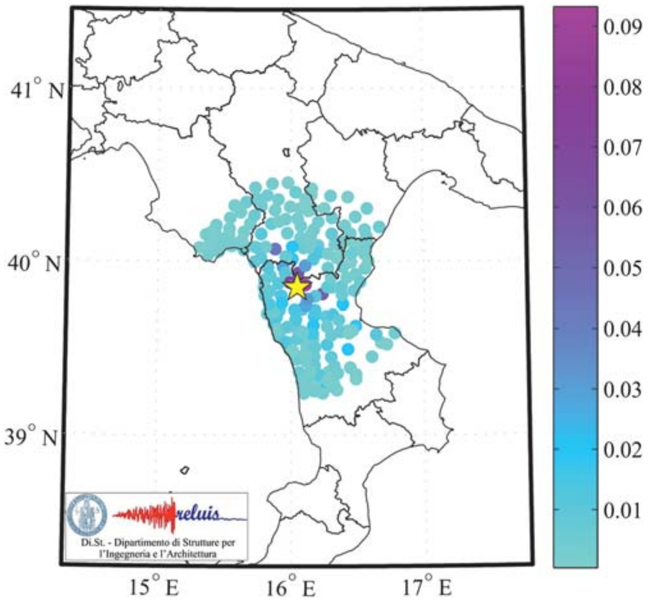

Figure 5. Considered municipalities within 70 km (in radius) from the center of the Pollino sequence (star). The colors of points are the expected number of fatalities, per municipality, in the week after 26 October 2012.

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 from these results may be obtained by comparing them with the weekly loss computed using the seismic source model of Meletti *et al.* (2008), which uses rates from Barani *et al.* (2009); these two studies 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 936, which 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 using a Gutenberg–Richter relationship with a b-value equal to 1. 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 this risk analysis, except for the rates, all others models and assumptions are the same

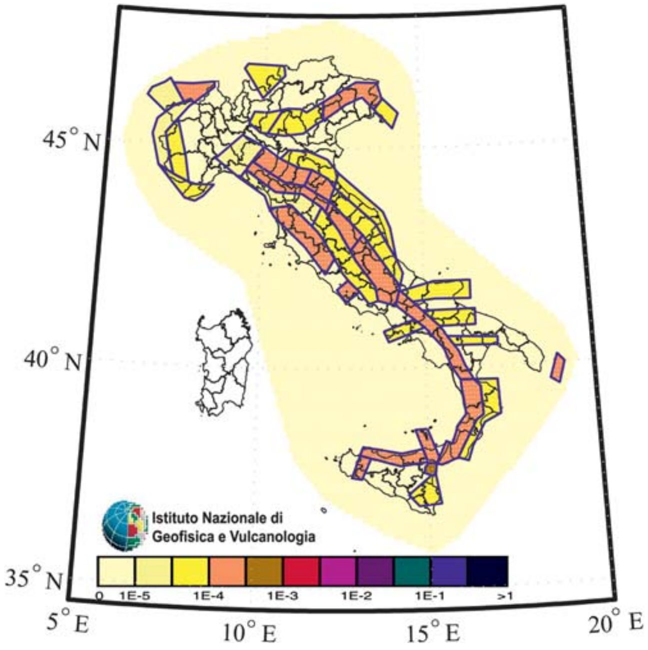

Figure 6. Weekly rates of M 4+ events in one week adjusted from Barani *et al.* (2009) and the seismic source model of Meletti *et al.* (2008). Points outside the polygons have zero associated rate.

as those for loss assessment based on OEF (i.e., those discussed above). Results are reported in Table 4, which shows a good agreement with those computed for instants (a) and (d) of the Pollino sequence. This was somewhat expected as (a) and (d) were identified as a preswarm and postswarm instants, and therefore the risk associated with 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.

Table 5

Ratio of Losses during the Pollino Sequence with respect to Long-Term Risk Estimates

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

Ratios of the cells in the columns collapsed buildings, displaced residents, injuries, and fatalities of Table 3 divided by the corresponding values from Table 4.

Conclusions

The study focused on the Italian case to discuss the feasibility of probabilistic short-term seismic loss (risk) assessment when the input is represented by the seismicity rates given by the OEF 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 INGV, 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 the 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 the vulnerability and exposure models employed, was developed. It refers to the 2012 Pollino (southern Italy) sequence.

