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THE ABDUS SALAM INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS

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Abstract

Using the available information about regional structural models, past seismicity, and the seismotectonic regime in Italy, we have generated a set of synthetic seismograms covering the whole Italian territory on a $0.2^\circ \times 0.2^\circ$ grid. Peak values of ground motion (displacement, DMAX, and velocity, VMAX) and Design Ground Acceleration (DGA) based on Eurocode 8 (EC8, 1993), extracted from the synthetic signals, have been compared with the macroseismic intensities felt in Italy. The correlation relations that we have obtained are in a good agreement with empirical relationships given by other authors and compare quite well with the few observations available in the Italian territory.

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1. Introduction

The procedure for the deterministic seismic zoning developed by Costa et al. (1992, 1993) represents one of the new and most advanced approaches and can, at the same time, be used as a starting point for the development of an integrated procedure that combines the advantages of the probabilistic and of the deterministic methods, thus minimizing their drawbacks.

Synthetic seismograms are constructed to model ground motion at the sites of interest, using the available knowledge of the physical process of earthquake generation and wave propagation in realistic anelastic media. In first-order zoning a database of seismograms covering the area of interest (at a regional scale) is computed, with a low order approximation of the effects of lateral heterogeneities. Synthetic seismograms are very efficiently generated by the modal summation technique (Panza, 1985; Florsch et al., 1991), so it is possible to perform detailed parametric analyses at reasonable costs. For example, different source and structural models can be taken into account in order to create a wide range of possible scenarios from which to extract essential information for decision making.

Once the parametric analysis is performed and the gross features of the seismic hazard are defined, a more detailed modelling of ground motion is possible. We can take into account the local geological and geotechnical conditions at a specific site of interest, using either the hybrid method, which combines, for the description of wave propagation in anelastic heterogeneous media, the modal summation with finite differences techniques (Fäh et al., 1990; Fäh, 1992), or the fully analytical modal summation method, extended to laterally varying media (Vaccari et al. 1989; Romanelli et al., 1996; 1997). This deterministic modelling goes well beyond the conventional deterministic approach taken in hazard analyses - in which only a simple wave attenuation relation is invoked - in that it includes full waveform modelling.

2. Deterministic zoning using synthetic seismograms

Starting from the available information on the Earth's structure, seismic sources and the level of seismicity of the investigated area, it is possible to estimate the maximum ground velocity and displacement in a given frequency band (VMAX and DMAX respectively), Design Ground Acceleration (DGA) or any other parameter relevant to seismic engineering, which can be extracted from the computed theoretical signals. This procedure allows us to obtain a realistic estimate of the seismic hazard also in those areas for which scarce (or no) historical or instrumental information is available, and to perform the relevant parametric analyses.

To reduce the amount of computations, the seismic sources can be grouped into homogeneous seismogenic areas, and for each group a representative focal mechanism can be defined. The scalar seismic moment associated with each source is determined from the analysis of the maximum magnitude observed in the epicentral area.

To derive the distribution of the maximum observed magnitude over the territory, the

image of the seismicity given by the earthquake catalogue is smoothed as follows. We divide the considered territory with cells 0.2° by 0.2° . To each cell we assign the magnitude value, M_i , of the most energetic event that occurred within it, and we use a centered smoothing window with a radius of 0.6° in order to take into account the source extension in space, and location uncertainties. Only the cells falling within the seismogenic areas are retained and a double-couple point source, corresponding to a magnitude M_i , is placed in the centre of each cell, with a depth equal 10 km for $M_i < 7$, and equal to 15 km for the larger events.

If available, reliable values of maximum expected magnitudes can be used in a straight-

Figure 1. Smoothed magnitude distribution for the cells belonging to the seismogenic zones defined by GNDT (Corsanego et al., 1997).

forward way instead of M_s .

Detailed examples of the input data used in the procedure are described by Costa et al. (1993) and Panza and Vaccari (1994).

The file NT (version 4.1) prepared by GNDT (Camassi and Stucchi, 1996) is used for the definition of seismicity. The smoothed magnitude distribution for the cells belonging to the seismogenic zones defined in April 1996 by GNDT (Corsanego et al., 1997) is given in Figure 1.

The synthetic signals are computed for an upper frequency limit of 1 Hz, and are properly scaled according to the (smoothed) magnitude (to be conservative we have assumed that all magnitude values given in the NT file are M_s) associated with the cell of the source, using the moment-magnitude relation given by Kanamori (1977) and the spectral scaling law proposed by Gusev (1983) as reported in Aki (1987). The deterministic results

Figure 2. Distribution of DGA, obtained as a result of the deterministic zonation extended to high frequencies using the design spectra of EC8 for soil A.

