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Intermediate-term Earthquake Prediction and Seismic Zoning in Northern Italy

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Intermediate-term earthquake prediction and seismic zoning in Northern Italy

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Summary

The algorithm CN for intermediate earthquake prediction has been applied to an area in Northern Italy, which has been chosen according to a recently proposed seismotectonic model. Earthquakes with magnitude ≥ 5.4 occur in the area with a relevant frequency and their occurence is predicted by algorithm CN. Therefore a seismic hazard analysis has been performed using a deterministic procedure, based on the computation of complete synthetic seismograms. The results are summarized in a map giving the distribution of peak ground acceleration, but the complete time series are available, which can be used by civil engineers in the design of new seismo-resistant constructions and in the retrofitting of the existing ones. This risk reduction action should be intensified in connection with warnings issued on the basis of the forward predicitons made by CN.

Riassunto

L'algoritmo CN per la previsione a medio termine dei terremoti è stato applicato in Italia settentrionale in un'area selezionata in base ad un recente modello sismotettonico. I risultati dell'analisi indicano che nell'area terremoti di magnitudo ≥ 5.4 si verificano con frequenza rilevante. E' stata pertanto condotta un'analisi di pericolosità sismica utilizzando una procedura deterministica, basata sul calcolo di sismogrammi sintetici completi. I risultati vengono rappresentati per mezzo di una mappa della distribuzione dell'accelerazione di picco. Le serie temporali complete rimangono comunque disponibili e possono essere utilizzate dagli ingegneri civili per la progettazione di nuove strutture antisismiche e per la ristrutturazione di quelle già esistenti. Tale opera di mitigazione del rischio deve essere intensificata in concomitanza delle previsioni effettuaute con l'algoritmo CN.

Key-words: earthquake prediction, seismic hazard, synthetic seismograms

Introduction

Recently the guidelines of the United Nations International Decade for Natural Disaster Reduction (IDNDR), for the drawing up of pre-catastrophe plans of action, have led to the consolidation of the idea that zoning can and must be used as a means of prevention in seismic areas even if they have not yet been hit by disasters but are potentially prone to it. The optimisation of techniques aimed at prevention will be one of the basic themes of the development of seismic zoning in the 21st century.

For such a purpose, one has to know the region where a strong earthquake may occur, approximately when and with which intensity. Once those elements are known, the next step is to analyse the possible effects that might be caused by such events in anthropised areas. The CN algorithm, formulated by Gabrielov et al. (1986) and Keilis-Borok and Rotwain (1990) is a very powerful tool for the intermediate-term prediction of strong seismic events. For the earthquake-prone areas, indicated by the results of CN, a deterministic analysis can be performed in order to obtain the motion parameters at the surface (e.g. acceleration time histories), that can be used by civil engineers to design earthquake-resistant structures and for the retrofitting of the existing constructions.

1. Intermediate-term earthquake prediction

The analysis of the Time of Increased Probability (TIP) of a strong earthquake with magnitude greater than, or equal to a given threshold M_0, is based on the algorithm CN. The algorithm makes use of normalized functions, therefore the original algorithm, developed for the California-Nevada region, can be directly applied to the Italian region without any adjustment of the parameters.
Using the seismotectonic model of Italy (Patacca et al., 1990), shown in Fig.1, and the epicentral distribution, the country can be divided in three main regions: Northern Italy, Central Italy and Southern Italy. The analysis is here concentrated on the Northern part of Italy (latitude above 44° N), which is characterized by the presence of the Alpine arc, generally uplifting (Mueller, 1982). The eastern part of the zone (Friuli), where one of the branches of Southern Alps turns to the South along the Adriatic sea (Dinaric Alps), the western part of the zone and the areas of contact between the Southern Alps and the Northern Apennines are characterized by compression caused by relative motions (Dal Piaz and Polino, 1989). In the Friuli zone some strike-slip motion in the western direction is also present (Pavoni et al., 1992). In Northern Italy the dominant seismogenic zones defined by Patacca et. al (1990) (Fig.1) are of compressive or transpressive type. The area where a strong earthquake has to be predicted must be the smallest possible, but the borders of the area must not cross continuous seismotectonic