The main conclusions from this feasibility study are that (1) probabilistically consistent continuous short-term seismic risk assessment in Italy appears to be feasible; (2) the approach is probabilistically rigorous and virtually independent of the OEF, the vulnerability, and the exposure models employed, while results, obviously, are not; (3) 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; and (4) because of the intrinsic feature of the OEF model employed, the largest risk is observed after the largest-magnitude event observed

Table 4

Indexes of Seismic Risk Derived from Seismogenic Zones and Seismic Rates from Barani *et al.* (2009)

Distance (km)	Total Buildings	Total Residents	Collapsed Buildings	Displaced Residents	Injuries	Fatalities	Collapsed Buildings (%)	Displaced Residents (%)	Injuries (%)	Fatalities (%)
≤10	4281	12,567	3.74×10^{-2}	3.56×10^{-1}	1.60×10^{-2}	4.09×10^{-3}	8.74×10^{-4}	2.84×10^{-3}	1.27×10^{-4}	3.25×10^{-5}
≤30	66,243	188,538	2.85×10^{-1}	3.19×10^{0}	1.33×10^{-1}	3.44×10^{-2}	4.30×10^{-4}	1.69×10^{-3}	7.04×10^{-5}	1.82×10^{-5}
≤50	149,733	438,990	6.04×10^{-1}	6.91×10^{0}	2.82×10^{-1}	7.33×10^{-2}	4.04×10^{-4}	1.57×10^{-3}	6.41×10^{-5}	1.67×10^{-5}
≤70	256,281	878,432	1.01×10^{0}	1.27×10^{1}	5.13×10^{-1}	1.34×10^{-1}	3.93×10^{-4}	1.44×10^{-3}	5.84×10^{-5}	1.53×10^{-5}

in the sequence, indicating the moment in which a worse earthquake is more likely.

Data and Resources

Operational earthquake forecasting (OEF) rates from the OEF-Italy system of the Italian National Institute of Geophysics and Volcanology (INGV) were provided by Warner Marzocchi. Damage probability matrices and exposure information were provided by Giulio Zuccaro. The rest of the data is from the listed references.

Acknowledgments

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Dipartimento di Strutture per l'Ingegneria e l'Architettura
Università degli Studi di Napoli Federico II
Via Claudio 21
80125 Naples, Italy
iunio.iervolino@unina.it
eugenio.chioccarelli@unina.it
giulio.zuccaro@unina.it
gaetano.manfredi@unina.it
(I.I., E.C., G.Z., G.M.)

Dipartimento di Ingegneria Industriale e dell'Informazione
Seconda Università degli Studi di Napoli
Via Roma 29
81031 Aversa (CE), Italy
massimiliano.giorgio@unina2.it
(M.G.)

Istituto Nazionale di Geofisica e Vulcanologia
Via di Vigna Murata 605
00143 Rome, Italy
warner.marzocchi@ingv.it
(W.M.)

Dipartimento della Protezione Civile
Presidenza del Consiglio dei Ministri
Via Ulpiano 11
00193 Rome, Italy
mauro.dolce@protezionecivile.it
(M.D.)

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Erratum to

Operational (Short-Term) Earthquake Loss Forecasting in Italy

by Iunio Iervolino, Eugenio Chioccarelli, Massimiliano Giorgio, Warner Marzocchi, Giulio Zuccaro, Mauro Dolce, and Gaetano Manfredi

The software processing the illustrative nationwide maps of figures 2 and 3 in Iervolino *et al.* (2015) was found to have a bug. The corrected figures are below (Figs. 1 and 2). None of the discussions or the conclusions of the study are affected by this error, yet the authors, who strive for the highest quality of their work, apologize.

Reference

Iervolino, I., E. Chioccarelli, M. Giorgio, W. Marzocchi, G. Zuccaro, M. Dolce, and G. Manfredi (2015). Operational (short-term) earthquake loss forecasting in Italy, *Bull. Seismol. Soc. Am.* **105,** no. 4, 2286–2298, doi: 10.1785/0120140344.