Figure 3a. Horizontal VMAX distribution, obtained as a result of the deterministic zonation.

may be extended to higher frequencies by using design response spectra (Panza et al., 1996), for instance Eurocode 8 (EC8, 1993), which define the normalized elastic acceleration response spectrum of the ground motion, for 5% critical damping. In general this operation should be made taking into account the soil type. For Italy, the used regional structural models (Costa et al., 1993) are all of type A, as defined in EC8, therefore we can immediately determine DGA (Figure 2) and the Maximum Spectral Value (MSV) using the EC8 parameters for soil A.

In addition to DGA we focus on the maximum ground velocity, and displacement, VMAX, and DMAX. We compute the complete time series, therefore we are not limited to this choice, and it is possible to consider other parameters, like Arias intensity (Arias, 1970) or other integral quantities that can be of interest in earthquake engineering or

engineering seismology. Since recordings of many different sources are associated to each site, different maps can be produced. If one single value is to be plotted on a map, then only the maximum value of the analyzed parameter is considered - maximum velocity and displacement respectively in Figures 3a and 4a. In Figures 3b and 4b the periods associated with the maxima given in Figures 3a and 4a are shown. It can be seen that in some regions, like for instance Central Italy around latitude 42°N, long periods in the range between 20s and 30s are very frequent. They belong to signals generated by strong earthquakes occurring at a large distance from the site (about 90km), while the magnitude of the closer events, which are responsible for the higher frequencies (between 2 s and 5 s in our computations), is not large enough to let high frequencies dominate the scenario.

The deterministic procedure, for the definition of seismic input, is particularly suitable in a situation like the one of Bucharest where the dominant periods of the larger accelerations are above 1 s. The results of the deterministic zonation of Romania have

Figure 3b. Period in seconds of the maximum of VMAX at each site.

Figure 4a. Horizontal DMAX distribution, obtained as a result of the deterministic zonation.

been shown by Radulian et al. (1997).

3. Validation of the synthetic models against independent observations

A quantitative validation is supplied by the observed accelerograms recorded during the Irpinia earthquake (23 November 1980) and the Friuli earthquake (6 May 1976). The source rupturing process of the Irpinia event is very complex (e.g., Bernard and Zollo, 1989) and the dimension of the source has been estimated to be of the order of several tens of km. Nevertheless, it seems that the signal recorded at the station of Sturmo is mostly due to a single sub-event that occurred rather close to the station itself, while the energy contributions coming from other parts of the source seem unimportant (Vaccari et al., 1990). With the cutoff frequency at 1 Hz, the horizontal components accelerograms recorded at

Sturno have been low-pass filtered to be compared with the computed signals for the Irpinia region. The example shown in Figure 5 refers to the NS component but the same considerations can be applied to the EW component of motion.

The early phases and the maximum (AMAX) of the recorded signal (upper trace) and the synthetic one computed in the point-source approximation (middle trace), are in very good agreement. The late part of the observed recording is more complicated and this is mostly related to the complexity of the source, which is deliberately neglected in the computation of the synthetic signal used in the first-order zoning. The lower trace is shown as an example of modelling of the source complexity.

For the same Irpinia event Nunziata et al. (1995) show results of the deterministic modelling of ground motion in good agreement with the accelerometric record in Torre del Greco, near Naples.

Sufficient agreement between observations and modelling is obtained considering the Tolmezzo record of the Friuli (1976) earthquake (Panza et al., 1996), and, in this case, the

Figure 4b. Period in seconds of the maximum of DMAX at each site.

point-source seems to be a satisfactory approximation for an event with $M_s=6.1$.

4. Ground motion models and intensity observations

The deterministic modelling can be used to derive correlation relations between the maximum felt macroseismic intensity, I , and $DMAX$, $VMAX$, and DGA (Panza et al., 1997a). This possibility is particularly relevant for countries with a long seismological history since it facilitates the engineering use of historical events, that are quantified only in terms of macroseismic intensity.

In this case the maximum observed magnitude is smoothed as follows. To each cell we assign the magnitude value of the most energetic event that occurred within it, and for events with $M_i > 6.75$, we use a centered smoothing window with a radius of 0.2° in order to take into account the source extension in space. Only the cells falling within the seismogenic areas are retained and a double-couple point source, corresponding to a magnitude M_i , is placed in the centre of each cell, with a depth equal to 10 km for $M_i < 7$ and equal to 15 km for the larger events.