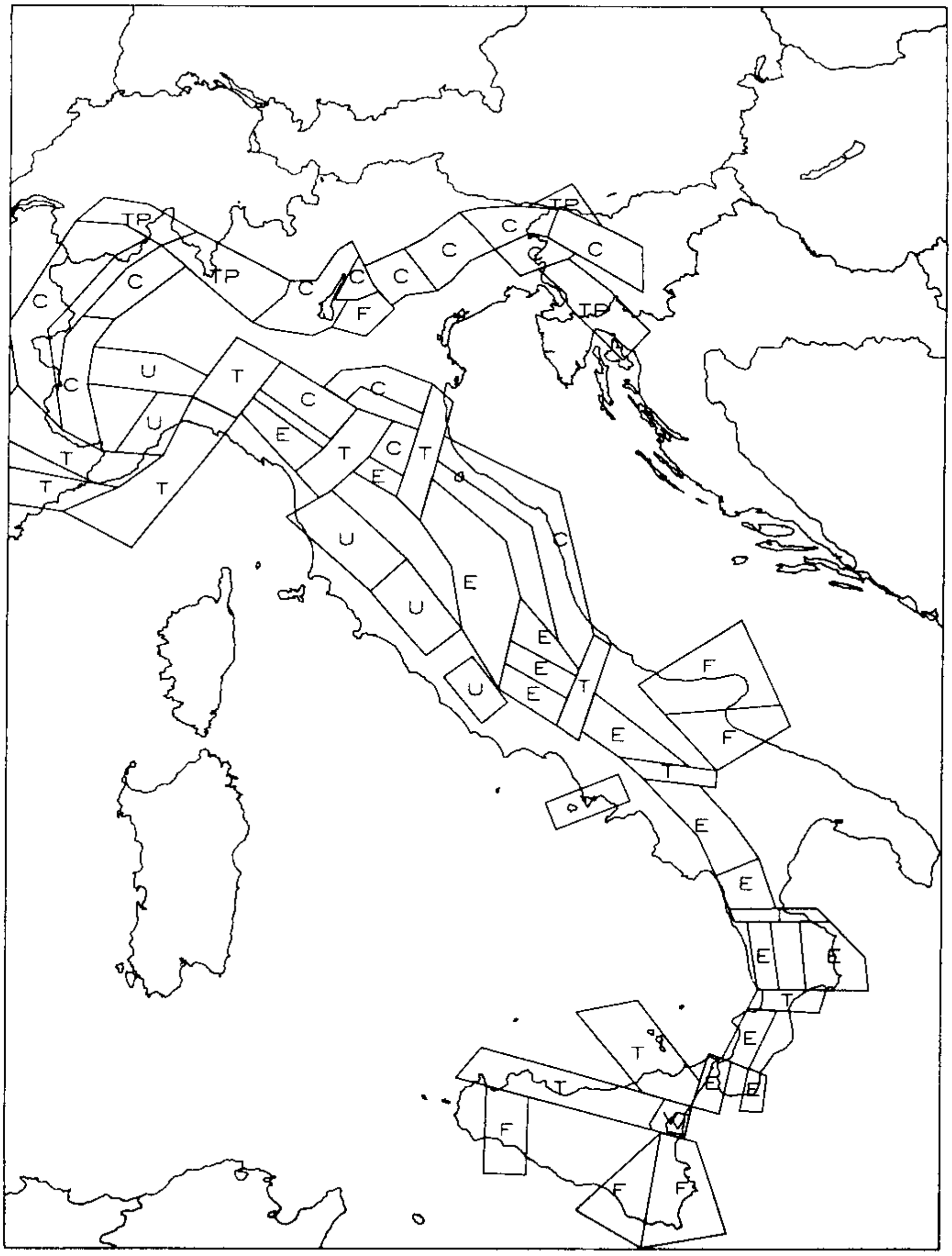

Fig. 1. Seismotectonic map of Italy (Patacca et al. 1990): E) Extensional areas, C) Compressional areas, T) Transition areas, F) Areas of fractures in foreland zone, V) Volcanic areas, TP) Transpressive areas.

zones and the annual number of earthquakes has to be at least three for the magnitude for which the catalog is complete.

Following these criteria the area shown in Fig.2 has been chosen for the application of the algorithm CN to Northern Italy. From the seismicity map it is possible to see that the area is characterized by the presence of maxima of seismicity in Liguria (LIG), Veneto (VEN), Friuli (FRI) and Slovenia (SLO).