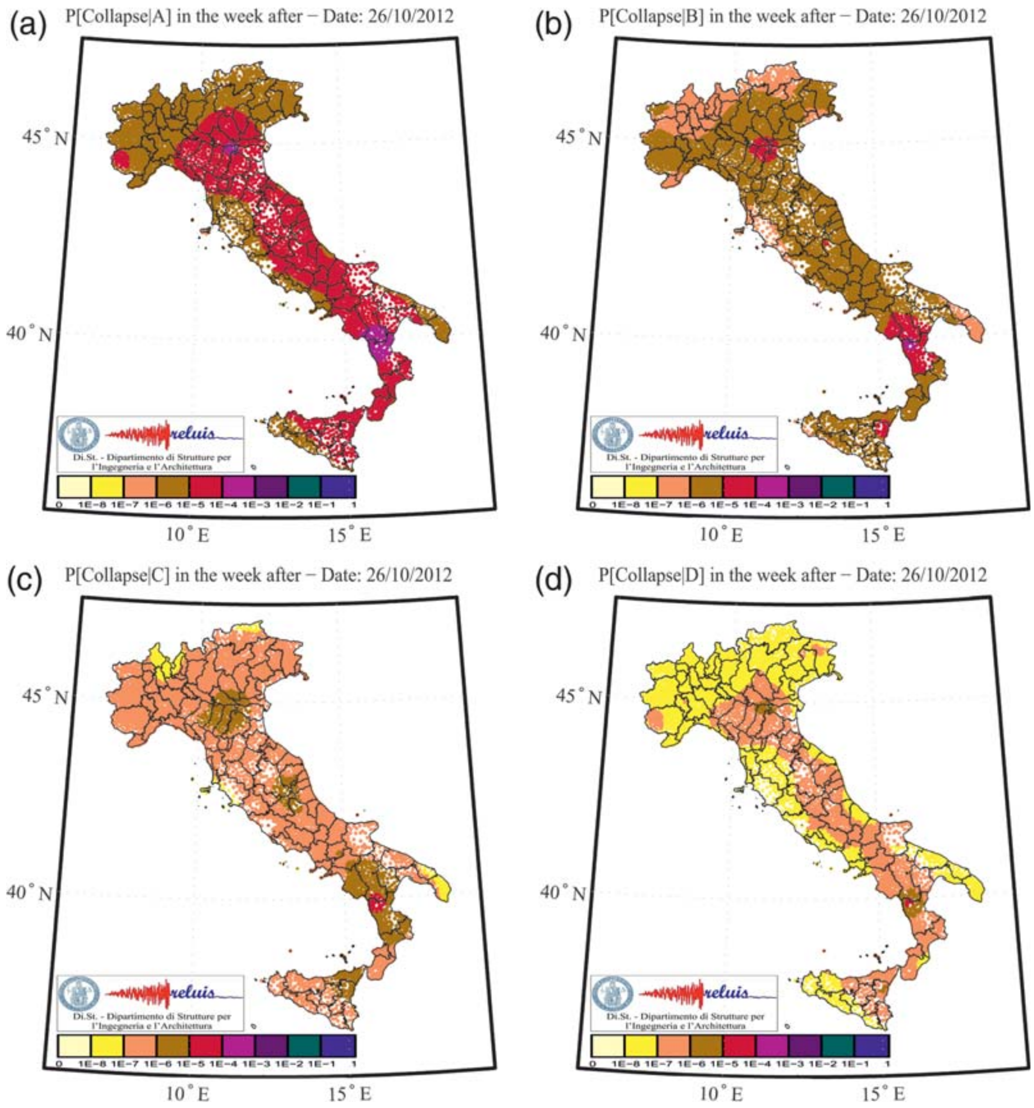

Figure 1. Weekly collapse probability per building vulnerability class after 26 October 2012.