Figure 5. NS component accelerogram recorded at Sturno (upper trace), low-pass filtered to be compared with the computed signals for the Irpinia region (middle trace). The lower trace is the result of a superposition of four sub-events, each one modelled with the middle trace properly weighted and shifted in time, accordingly with the model by Vaccari et al. (1990).

Panza et al. (1997a) have used two sources for intensity data: (1) a map of maximum macroseismic intensity felt in Italy, made by Istituto Nazionale di Geofisica (ING intensity) (Boschi et al., 1995), where the intensity ranges between the V and the XI grade of MCS scale, the intensity value V including values below V; and (2) a set of maximum intensity felt in every municipal land, compiled jointly by ING, SSN and GNDT (ISG intensity) (Molin et al., 1996), where the intensity ranges between the VI and the X grade of the MCS scale. Grade VI includes values below VI and grade X includes values above X.

Peak values of ground motion and intensity are poorly correlated and their scatter is considerable (Ambraseys, 1974, Decanini et al., 1995). If we apply the correlation hypothesis:

$$\log(y) = b_0 + b_1 I \quad (1)$$

(where y is a peak value or DGA and I is the intensity) to the whole set of data, the χ^2 test indicates that hypothesis (1) must be rejected (the hypothesis is statistically significant), while equation (1) becomes acceptable if average values of y , determined in correspondence of each intensity, are used.

The application of (1) to ING and ISG data gives the coefficients reported in Table I and Table II, where the χ^2 is determined assigning to the value obtained from the regression coefficients an error of 2σ . For each intensity data set (ING and ISG) the slopes of (1) are comparable between themselves, but the slopes obtained with ING data are systematically smaller than the slopes obtained with ISG data. In Figures 6 and 7 we compare our log-linear relations with some earlier results, obtained considering global data, and in Table III we give the conversion between Intensity, I , and Maximum Spectral Value, MSV.

At a fixed intensity, means of peak values, in general, decrease with epicentral distance. Decanini et al. (1995) show an example of 9 events with $I=VII$, for which the mean of PGA for $R \leq 50$ km is almost 110 cm/s^2 , while for $50 < R < 80$ km the mean PGA is 42 cm/s^2 , and introduce the regression law for peak values:

$$\log(y) = b_0 + b_1 I + b_2 \log R \quad (2)$$

with $R = \sqrt{(D^2 + h^2)}$, where D is the epicentral distance and h the focal depth.

Tables IV and V contain the results of the regression with synthetic data, that are quite close to the ones given by Decanini et al. (1995) for observations. These tables contain the values obtained using the NT4.1 catalogue instead of the preliminary version NT3.1 (Stucchi et al., 1995) used by Panza et al. (1997a). The new regressions have been performed with a larger set of data, including intensities VI, VII and VIII, not considered by Panza et al. (1997a). A remarkable agreement with the observation in South Eastern Sicily and Irpinia (Decanini et al., 1995) is obtained when considering MSV and velocity. As an example, in Figures 8 and 9 we show the results we obtained with ISG data (the results obtained with ING data are very similar). In these figures we have plotted observations as solid squares and the modelled values as open circles. The solid and dashed lines are respectively the regression for the observations and for our modeled values. For accelerations we have

TABLE I. Results of regression (1) for ING data.

Displacement	Velocity	Acceleration	DGA
$b_0 = -2.0 \pm 0.5$	$b_0 = -1.85 \pm 0.35$	$b_0 = -4.25 \pm 0.35$	$b_0 = -3.5 \pm 0.3$
$b_1 = 0.31 \pm 0.06$	$b_1 = 0.32 \pm 0.05$	$b_1 = 0.32 \pm 0.04$	$b_1 = 0.28 \pm 0.04$
$\chi^2_5 = 4.1$	$\chi^2_5 = 4.2$	$\chi^2_5 = 4.3$	$\chi^2_5 = 4.1$

TABLE II. Results of regression (1) for ISG data.

