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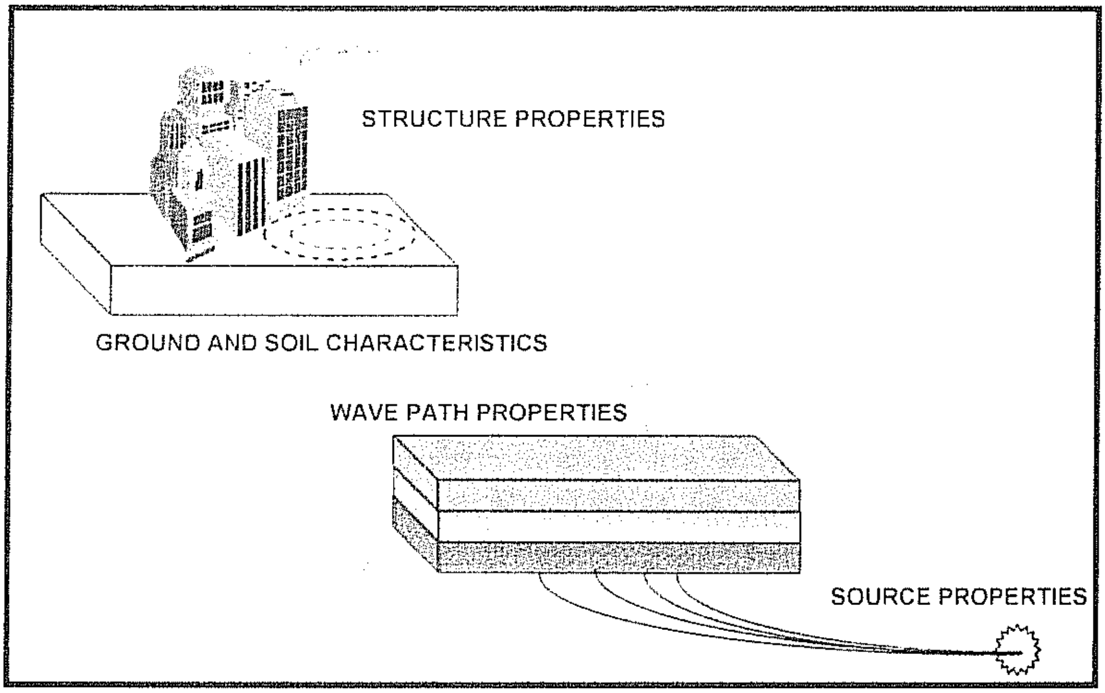

Edited By:
K.C. MAKROPOULOS
NATIONAL AND KAPODISTRIAN UNIVERSITY
OF ATHENS
DEPARTMENT OF GEOPHYSICS - GEOTHERMY
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Seismic Hazard Assessment: Regional Versus Site-Specific Estimates

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Peter Suhadolc and Angela Sarao

Department of Earth Sciences,
University of Trieste
Via Weiss 1, 34127 Trieste, Italy

E-mail: suhadolc@dst.univ.trieste.it
fax: +39-40-6762111

PART 1

Regional seismic hazard assessment:
A deterministic-probabilistic approach

I.1 Introduction

Seismic Hazard Analysis (SHA), i.e. the description and/or the evaluation of the effects of a possible future earthquake on human activities, is the research area in seismology which has the strongest impact on society.

The numerous methods of SHA used nowadays can be divided into two main groups (Reiter, 1990): the deterministic ones, which are based on numerical simulation of earthquakes and their consequences, and the probabilistic ones, which use statistical methods to analyse the past seismicity and thus construct probabilistic models to describe the future one.