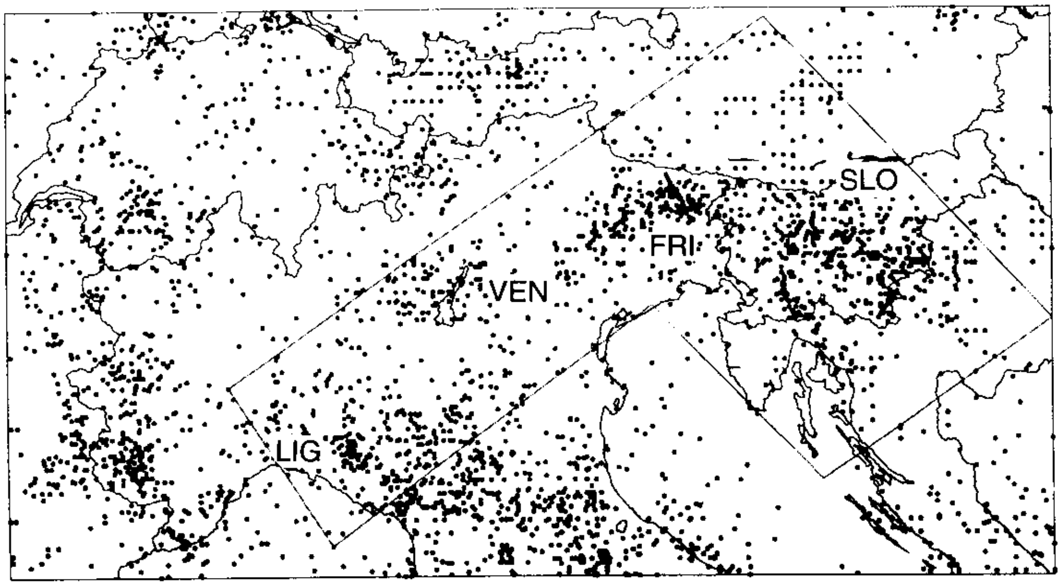

Fig. 2. Polygon (solid line) used to delimit the events considered in the application of the algorithm CN to Northern Italy. Dots represent the main shocks ($M \geq 3$ in the time interval from 1900 to 1993) belonging to the catalogue ALPOR+PFGING+NEIC.

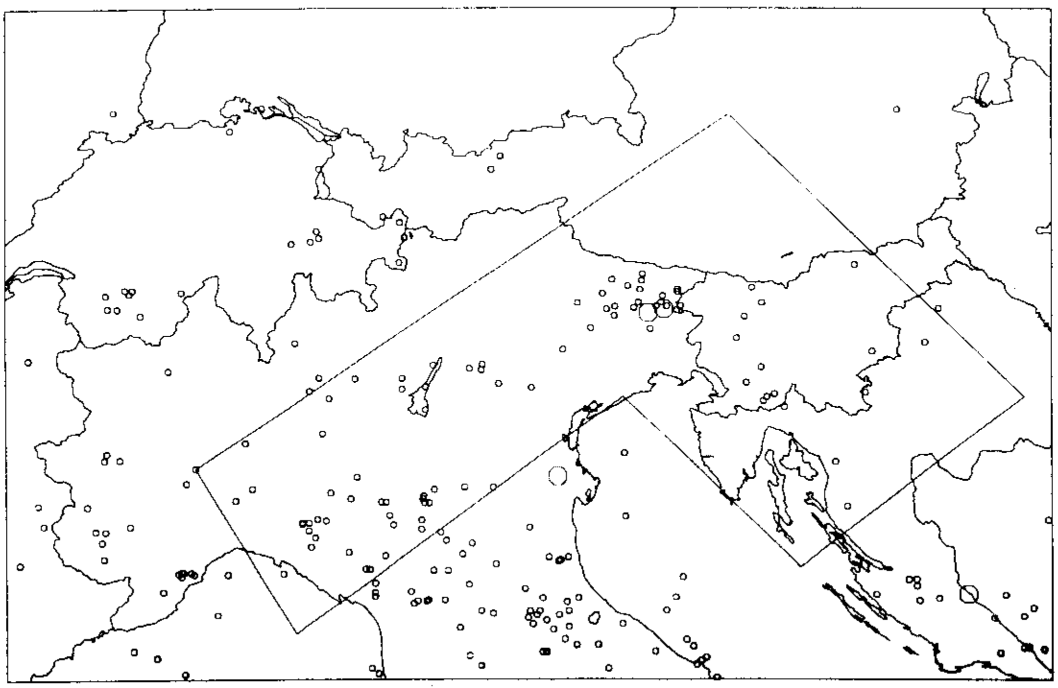

Fig. 3. The solid line indicates the polygon within which are contained the main events (Catalogue ALPOR+PFGING+NEIC) with magnitude greater than 4.0 used in the definition of the functions. The large dots indicate the events with magnitude $M \geq M_0 = 5.4$.

Table 1.
Procedure followed to merge the catalogues: ALPOR, PFGING and NEIC. m_i is the magnitude obtained from intensity, m_d is duration magnitude, m_l is local magnitude, m_b is body waves magnitude, m_s is surface waves magnitude.

CATALOGUE	TIME INTERVAL	MAGNITUDE	PRIORITY
PFGING	1000-1992	m_i, m_d, m_l	m_l, m_d, m_i
ALPOR	1000-1985	m_i, m_l	m_l, m_i
NEIC	1900-1992	m_b, m_s, m_l	m_l, m_s, m_b
FINAL	1900-1992	$m_{(ALPOR)}$, $m_{(PFGING)}$, $m_{(NEIC)}$	MAX

This area includes the compressive domains in the Eastern Alps (Fig.1, Patacca et al., 1990) and the intersection zone between the Alps and the Apennines characterized by extensional, compressional and transitional domains. The main tectonic feature of this area is the intersection of the Alpine and the Dinaride structures in the Friuli area.