Displacement	Velocity	Acceleration	DGA
$b_0 = -2.0 \pm 0.2$	$b_0 = -2.1 \pm 0.1$	$b_0 = -4.6 \pm 0.1$	$b_0 = -3.7 \pm 0.1$
$b_1 = 0.31 \pm 0.03$	$b_1 = 0.35 \pm 0.01$	$b_1 = 0.35 \pm 0.01$	$b_1 = 0.30 \pm 0.01$
$\chi^2_3 = 1.9$	$\chi^2_3 = 2.0$	$\chi^2_3 = 2.2$	$\chi^2_3 = 2.1$

plotted $a(1)=\log(\text{PGA})-0.07I$ and $a(2)=\log(\text{MSV})-0.1I$ (single points), $a(1)=-0.24-0.8\log(R)$ and $a(2)=-0.85-0.5\log(R)$ (regressions). For velocity we have plotted $b(1)=\log(\text{PGV})-0.15I$ and $b(2)=\log(\text{Velocity})-0.15I$ (single points), $b(1)=1.00-0.7\log(R)$ and $b(2)=0.43-0.53\log(R)$ (regressions). The values of b_2 are, in the case of displacement, lower than the ones obtained for velocity and DGA; they range from 0.1 (ING data set) to 0.3 (ISG data set), and indicate a weak dependence on distance.

The χ^2 test, applied to the modelled values and to the experimental data plotted in Figures 8 and 9, indicates that hypothesis (2) is statistically significant.

5. Detailed zoning combining observation and modelling of ground motion

The results obtained with a first-order zoning cannot be refined by simply assuming a higher cutoff frequency (> 1 Hz) in the computation of the synthetic seismograms. A more detailed zoning requires a better knowledge of the seismogenic process in the region. Furthermore, to model wave propagation in greater detail the structural models used in the computation of synthetic seismograms must take into account lateral heterogeneities.

Detailed numerical simulations play an important role in the estimation of ground motion in regions of complex geology. They can provide synthetic signals for areas where recordings are absent, that are particularly relevant for engineering seismology and earthquake engineering. Numerical simulations are, therefore, very useful for the design of earthquake-resistant structures.

As we have seen in section 2 the deterministic computation can be extended to higher

Figure 6. Experimental curves, taken from literature (Decanini et al., 1995; Richter, 1959 and Cancani, 1904) and our estimated values ($\pm \sigma$) of DGA and MSV (ING data set).

Figure 7. Experimental curves, taken from literature (Decanini et al., 1995; Richter, 1959 and Cancani, 1904) and our estimated values ($\pm \sigma$) of DGA and MSV (ISG data set).

frequencies by the use of the existing standard design spectra. The matching of the long-period portion of the normalized spectra with the ones computed from synthetic accelerograms, allows us to obtain, for any portion of the considered territory, an absolute spectrum, provided a satisfactory classification of soils is available. The preliminary soil classification of EC8 considers three classes, A, B, and C, ranging from hard rock to loose uncemented sands. Accordingly with EC8 for sites with soil conditions not matching the three classes A, B and C, special studies for the definition of the ground acceleration response spectrum are necessary.

When detailed special studies are required by EC8 or by the presence, in the built environment, of special objects, the standard seismic prospecting techniques, used for the detailed definition of the elastic properties of subsurface geology, do not give satisfactory results since they treat wave propagation in laterally heterogeneous structures with as-

TABLE III. Correspondence between macroseismic intensity, I, and MSV, in units of g, for ING data set. Values in parentheses correspond to ISG data.

I	MSV (g)
V	0.02 ± 0.02
VI	0.04 ± 0.03 (0.030 ± 0.005)
VII	0.08 ± 0.04 (0.065 ± 0.005)
VIII	0.15 ± 0.12 (0.13 ± 0.01)
IX	0.28 ± 0.15 (0.26 ± 0.03)
X	0.53 ± 0.36 (0.52 ± 0.07)
XI	1.01 ± 0.90

TABLE IV. Results of regression (2) for ING data.

Displacement	Velocity	DGA
$b_0 = -0.4 \pm 0.3$	$b_0 = 0.5 \pm 0.5$	$b_0 = -0.6 \pm 0.5$
$b_1 = 0.12 \pm 0.02$	$b_1 = 0.16 \pm 0.03$	$b_1 = 0.07 \pm 0.03$
$b_2 = 0.1 \pm 0.1$	$b_2 = -0.6 \pm 0.2$	$b_2 = -0.7 \pm 0.2$
$\chi^2_{46} = 212$	$\chi^2_{40} = 139$	$\chi^2_{38} = 141$

TABLE V. Results of regression (2) for ISG data.