Both the approaches have their positive and negative sides (see Reiter, 1990). The deterministic approaches are transparent, their input and output parameters are easy to understand, but they do not treat model and data uncertainties unless a huge amount of parametric analysis is performed. Consequently, there is usually no measure of the uncertainties of the final results. On the other hand, the probabilistic methods reflect in a correct way the actual knowledge of the seismicity, but their results are difficult to explain to non-specialists, strongly depend of the probabilistic models used and it is difficult to evaluate how a given input parameter affects the final results. The deterministic approaches would be the best to use in SHA if the nature of the seismic process and its effects were well understood; the probabilistic ones would be the best to use, if the uncertainty in the earthquake occurrence were very well known in order to overcome the lack of information.

The "deterministic-probabilistic" method for SHA (Orozova and Suhadolc, 1999) is based on a deterministic procedure (Costa et al., 1993), which consists of a calculation of synthetic seismograms, i.e. the ground motion, over a grid of sites of observation. The hazard parameter (ground motion) at each site is estimated by numerically simulation of possible earthquakes of a given size. Furthermore, some statistical analysis of the past seismicity is used to construct a probabilistic model of future earthquake occurrence, which is used to assign the probability of exceedance at each site of an "a priori" chosen threshold of the estimated ground motion parameter.

The deterministic part of this method is very useful in the definition of different scenarios in the SHA, i.e. the effects at a particular site (bridge, highway, pipeline etc.) of a given earthquake, e.g. of magnitude 7, which can occur at a given distance. The probabilistic part of this method is very useful to give a rough probability that at the level of the ground motion, will be exceeded independently of a particular event and to provide a mean return period of the calculated ground motion parameter.

The "deterministic-probabilistic" approach is based on the SHA procedure developed by Costa et al. (1993). This procedure consists of the calculation of synthetic seismograms using physical models and parameters for the seismic source (equivalent force system and radiation pattern, source "strength", fault geometry) and for the media (density, geometry, seismic wave velocities) in which the seismic waves propagate. In order to model realistically the seismic wave propagation, the studied territory is divided into a number of 1-D polygonal lithospheric structures. Each structure consists of a number of flat layers which are parametrized with their thickness, density, P- and S-wave velocities and related Q factors.

The input data set used in the numerical simulation of future events consists of the seismotectonic model of the studied territory, the catalogue of the past earthquakes and the catalogue of available fault-plane solutions.

In the numerical simulation of future seismicity the following basic assumptions are used:

- the expected earthquakes will occur only inside predefined seismogenic zones. This hypothesis implies that the areas outside the seismogenic zones are aseismic; Frankel (1995) has proposed in his probabilistic approach to SHA to consider a "background" seismicity outside seismogenic zones capable of producing M 5 events. This scenario can be easily incorporated in the procedure.
- the seismic event is considered as an instantaneous point-like energy release due to a double-couple equivalent force system. It is assumed that the point-source approximation is valid for frequencies up to 1 Hz. However, to account for the bigger spatial extension of the M>6 events, we have chosen to scale their spectra. For larger frequencies the finite dimensions of the earthquake source cannot be neglected and a rupturing process on a spatially extended fault has to be defined (**see Part II**).

The fault-plane solutions considered as representative for a given seismogenic zone are used to model the double-couple radiation of all point sources in that zone.

The "strengh" of the earthquake source is expressed in terms of the scalar seismic moment, Mo. When direct determinations of the moment are not available, its value (in dyne cm) is obtained from the magnitude, M, according to the relation (Kanamori, 1977):

$$\log M_0 = 1.5M + 16.1 \qquad (1)$$

Once the input data sets have been prepared, it is necessary to define the location of the seismic sources and the sites of observation at which the time series will be estimated. The study region is divided into a regular grid with given spacing (for example 0.2°lon x 0.2°lat). The centres of the cells are used as locations of the point-sources, while the sites at which the time series will be calculated are located at the nodes of the grid. In such a way the source and observation sites never overlap.

The point source is placed at a depth considered to be a representative for the seismicity of the considered territory beneath the center of the cells falling inside a seismogenic zone. In such a way the seismicity in each seismogenic zone *k* is simulated by a number of regularly spaced point sources, L_k. Obviously this number depends on the size of the seismogenic zone and on the grid spacing.

