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Forecasting seismic scenarios on Etna volcano (Italy) through probabilistic intensity attenuation models: A Bayesian approach

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ABSTRACT

In this paper, we apply a probabilistic procedure to model the attenuation of the macroseismic intensity in the Mt. Etna region, which allows estimating probabilistic seismic scenarios. Starting from the local earthquake catalogue, we select a dataset of 47 events having epicentral intensity I_0 from VI to IX–X EMS, and update the model parameters previously achieved for Italy according to the Bayesian paradigm. For each class of epicentral intensity I_0, we then estimate the probability distribution of the intensity at a site conditioned on the epicentre-site distance through a binomial-beta model, under the assumption of a point seismic source and isotropic decay (circular). The mode of the distribution is taken as the expected intensity I_s at that site. Since the strongest earthquakes show a preferential propagation of shaking along the fault strike and a rapid decrease in the perpendicular direction, we also consider the anisotropic decay (elliptical) of the intensity due to a linear source (finite fault). We therefore transform the plane so that the ellipse has the length of the fault rupture as maximum axis and its strike as azimuth is changed into a circle with fixed diameter; then we apply the probabilistic model obtained for the isotropic case to the modified data. The entire calculation procedure is implemented in the software PROSCEN which, given the location and the epicentral intensity (and eventually the fault parameters) of the earthquake to be simulated, generates the probabilistic seismic scenario according to the isotropic and anisotropic models of attenuation. The results can be plotted on grid maps representing (1) the intensity that can be exceeded with a fixed probability, or (2) the probability of exceeding a fixed intensity value. The first representation may also find application in seismic monitoring at Etna volcano, in order to produce real-time intensity ShakeMaps based on the instrumental parameters calculated by the automatic earthquake processing system.

1. Introduction

Simulating the effects produced by an earthquake is a multidisciplinary field of investigation aimed at assessing the level of seismic risk to which an area is exposed and preparing emergency plans. A variety of methods, leading to deterministic or probabilistic seismic scenarios, have been developed according to different levels of accuracy required — the most complete generally being based on numerical models that take account of ground-motion predictive relationships (expressed in acceleration, velocity or displacement), local geologic conditions (site effects), historical macroseismic intensity data, together with building typologies and their vulnerability. These seismic scenarios are normally envisaged for large cities and refer to the strongest earthquakes or their occurrence probability (for an overview in Europe, see Faccioli, 2006 and references herein). Regarding volcanic regions, a few applications have focused on Mts. Etna (Faccioli et al., 1999) and Vesuvius (Galluzzo et al., 2008), Iceland (Sigbjörnsson et al., 2007) and the Azores Islands (Zonno et al., 2010) with varying degrees of detail.

On the other hand, a simplified approach adopted worldwide to provide a preliminary, semi-quantitative assessment of the level of shaking and extent of potential earthquake hazard is obtained through the software package ShakeMap (Wald et al., 1999). This procedure seeks to automatically estimate, in a few minutes, the level of expected ground shaking using real-time data acquired by a seismic network, which are converted into maps of peak ground acceleration (PGA), peak ground velocity (PGV) and macroseismic intensity. The last parameter, in particular, is the most used for non-specialist applications of civil protection to evaluate simplified scenarios in support of possible actions of first intervention. Its application in Italy is quite recent (Michelini et al., 2008), namely the Centro Nazionale Terremoti—INGV producing real-time MCS intensity maps for $M_L > 3.0$ earthquakes (http://earthquake.rm.ingv.it/shakemap/shake/index.html). The 'instrumental intensity' values deriving from the conversion of PGA–PGV parameters, are obtained through correlation relationships calibrated for the national territory (Faenza and Michelini, 2010).

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However, ShakeMap cannot be used at Etna due to the different attenuation and scaling laws of tectonic events vs volcanic earthquakes (Rovelli et al., 1988; McNutt, 2005; Giampiccolo et al., 2007). Milana et al. (2008) therefore proposed an alternative procedure aimed at identifying, in near-real time, potentially damaging earthquakes starting from the value of the instrumentally determined magnitude. Through the computation of pseudo-velocity response spectra, this method provides a preliminary estimate of the macroseismic intensity at the epicentre (I_0), but it does not reproduce the areal distribution of the expected intensities. However, it must be stressed that these two methods are based on a succession of conversion relationships from instrumental ground-motion parameters into macroseismic intensity.

In this paper, we tackle the problem of seismic scenarios at Etna entirely in terms of macroseismic intensity, exploiting as best as we can on the huge amount of data available from the local historical earthquake catalogue (Azzaro et al., 2000). By adopting a probabilistic approach based on the Bayesian statistics (Rotondi and Zonno, 2004), we analyse the decay of the intensity from the source according to the two attenuation models, isotropic (point source, symmetric decay) and anisotropic (linear source, decay depending on the direction), and calculate the probability distribution of the intensity at a given site (I_s) conditioned on the epicentral intensity (I_0) of the earthquake and the epicentre-site distance through a binomial-beta model (Zonno et al., 2009). The backward validation of the results and comparisons with simulations from a deterministic approach, are also presented. The entire procedure is finally implemented in software to produce probabilistic ShakeMaps expressed in terms of macroseismic intensity. This application is proposed as a practical tool to be applied at INGV—Catania data acquisition centre for obtaining real-time seismic scenarios at Etna.