According to the standards used for the California-Nevada region, the magnitude threshold chosen for the definition of the strong earthquakes is $M_0 = 5.4$. The period of analysis has been chosen 1960-1992, because of the incompleteness of the catalogue before 1960. The same time interval has been used as period of learning, since in the region only two strong earthquakes occurred during the last thirty years (Fig.3).

To analyze the complete region, extending outside the border of Italy, it has been necessary to merge, following the procedure shown in Table 1, three different catalogues: NEIC, PFGING and ALPOR. NEIC is the catalogue of the National Earthquake Information Center (NEIC, USGS, Denver, USA). PFGING is the national Italian catalogue and ALPOR is the catalogue of the Eastern Alps, produced by the Osservatorio Geofisico Sperimentale (OGS, Trieste, Italy).

The results of the CN analysis are given in Fig.4. The two strong events occurred during the analyzed period are predicted, and the TIP durations cover about the 27% of the total time, there is only the false alarm just after the strong earthquake of 1988.

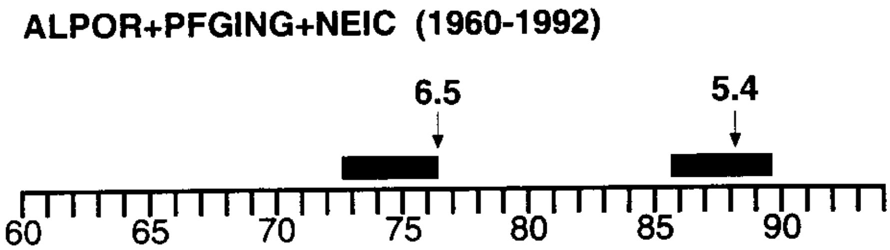

Fig. 4. Results of the diagnosis of TIPs for Northern Italy as deduced from catalogue ALPOR+PFGING+NEIC from 1960 to 1993. The time of occurrence of a strong earthquake, i.e. with magnitude $M \geq M_0 = 5.4$, is indicated by an arrow and a number above giving its magnitude; TIP is indicated by block rectangle.

These results indicate that the analyzed region is a seismic area where strong earthquakes with magnitude ≥ 5.4 can occur with a relevant frequency. Therefore a detailed study of the region, in order to predict the effects of the strong events in terms of maximum ground acceleration is very important, and can be used by civil engineers for retrofitting purposes and to design earthquake-resistant structures, to reduce damages and casualties.

2. Deterministic seismic zoning

The pilot example of the deterministic approach to seismic zoning, developed at the Istituto di Geodesia e Geofisica of the Università di Trieste (Costa et. al., 1993) for the whole Italian territory, in the framework of the activities of the GNDT (Gruppo Nazionale per la Difesa dai Terremoti, Consiglio Nazionale delle Ricerche) represents one of the most advanced results in this field.
Synthetic seismograms are constructed to model ground motion at the sites of interest, using knowledge of the physical process of earthquake generation and wave propagation in realistic media. In the first order zoning a database of seismograms covering the area of interest (at a regional scale) is computed, neglecting the effects of lateral heterogeneities. Synthetic seismograms are generated in a very efficient way by the modal summation technique for layered

anelastic structures (Panza 1985; Florsch et al. 1991), so it becomes 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.

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 (routinely at frequencies as high as 10 Hz) the Peak Ground Acceleration (PGA) or any other parameter relevant in seismic engineering, which can be extracted from the theoretical accelerations computed using the modal summation technique (Panza et al., 1985; Florsch et al. 1991). 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