Once the distribution of the point sources and observation sites is defined, the synthetic seismograms are calculated at each site. The time series are calculated using the modal summation technique (Panza, 1985; Panza and Suhadolc, 1987; Florsch et al., 1991). In order to reduce the amount of calculations the synthetic seismograms are computed for source-site distances up to 90 km, since the acceleration level is small beyond such distances even for strong events.

Initially the synthetic seismograms are computed for a scalar seismic moment of 1 dyn cm. In order to account for the source finiteness, the amplitudes of the time series are properly weighted in the frequency domain using the ω^{-2} source spectrum, introduced by Aki (1967) and the magnitude of the modeled event.

To each point-source six magnitudes (M=5, 5.5, 6, 6.5, 7 and 7.5) are assigned. In such a way, six synthetic seismograms are obtained for each source-site couple.

The parameter representing the seismic hazard, that is plotted as a result, can be extract in different ways, from the computed time series: the maximum horizontal acceleration at 1 Hz (AMAXA), the related Design Ground Acceleration (DGA), the Arias intensity, or other damage factors proposed in the engineering community.

The obtained results are those typical of the deterministic methods of SHA: a fixed value of the ground motion parameter at given site, produced by a "fixed earthquake", or the so-called "controlling earthquake" (Reiter, 1990), i.e. an event of known location, size and source mechanism. These results can be used to study different hazard scenarios.

The deterministic methods, using large earthquakes as "controlling" events, model well the worst scenario, but they do not take into account that such events occur very rarely (their return period could be of the order of several hundreds or thousands of years). On the other hand, smaller but more frequent earthquakes (with return periods of the order of a few decades) could significantly affect human activities over a short time span.

In the "deterministic-probabilistic" method the ground motion is estimated "deterministically", i.e. through a numerical simulation of the generation and propagation of seismic waves as described before; however, for each ground motion value a probability of exceedance (or nonexceedance) and/or mean return period can be estimated on the basis of statistical analysis and probabilistic models of the seismicity.

In order to do this, the simplest assumption is that the earthquake occurrence is a Poisson stationary process. This assumption implies that the earthquakes are considered to be random events, each independent from the other, with constant mean rate, λ_0, per unit time (usually 1 year). Obviously, in order to use this hypothesis, the aftershocks have to be excluded from the analysis. According to the Poisson model the annual probability of occurrence of **n** events, given λ_0, is:

$$P(n|\lambda_0) = \lambda^n \exp(-\lambda_0)/n! \qquad (2)$$

The assumption of stationarity (i.e. λ_0 = constant in any time interval) is commonly used in the zones where the actual stage of the seismic process is unknown. The mean occurrence rate is then estimated simply by dividing the total number of events in the catalog, N_0, by the time span, T, covered by the catalog:

$$\lambda_0 = N_0/T \qquad (3)$$

The earthquake magnitude is also assumed to be a random independent variable with exponential distribution between a lower and an upper limit, M_0 and M_u, respectively. The cumulative distribution function of the magnitude is therefore:

$$P(M \geq m) = [\exp(-\beta m)-\exp(-\beta M_u)]/[\exp(-\beta M_0)-\exp(-\beta M_u)] \qquad (4)$$

The expected mean annual number of events with $M \geq m$ is defined as:

$$\lambda (M \geq m) = \lambda_0 P(M \geq m). \qquad (6)$$

The annual probability that at least 1 event of $M \geq m$ occurs (the so-called probability of exceedance) is then expressed as:

$$P = 1 - \exp[-\lambda (M \geq m)] = 1 - \exp[-\lambda_0 P(M \geq m)]. \qquad (7)$$

The probability of exceedance in t years is given by:

$$P(t) = 1 - \exp[-\lambda_0 P(M \geq m)\, t]. \qquad (8)$$

The occurrence of a ground motion at a given site is assumed also to be Poissonian, as it is the effect of the earthquake occurrence. The probability that at a given site of observation a ground parameter A exceeds a specified threshold value A_0 in a time period t is then:

$$P(A \geq A_0) = 1 - \exp[-\lambda\, A \geq A_0)\, t] \qquad (9)$$

where $\lambda (A \geq A_0)$ is the annual mean number of events which produce $A \geq A_0$ at the site of observation (see Orozova and Suhadolc, 1999, for more details).