2. Intensity attenuation: conceptual background and input data

The problem of the macroseismic intensity attenuation and its variation as a function of the distance from the source, is a key element in seismic hazard assessment (Albarello and D'Amico, 2004, 2005; Pasolini et al., 2008a). This issue has widely been analysed from the deterministic point of view by applying linear regressions which express the intensity at site (I_s) as a function of the epicentre-site distance, the epicentral intensity I_0 and other factors like the depth; to take into account the wide scatter of the observations around the expected values, these relationships may be provided with a gaussian error. Pasolini et al. (2008b and references herein) recently calculated a unique attenuation pattern for the whole of Italy according to an isotropic model of decay, which has the obvious limitation of not considering different regional attenuation trends, source directionality, or possible local effects. On the other hand, Azzaro et al. (2006) derived specific regression relationships for the intensity attenuation in the volcanic districts, finding for Etna an intensity decay ΔI (the difference between I_0 and I_s) of 4 degrees in 20 km of distance from the epicentre, under the same assumption of isotropic model (i.e. point source). In general, this determines highly localised macroseismic effects with respect to the tectonic earthquakes occurring in the national territory. Moreover, the same authors also pointed out the importance of the anisotropy due to a linear source in the attenuation pattern, which at Etna is characterised by a preferential propagation (i.e. highest intensities) along the fault strike and a rapid decrease of the effects in the perpendicular direction. The decay of intensity, given by the difference between maximum and minimum attenuation, reaches 2 intensity degrees at equal distances from the epicentre. As a result, the mesoseismal areas appear typically elliptical, with extensions up to 5 km long and 2 km wide astride the causative fault (Azzaro, 2004). Taking the strike of the source into account is therefore important for modelling hazard scenarios in the near-field, where the expected effects have to be simulated as realistically as possible.

The probabilistic approach to the analysis of the seismic attenuation has been developed in order to quantify the intrinsic uncertainty of the decay process (Magri et al., 1994; Albarello and D'Amico, 2005). In Zonno et al. (1995) the intensity decay ΔI, normalised on I_0, is considered as a random variable that follows a Beta distribution with the mean proportional to a known attenuation law and deviation depending on the distance from the epicentre. Then, avoiding the use of any deterministic attenuation relationship, Rotondi and Zonno (2004) proposed another probabilistic model calibrated by exploiting information from zones that, on the basis of their seismotectonic features, are assumed as homogeneous from the viewpoint of attenuation. This debatable assumption was replaced in Rotondi et al. (2008), Zonno et al. (2009) by a hierarchical agglomerative clustering method employed to separate a set of representative macroseismic fields – the so called learning dataset – into homogeneous groups from the viewpoint of attenuation. In this way, three classes with decreasing attenuation (C_A, C_B, C_C) have been identified in Italy, and in each of them the probability distributions of I_s conditioned on the epicentral intensity I_0 and the epicentre-site distance, were estimated. Because of the higher attenuation of seismic intensity (Azzaro et al., 2006), the Italian volcanic areas were excluded from these analyses.

The application of the probabilistic procedure of attenuation at Etna volcano requires an ad-hoc calibration of some parameters through a reference macroseismic dataset. To this end, we use the most updated release of the macroseismic catalogue of Mt. Etna earthquakes (CMTE Working Group, 2008). It represents a homogeneous macroseismic database compiled through the revision of the original coeval sources, intensity assigned by using the European macroseismic scale (EMS, Grünthal, 1998) and epicentral parameters defined according to standard procedures. Unlike the Italian seismic catalogue (CPTI Working Group, 2004), it does not adopt any intensity threshold (or equivalent magnitude) and reports, for the major events, the association seismogenic fault-earthquake defined on the basis of occurrence of coseismic surface faulting (Azzaro, 1999), or the distribution of the highest intensities with respect to the tectonic pattern (Azzaro, 2004). These last features, together with the aforementioned very high intensity decay with distance, ensure that the accuracy of the epicentre locations in densely urbanised areas is fairly high, with errors around 1 km.

In order to limit the uncertainties due to poorly constrained parameters, we select a set of 47 events with epicentral intensity $I_0 \geq$ VI EMS and macroseismic fields characterised by a uniform distribution of the intensity data points (N_{ip}); the related intensity database consists of 1403 macroseismic observations regarding 229 localities. As shown in Fig. 1, this selection includes most of the destructive or severely damaging earthquakes occurring at Etna, which struck localities very close to each other in the eastern flank of the volcano. These events are mainly due to the activity of the Timpe fault system (Azzaro, 2004).

In particular, for the isotropic model (point source) we use 44 earthquakes with $N_{ip} \geq 10$, while for the anisotropic model (linear source) we analyse a slightly different subset consisting of 17 events with $I_0 \geq$ VII EMS and $N_{ip} \geq 7$; the dataset is reported in Table 1 (for brevity, the events with $I_0 =$ VI EMS are only listed in the caption). For the purposes of our analysis, the values of I_0 expressed with an intensity range (VII–VIII, VIII–IX etc) are assumed as being of lower degree; such a choice is due to a non-representative distribution of the highest intensity data points in the macroseismic field.

3. Binomial-beta model for macroseismic intensity at a site

3.1. Isotropic model

In this paragraph, we deal with seismic attenuation under the assumption of point source model; this means that in the simulated