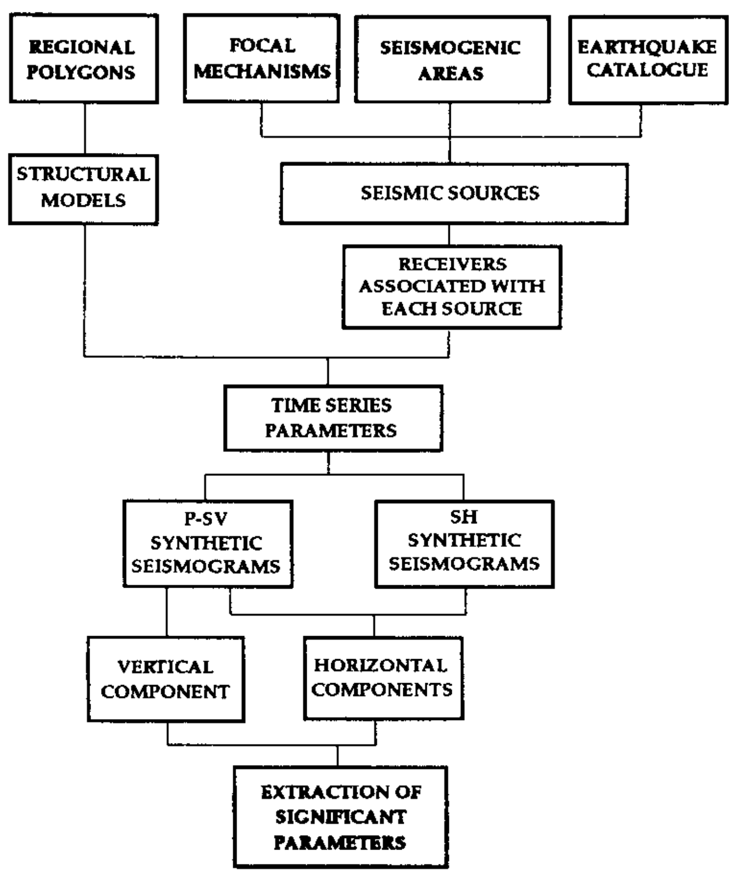

Fig.5. Flow chart of the deterministic procedure used for the estimation of seismic hazard.

easily the relevant parametric analyses. The flow-chart of the procedure is shown in Fig.5.

On the basis of lithospheric characteristics, determined by active and passive seismology (e.g. Italian Explosion Seismology Group and Institute of Geophysics, ETH, 1981; Miller et al., 1982), the territory is divided into several polygons and a layered structural model is associated with each polygon. The different layers are described by their thickness, density, P- and S-wave phase velocity and phase attenuation.

For the analysis of seismicity, unlike in the case of intermediate-term earthquake prediction, the Italian earthquake catalogue (PFGING) is used also in its historical part (starting from year 1000), since the completeness of the catalogue is not requested by the procedure. Only main shocks, shallower than 50 km, have been considered and the aftershocks have been identified with the algorithm suggested by Keilis-Borok and Rotwain (1990).

Seismic sources are grouped into homogeneous seismogenic areas, and for each group the representative focal mechanism is kept constant. The scalar seismic moment associated with each source is determined from the analysis of the maximum magnitude observed in the epicentral area. The spatial distribution of sources covers the seismogenic areas defined by the GNDT (GNDT, 1992) on the basis of seismological data and seismotectonic observations (Patacca et al., 1990; Meletti and Scandone, 1993). For the definition of the source mechanisms, the available fault-plane solutions grouped in a database (Suhadolc, 1990; Suhadolc et al., 1992) are used.

To derive the distribution of the maximum observed magnitude over the territory, the image of the seismicity given by the earthquake catalogue was discretised into cells and then smoothed using the procedure described in Costa et al. (1993). The map shown in Fig.6 is the result of the application of this method to the PFGING earthquake catalogue.

A seismic source modelled by a double-couple with zero moment is then placed at the centre of each cell. The orientation of the double couple is obtained from