I.2 Application to Umbria-Marche

An example of the deterministic-probabilistic method applied to estimate the seismic hazard of the Umbria-Marche region in Central Italy (Laurenzano, 1998) is shown in **Fig. 1-3**.

In the analysis of the observed seismicity in Italy the earthquake catalogue prepared in the framework of the activities of the Italian "Gruppo Nazionale per la Difesa dai Terremoti", hereafter referred as the GNDT catalogue, has been used (Stucchi et al., 1993). The main events with $M \geq 3.5$ occurred in the period 1900-1993 are used in the statistical analysis of the seismicity, because the GNDT catalogue can be considered fairly complete above this threshold only for this century (Molchan et al., 1995).

Recently, Molchan et al. (1997) have defined the so called "B-areas", in which the Gutenberg-Richter *b-value* can be considered constant and have estimated this parameter, using the GNDT catalogue. Their values are used to estimate the probability distribution functions (Orozova and Suhadolc, 1999) needed in the method.

The seismogenic zones used in our deterministic-probabilistic approach (**Fig. 1**) are those defined for Italy by Scandone et al. (1993). The fault plane solution, representative for each seismogenic zone has been extracted from the catalogue of

Italian focal mechanisms (Suhadolc, 1990; Suhadolc et al., 1992).

The map of the probability that DGA will exceed 0.01g in 50 years is presented in **Figure 2**. The highest probability (90%) is estimated for the area to the NE of the towns of Rieti and Terni. This result can be explained by the fact that the area is characterized by quite frequent, even if not stronger than about M=6, events.

Alternatively, one can use the map showing the value of DGA that has a 10% probability not to be exceeded in 50 years (**Fig. 3**).