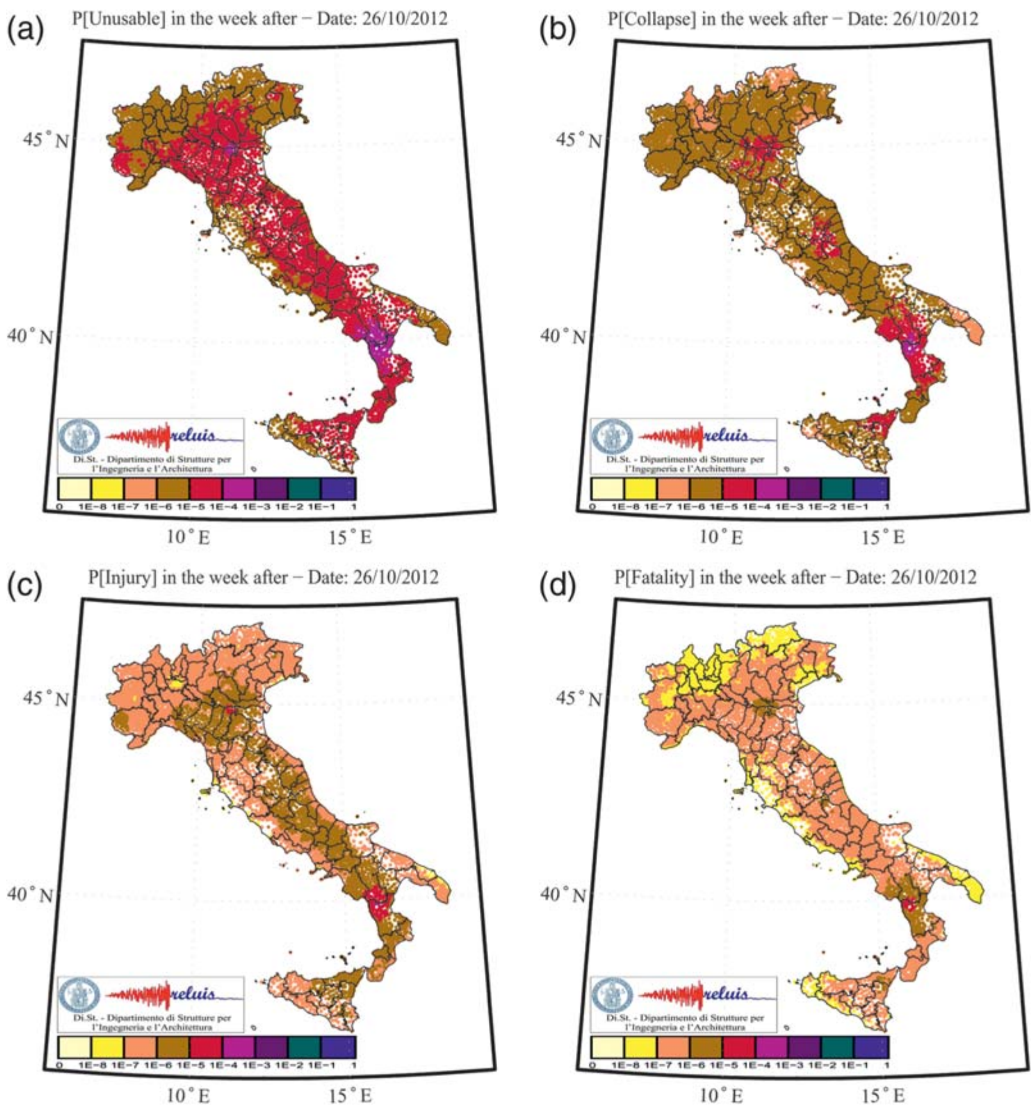

Figure 2. Weekly probabilities of (a) unusable buildings, (b) collapsed buildings, (c) injury occurrence, and (d) fatalities after 26 October 2012.

Dipartimento di Strutture per l'Ingegneria e l'Architettura
Università degli Studi di Napoli Federico II
Via Claudio 21
80125 Naples, Italy
iunio.iervolino@unina.it
eugenio.chioccarelli@unina.it
giulio.zuccaro@unina.it
gaetano.manfredi@unina.it
(I.I., E.C., G.Z., G.M.)

Dipartimento di Ingegneria Industriale e dell'Informazione
Seconda Università degli Studi di Napoli
Via Roma 29
80131 Aversa (CE), Italy
massimiliano.giorgio@unina2.it
(M.G.)

Istituto Nazionale di Geofisica e Vulcanologia
Via di Vigna Murata 605
00143 Rome, Italy
warner.marzocchi@ingv.it
(W.M.)

Dipartimento della Protezione Civile
Presidenza del Consiglio dei Ministri
Via Ulpiano 11
00193 Rome, Italy
mauro.dolce@protezionecivile.it
(M.D.)

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