Displacement	Velocity	DGA
$b_0 = -1.3 \pm 0.4$	$b_0 = 0.4 \pm 0.5$	$b_0 = -1.25 \pm 0.45$
$b_1 = 0.17 \pm 0.03$	$b_1 = 0.15 \pm 0.03$	$b_1 = 0.11 \pm 0.03$
$b_2 = 0.3 \pm 0.2$	$b_2 = -0.5 \pm 0.2$	$b_2 = -0.5 \pm 0.2$
$\chi^2_{39} = 118$	$\chi^2_{38} = 111$	$\chi^2_{37} = 109$

Figure 8. Variation with hypocentral distance, R , (attenuation relationship) of PGA (solid squares) and MSV (open circles), normalized with respect to I . The solid line represents $a(1) = -0.24 - 0.8 \log(R)$, and the dashed line $a(2) = -0.85 - 0.5 \log(R)$.

Figure 9. Variation with hypocentral distance, R , (attenuation relationship) of PGV (solid squares) and velocity (open circles), normalized with respect to I . The solid line represents $b(1) = 1.00 - 0.7 \log(R)$, and the dashed line $b(2) = 0.43 - 0.53 \log(R)$.

ymptotic forms valid for high frequencies. These methods, called “ray methods”, can only be applied to smoothly varying media, where the characteristic dimensions of the inhomogeneities are considerably larger than the prevailing wavelength. They fail to predict ground motion at sites close to lateral heterogeneities such as edges of sedimentary basins and at sites above irregular bedrock-sediment interfaces, where excitation of local surface waves and resonance effects can be important.

Far away from lateral heterogeneities, a local structure can sometimes be approximated by a horizontally-layered structural model, and the modal summation method is the most powerful tool for computing broadband synthetic seismograms. This method is still suitable when lateral variations can be schematized with vertical discontinuities (Vaccari et al., 1989, Romanelli et al., 1996; 1997). When dealing with special, detailed investigations the influence of the local and irregular heterogeneities can be included in the numerical modelling combining the modal summation and the finite difference techniques (Fäh et al., 1990; Fäh, 1992).

Examples of possible procedures for the detailed deterministic modelling of ground motion are given by Suhadolc and Marrara (1997) and a specific example referring to Bucharest is given by Moldoveanu and Panza (1997). Here, in Figures 10a and 10b, we give an example describing the results obtained for the microzoning of Rome.

6. Conclusions

Traditional deterministic methods for seismic zoning can only lead to a kind of “post-event” zoning whose validity cannot easily be extrapolated in time and to different regions and which, therefore, must be considered obsolete.

On the contrary the computation of realistic synthetic seismograms, using methods that make it possible to take source and propagation effects into account, utilizing the huge amount of geological, geophysical and geotechnical data, already available, goes well beyond the conventional deterministic approach and gives a very powerful and economically valid scientific tool for seismic zonation and microzonation.

Because of its flexibility, the method is suitable for inclusion in new integrated procedures, a kind of compromise between probabilistic and deterministic approaches, that can be developed in order to minimize the drawbacks of each of the two procedures.

The ability to estimate accurately seismic hazard at very low probability of exceedance may be important in protecting, against rare earthquakes, the existence of special objects in the built environment. The deterministic approach, based upon the assumption that several earthquakes can occur within a predefined seismic zone, represents a conservative definition of seismic hazard for pre-event localized planning for disaster mitigation, over a quite broad-band of periods.

With the deterministic modelling it is possible to derive reliable, region specific, correlations between intensity, I , and $DMAX$, $VMAX$, and DGA , that facilitate the engineering use of historical data. The availability of correlations, that are valid for a specific region, is quite important, since the use of information collected on a global scale may introduce quite unsatisfactory biases (Trifunac, 1992).

Figure 10a. Microzoning for the city of Rome based on local soil classification and on the computation of synthetic spectral amplifications (modified from Panza et al., 1997b).

The results of tests made against instrumentally recorded accelerograms show that, even an approximate knowledge of the geometry and of the mechanical properties of the uppermost layers and the use of commonly available data on the seismic source geometry, is sufficient to make a realistic prediction of the ground motion.

The definition of realistic seismic input can be obtained from the computation of a wide set of time histories and spectral information, corresponding to possible seismotectonic scenarios for different source and structural models. Such a data set can be very fruitfully used by civil engineers in the design of new seismo-resistant constructions and in the reinforcement of the existing built environment, and therefore supply a particularly

Figure 10b. Maximum absolute spectral accelerations (5% damping) obtained for five zones in the city of Rome (modified from Panza et al., 1997b)

powerful tool for the prevention aspects of Civil Defence.

The procedure is scientifically and economically valid for the immediate (no need to wait for a strong earthquake to occur), first order, seismic microzonation of any urban area, where the geotechnical data are available.

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