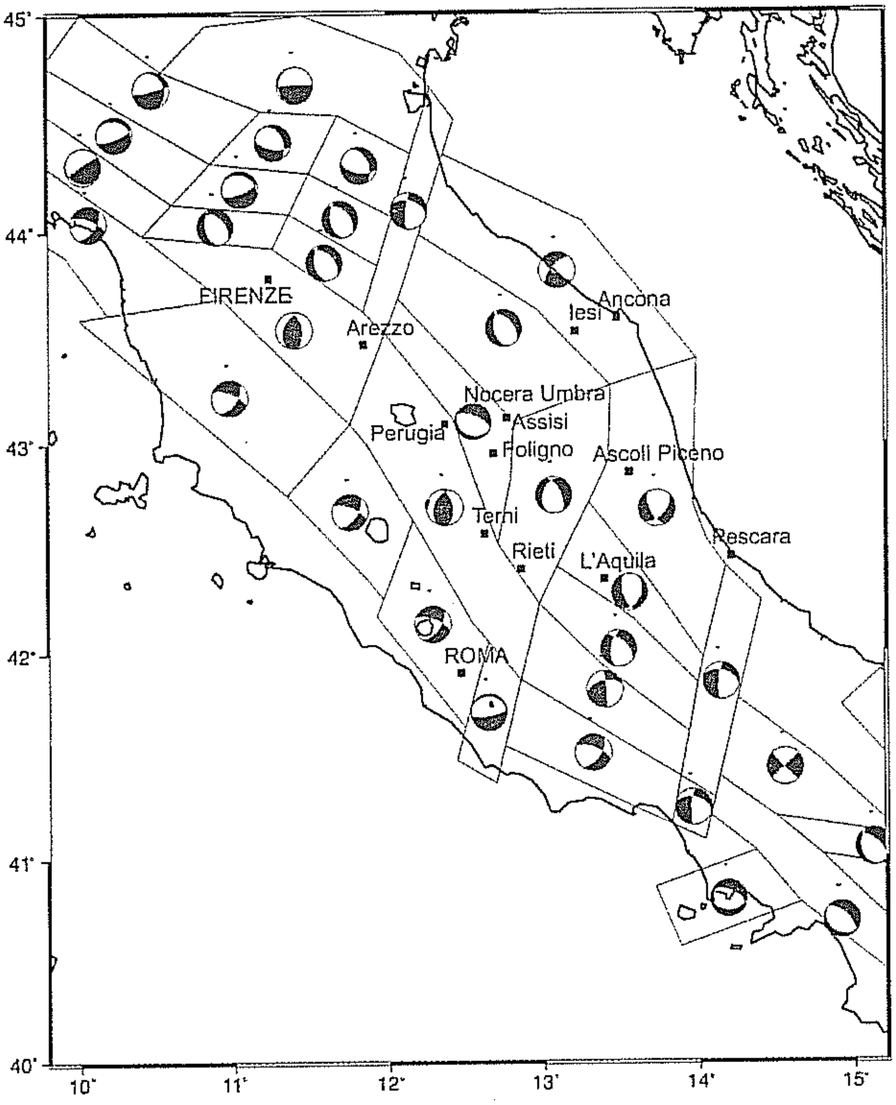

Figure. 1. Seismogenic zones as defined by Scandone et al. (1993) used in our deterministic-probabilistic approach. For each seismogenic zone the representative fault plane solution has been extracted from the catalogue of Italian focal mechanisms (Suhadolc, 1990; Suhadolc et al., 1992).