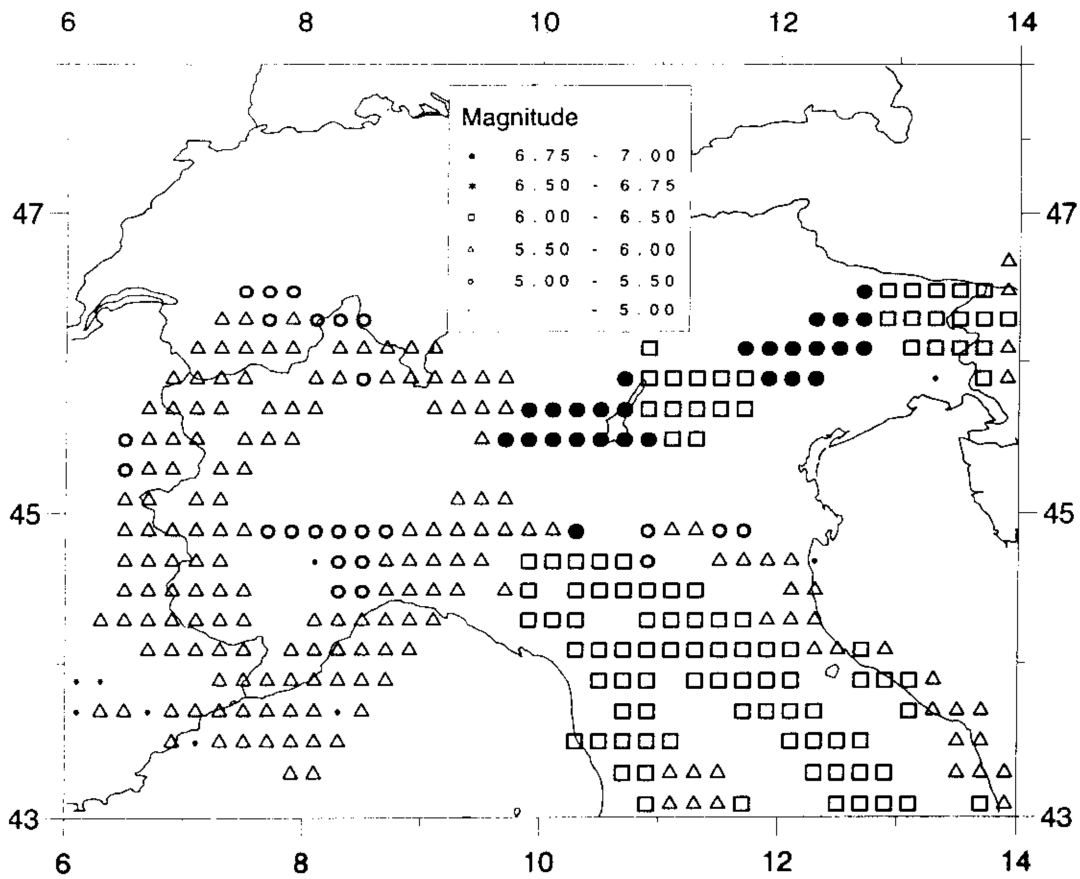

Fig.6. Discretised image of the seismicity for Northern Italy (0.2° x 0.2° cells). Only the cells belonging to seismogenic zones are plotted.

the database of the fault-plane solutions. For each seismogenic area, a representative focal mechanism is selected as the arithmetic average of the tensor elements of the available mechanisms, preserving the double-couple property. This procedure appears to be reasonable when the mechanisms to average are not too different, and this condition was satisfied for every seismogenic area.
In this example, the synthetic signals are computed for an upper frequency limit of 1Hz, and the point-source approximation is still acceptable. This is fully justified by practical considerations, since, for instance, several-story buildings have a peak response in the frequency range below 1 Hz (e.g. Manos et al., 1992) and by the fact that modern seismic design approaches and technologies, like seismic isolation, tend to lower the oscillations frequencies of buildings. When shorter periods are considered, it is no longer possible to neglect the finite

dimensions of the faults and the rupturing process at the source, with the consequent necessity for complete parametric analyses.

P-SV (radial and vertical components) and SH (transverse component) synthetic seismograms are originally computed for a seismic moment of 1 10^{-7} N m. The amplitudes are then properly scaled according to the (smoothed) magnitude associated with the cell of the source. For the moment-magnitude relation we chose the one given by Boore (1987), and to obtain the values which are valid for the cut-off frequency of 1 Hz we used the scaling law proposed by Gusev (1983). At each point of the grid of receivers the horizontal components are first rotated to a reference system common to the whole territory (North-South and East-West directions) and then the vector sum is computed. Among the parameters representative of the strong ground motion we have, for the moment, focused