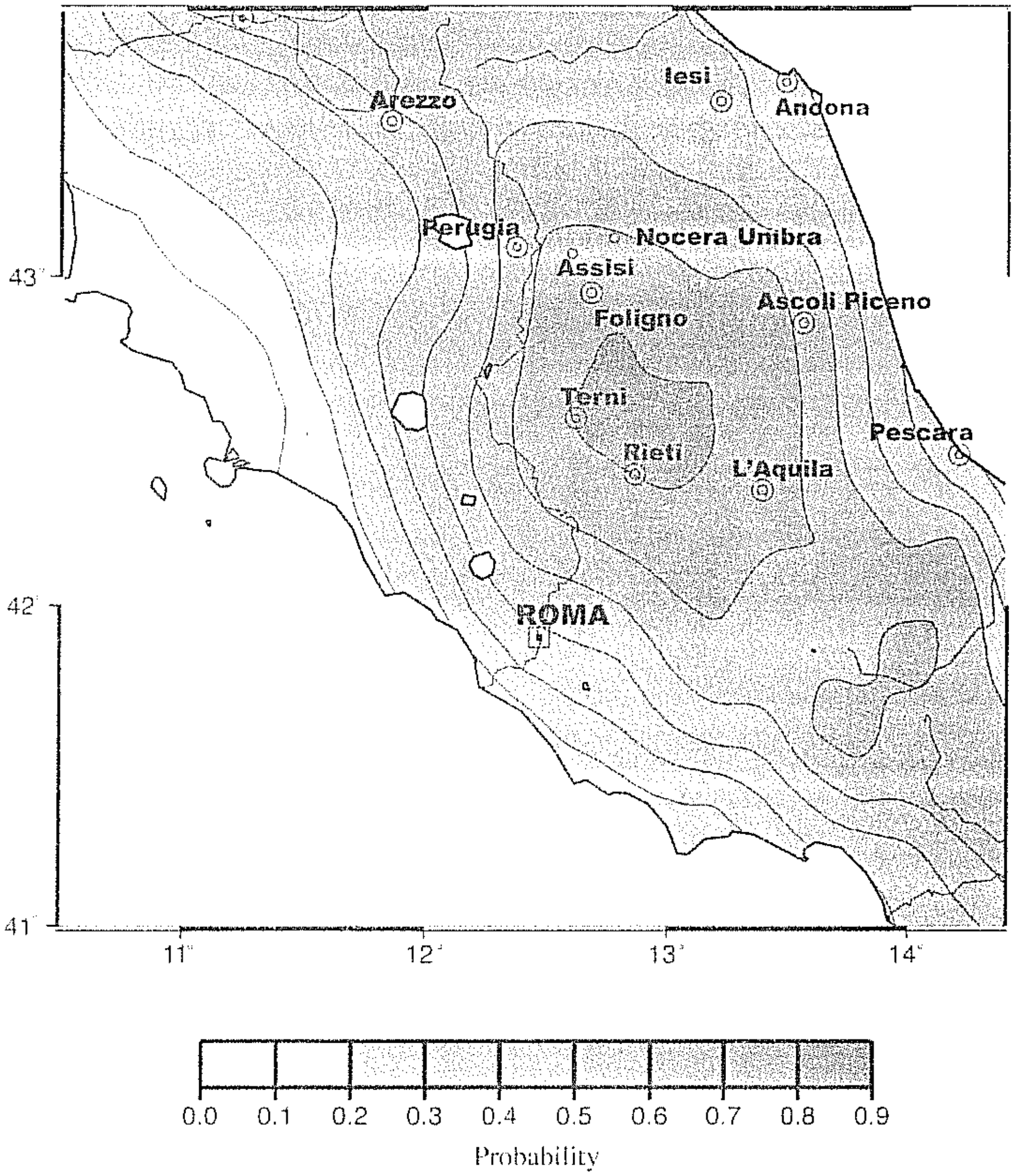

Figure 2. Map of the probability that DGA will exceed 0.01g in 50 years in the Umbria-Marche region.