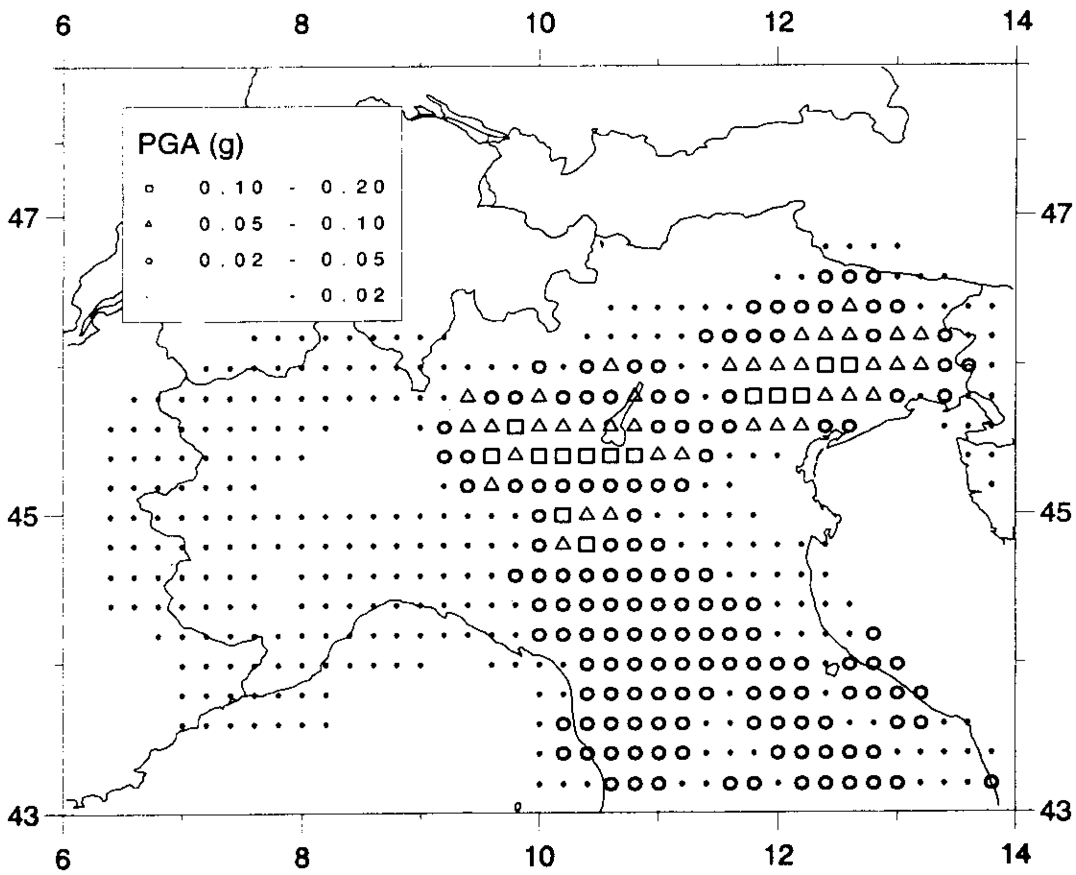

Fig.7. PGA distribution obtained in Northern Italy by means of the deterministic procedure based on the computation of synthetic seismograms.

our attention on Peak Ground Acceleration (PGA). Since we compute the complete time series we are not limited to this choice, and it is also possible to consider other parameters, like Arias (1970) intensity or other integral quantities that can be of interest in seismic engineering. Since recordings of many different sources are associated to each receiver but one single value is to be plotted on a map (Fig.7), only the maximum value of the analysed parameter is considered. Of course it is not possible to refine the results obtained with a first order zoning of the whole Italian territory by simply assuming a finer grid of receivers and possibly a higher cut-off 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. To model wave propagation in greater detail, the influence of lateral heterogeneities in the structural model must be taken into account in the computation of synthetic seismograms. So the results shown in Fig.7 can be considered the starting point for more accurate investigations, like for instance, the hybrid approach which combines the modal summation with the finite differences techniques, developed at the Istituto di Geodesia e Geofisica of the Università di Trieste (e.g. Iodice et al., 1992, Fäh et al., 1993).
However, an immediate use of the deterministic procedure is represented by the possibility of scaling the existing design response spectra, which are given for different lithological conditions, using the synthetic accelerations estimated around 1s as a reference level.

Conclusions

The results of the CN analysis of the TIPs in the Northern Italy indicate that the region, selected on the basis of seismotectonic considerations, is a seismic area where strong earthquakes with magnitude $M \geq M_0 = 5.4$ can occur with a relevant frequency. The two strong events, with magnitude $M \geq M_0$ that occurred in the region in the period 1960-1993 are predicted with a TIP duration of about 27% of the total time.

Once the seismic region, where a strong earthquake can occur, has been defined, the possible ground motion that might be caused by such an event can be estimated by using a deterministic procedure.

The traditional deterministic methods of first order seismic zoning have the main disadvantage of neglecting the existing models of earthquake sources and realistic wave propagation, and are generally based upon some empirical attenuation laws of seismic energy with distance. As a consequence, traditional deterministic methods can only lead to a kind of "post-event" zoning whose validity cannot be easily extrapolated in time and to different regions and which therefore must be considered obsolete. On the contrary, the method developed at the Istituto di Geodesia e Geofisica of the Università di Trieste, being based on the computation of realistic synthetic seismograms, makes it possible to take source and propagation effects into account.

The detailed modeling of ground motion, utilizing a huge amount of geological and geotechnical data, already available, is a powerful tool for the prevention aspects of Civil Defence. With the method described, which permits the computation of a wide set of time histories and spectral information corresponding to possible seismotectonic scenarios for different seismic sources and structural models, it is possible to obtain, at low cost and exploiting large quantities of already existing data, the definition of realistic seismic input to structures of interest. Such a data set can be very fruitfully used by civil engineers in the design of new seismo-resistant constructions and in the retrofitting of the existing ones.

References

Arias, A., 1970. A measure of earthquake intensity, in: Seismic design for nuclear power plants (Ed. R. Hansen), Cambridge, Massachussets.

Boore, D.M., 1987. The prediction of strong ground motion, in: Strong ground motion seismology (Eds. M.Ö. Erdik and M.N. Toksöz), D. Reidel Publishing Company, Dordrecht, 109-141.

Costa, G., Panza, G.F., Suhadolc, P. and Vaccari, F., 1993. Zoning of the Italian territory in terms of expected peak ground acceleration derived from complete synthetic seismograms. In: R. Cassinis, K. Helbig and G.F. Panza (Eds.), Geophysical Exploration in Areas of Complex Geology, II. J. Appl. Geophys., 30, 149-160.

Dal Piaz, G.V. and Polino, R., 1989. Evolution of the Alpine Tethys. In: A. Boriani, M. Bonafede, G.B. Piccardo and G.B. Vai (Eds.) The lithosphere in Italy, Accademia Nazionale dei Lincei, Atti dei Convegni Lincei, Roma, Italy, pp. 93-109.

Fäh, D., Suhadolc, P. and Panza, G.F., 1993. Variability of seismic ground motion in complex media: the Friuli area (Italy). In: R. Cassinis, K. Helbig and G.F. Panza (Eds.), Geophysical Exploration in Areas of Complex Geology, II , J. Appl. Geophys., 30, 131-148.

Florsch, N., Fäh, D., Suhadolc, P. and Panza, G.F., 1991. Complete synthetic seismograms for high-frequency multimode SH-waves, Pure and Applied Geophys., 136, 529-560.

Gabrielov, A.M., Dmitrieva, O.E., Keilis-Borok, V.I., Kosobokov, V.G., Kuznetsov, I.V., Levshina, T.A., Mirzoev, K.M., Molchan, G.M., Negmatullaev, S.Kh., Pisarenko, V.F., Prozorov, A.G., Rinehart, W., Rotwain, I.M., Shebalin, P.N., Shnirman, M.G., and Schreider, S.Yu., 1986. Algorithms of Long-Term Earthquakes' Prediction. International School for Research Oriented to Earthquake Prediction-Algorithms, Software and Data Handling (Lima, Perù, 1986).

GNDT, 1992. Convegno Nazionalé sul Modello Sismotettonico d'Italia. Milano, Italy, 25-26 May 1992.

Gusev, A.A., 1983. Descriptive statistical model of earthquake source radiation and its application to an estimation of short period strong motion, Geophys. J.R. Astron. Soc., 74, 787-800.

Iodice, C., Fäh, D., Suhadolc, P. and Panza, G.F., 1992. Un metodo generale per la zonazione sismica rapida ed accurata di grandi metropoli: applicazione alla città di Roma, Memorie dell'Accademia Nazionale dei Lincei, 3, 195-217.

Italian Explosion Seismology Group and Institute of Geophysics, ETH, Zürich, 1981. Crust and upper mantle structures in the Southern Alps from deep seismic sounding profiles (1977, 1978) and surface waves dispersion analysis. Boll. di Geof. teor. ed appl., 23, 297-330.

Keilis-Borok, V.I. and Rotwain, I.M., 1990. Diagnosis of Time of Increased Probability of strong earthquakes in different regions of the world: algorithm CN. Phys. Earth Planet. Int., 61, 57-72.

Keilis-Borok, V.I., Kuznetsov, I.V., Panza, G.F., Rotwain, I.M. and Costa, G., 1990. On intermediate-term earthquake prediction in Central Italy, Pageoph., 134, 79-92.

Manos, G.C. and Demosthenous, M., 1992. Design of R.C. structures according to the Greek Seismic Code Provisions. Bull. of IISEE, 26, 559-578.

Meletti, C. and Scandone, P.: Seismotectonic analysis. Basic tool for hazard evaluations, Proceedings of the Europrotech Conference, Udine, Italy, 6-8 May 1993, in press.

Miller, H., Müller, St. and Perrier, G., 1982. Structure and dynamics of the Alps: a geophysical inventory. In: H. Berkhemer and U. Hsü (Editors) Alpine-Mediterranean Geodynamics, Geophys. Ser. A.G.U., 7, 175-203.

Mueller, S., 1982. Deep structure and recent dynamics in the Alps, in: K.J. Hsu (Ed.) Mountain building processes, Academic Press, 181-199.

Panza, G. F., 1985. Synthetic seismograms: The Rayleigh waves modal summation, J. Geophysics, 58, 125-145.

Patacca, E., Sartori, R. and Scandone, P.,1990. Tyrrhenian basin and Apenninic arcs: kinematic relations since late Tortonian times, Mem. Soc. Geol. It., 45, 425-451.

Pavoni, N., Ahjos, T., Freeman, R., Gregersen, S., Langer, H., Leydecker, G., Roth, Ph., Suhadolc, P. and Uski, M., 1992. Seismicity and focal mechanisms. In R. Freeman and S. Mueller (Eds.), A continent revealed - the Europen geotraverse: atlas of compiled data, Cambridge University Press, Cambridge, pp. 14-19.

Suhadolc, P., 1990. Fault-plane solutions and seismicity around the EGT southern segment. In: R. Freeman and St. Müller (Eds.), Sixth EGT Workshop: Data Compilations and Synoptic Interpretation, European Science Foundation, Strasbourg 1990, 371-382.

Suhadolc, P., Panza, G.F., Marson, I., Costa, G. and Vaccari, F., 1992. Analisi della sismicità e meccanismi focali nell'area italiana, Atti del Convegno del Gruppo Nazionale per la Difesa dai Terremoti, Pisa 1990, 1, 157-168.