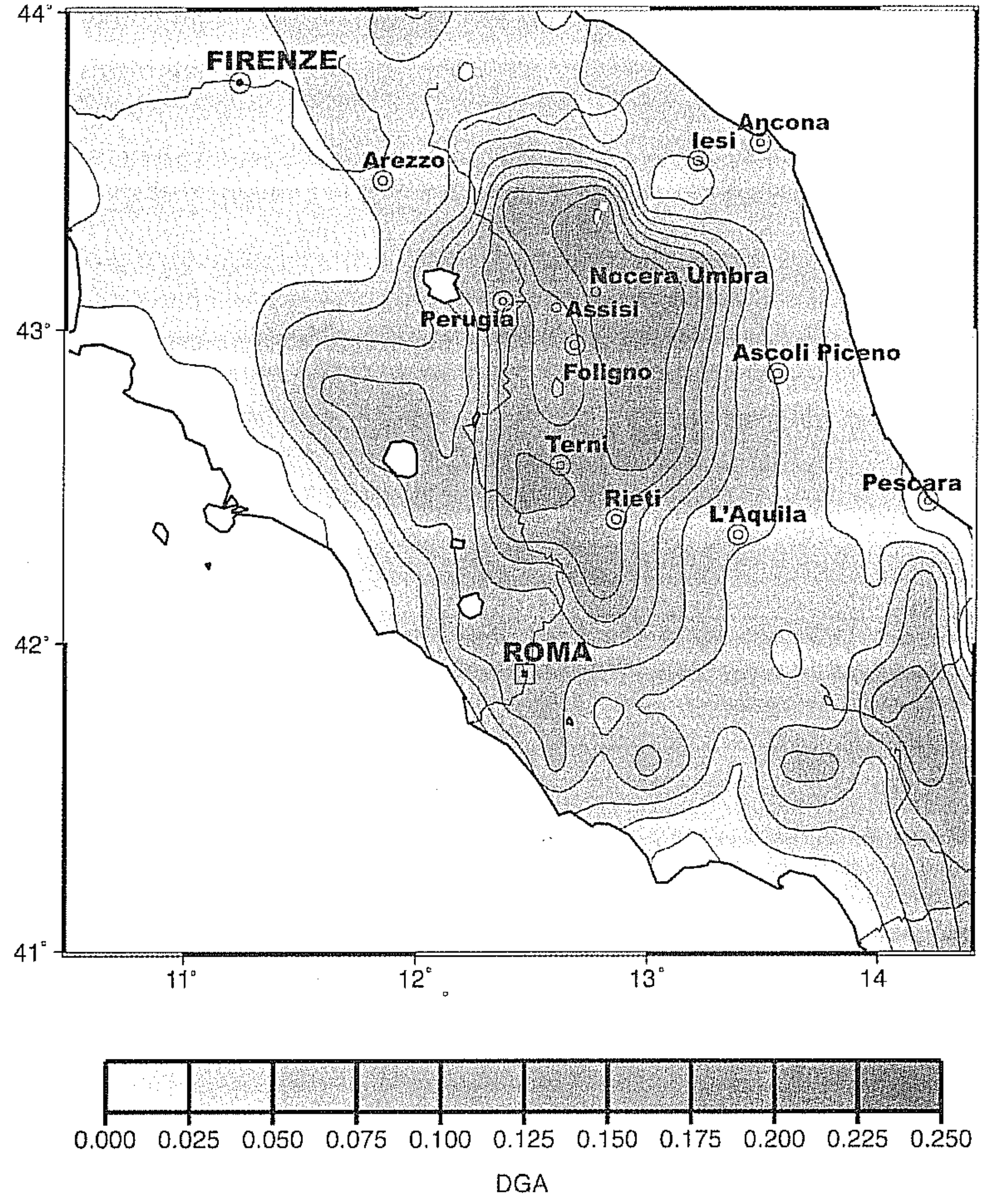

Figure 3. Map of DGA values that have a 10% probability not to be exceeded in 50 years in the Umbria-Marche region.

The validation of the results is performed by estimating the acceleration level at the station Monte Fiegni that has recorded the event. Following the procedure proposed by Panza et al. (1996), that fits the computed long-period (T>1s) spectral response to the Eurocode-8 spectral response, we estimate a DGA of 0.039 g for this station, while the actually observed DGA during the September 26, 1997 event was 0.028 g. It looks like our estimate is a good upper bound for the site.

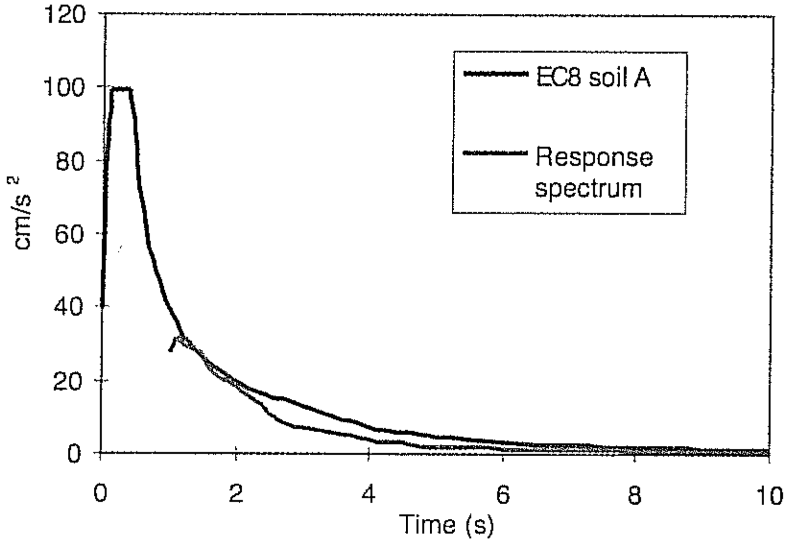

Figure 4. Estimate of DGA at Monte Fiegni site for the 1997, 26 September main earthquake.