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PATTERN RECOGNITION METHODOLOGIES AND DETERMINISTIC EVALUATION OF SEISMIC HAZARD: A STRATEGY TO INCREASE EARTHQUAKE PREPAREDNESS

Antonella Peresan[1]
Dipartimento di Scienze della Terra, Università degli Studi di Trieste,
Via E. Weiss 4, 34127 Trieste, Italy,

Giuliano F. Panza
Dipartimento di Scienze della Terra, Università degli Studi di Trieste,
Via E. Weiss 4, 34127 Trieste, Italy
and
The Abdus Salam International Centre for Theoretical Physics, SAND Group, Trieste, Italy,

Alexander I. Gorshkov
International Institute of Earthquake Prediction Theory and
Mathematical Geophysics, Russian Academy of Sciences, Moscow, Russian Federation
and
The Abdus Salam International Centre for Theoretical Physics, SAND Group, Trieste, Italy

and

Abdelkrim Aoudia
The Abdus Salam International Centre for Theoretical Physics, SAND Group, Trieste, Italy.

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[1] E-mail: anto@dst.univ.trieste.it

Abstract

Several algorithms, structured according to a general pattern-recognition scheme, have been developed for the space-time identification of strong events. Currently, two of such algorithms are applied to the Italian territory, one for the recognition of earthquake-prone areas and the other, namely CN algorithm, for earthquake prediction purposes. These procedures can be viewed as independent experts, hence they can be combined to better constrain the alerted seismogenic area.

We examine here the possibility to integrate CN intermediate-term medium-range earthquake predictions, pattern recognition of earthquake-prone areas and deterministic hazard maps, in order to associate CN Times of Increased Probability (TIPs) to a set of appropriate scenarios of ground motion. The advantage of this procedure mainly consists in the time information provided by predictions, useful to increase preparedness of safety measures and to indicate a priority for detailed seismic risk studies to be performed at a local scale.

Introduction

Several algorithms, structured according to a general pattern-recognition scheme, have been developed for the space-time identification of strong events. Currently, two of such algorithms are applied to the Italian territory, one for the recognition of earthquake prone areas and the other, namely CN algorithm, for earthquake prediction purposes. These procedures are independent experts, hence they can be combined to try and reduce the space uncertainty of predictions.

The algorithm for the recognition of earthquake prone areas, based on the pattern-recognition technique, is used to identify the sites where strong earthquakes are likely to occur, independently from seismicity information. This method is based on the assumption that strong events nucleate at the nodes (GELFAND *et al.*, 1972; GABRIELOV *et al.*, 1996), specific structures that are formed at the intersections of lineaments. Lineaments are identified by the Morphostructural Zonation (MZS) Method (ALEXEEVSKAYA *et al.*, 1977), that delineates a hierarchical block structure of the studied region, using tectonic and geological data, with special care to topography. In Italy, this study has provided new information on the geodynamic framework of the peninsula and it has allowed us to identify the sites where stronger events, with magnitude larger or equal to 6.0 or 6.5, may occur (GORSHKOV *et al.*, 2001).

The algorithm CN (KEILIS-BOROK & ROTWAIN, 1990) indicates the probable occurrence of strong events, inside a given region and time window, on the basis of a quantitative analysis of the seismic sequence. A regionalization, strictly based on the seismotectonic zoning and taking into account the main geodynamic features of the Italian area, is used for the application of the algorithm CN (PERESAN et. al, 1999).

We examine the possibility to combine CN intermediate-term medium-range earthquake predictions, pattern recognition of earthquake-prone areas and deterministic hazard procedure, in order to associate CN Times of Increased Probability (TIPs) to a set of appropriate scenarios of hazard. The effectiveness of the different methodologies, on which the integrated procedure relies, appears substantiated by the results obtained from their application in various regions of the world.

The procedure for deterministic seismic hazard assessment, developed by COSTA *et al.* (1993), is based on the possibility to compute synthetic seismograms; the expected ground motion can be modelled at any desired point, starting from the available information about seismic sources and regional structural models (PANZA *et al.*, 1999). Here, according to the flow chart shown in figure 1, the subset of sources included in the CN region is selected from the available databases, produced for seismic hazard estimations, and it is used as seismic input for the realistic modelling of ground motion. Hence, a TIP can be associated to the scenario of ground motion identified for the sources included in the CN region. In a second step, a set of scenarios of hazard, corresponding to the earthquake-prone areas within the CN region, as inferred by MZS and pattern recognition, are considered for the possible strongest events, with magnitude larger or equal to 6.0 and 6.5, respectively.

The association of deterministic hazard and recognition of earthquake prone areas appears especially useful in areas where historical and instrumental information is scarce. In such conditions it represents an effective way to estimate the seismic hazard, more realistic than that based on the unavoidably incomplete observations. Furthermore, the procedure for seismic hazard assessment based on the computation of synthetic seismograms provides a realistic modelling of ground motion and not only an upper bound for the maximum possible ground shaking. The seismic input, defined by means of complete waveforms modelling, can be used to perform detailed studies of the effects of the expected ground motion on the relevant man made structures. In fact, complete seismograms are necessary for engineering dynamic analysis, in order to compute the full non-linear response of the structures (FIELD *et al.*, 2000).

The advantage of the integrated procedure proposed in this work mainly consists in the time information provided by predictions, useful to increase preparedness of safety measures and to indicate a priority for local seismic risk studies.

Intermediate-term CN predictions

The algorithm CN (KEILIS-BOROK & ROTWAIN, 1990) is structured according to a pattern recognition scheme to allow a diagnosis of the Times of Increased Probability (TIPs) for the occurrence of strong earthquakes. It indicates the probable occurrence, inside a given region and time window, of events with magnitude greater than a fixed threshold M_0, on the basis of a quantitative analysis of the seismic flow. The quantification of the seismicity patterns is obtained through a set of empirical functions of time, evaluated on the sequence of the events which occurred in the analysed region, and describing the level of seismic activity, seismic quiescence and space-time clustering of events. Symptoms considered are "non-Earth-specific" (KEILIS-BOROK, 1996), and can be observed in many non-linear systems before collapse; in our case the non-linear system corresponds to the system of active faults and the small earthquakes are the source of perturbation of the system. Hence, CN makes use of the information given by small and moderate earthquakes, having quite good statistics within the delimited region, to predict the stronger earthquakes, which are rare events.

CN predictions are characterised by a time uncertainty of the order of years (intermediate-term predictions), since the duration of TIPs ranges from a few months to a few years, and by a space uncertainty of hundreds of kilometres (medium-range predictions), corresponding to a whole single monitored region. According to CN, when a TIP is declared, the strong earthquake could occur in any point of the alerted area; hence regions defined should be as small as possible. Nevertheless, the algorithm is based on precursors that may be hosted in an area with linear dimensions much larger than the length of the expected source (KEILIS-BOROK, 1996). Algorithms have been developed to reduce the spatial uncertainty of predictions, making use of the information carried by lower magnitude seismic activity (KOSSOBOKOV *et al.,* 1999), but their applicability is limited by the difficulty to keep a high level of detection.

The properties of the algorithm CN permit its widespread testing, that is ongoing in more than twenty regions world wide. From the global retrospective tests performed, it turns out that the algorithm CN is able to indicate the occurrence of about 80% of the strong events, with TIPs occupying, on average, about 30% of the total time (KEILIS-BOROK, 1996). The tests in advance predictions, carried out during the period 1983-1998, allowed a first statistical evaluation of CN predictions. The significance level of the obtained results, estimated around 95% (ROTWAIN & NOVIKOVA, 1999), seem to substantiate the predictive capability of the algorithm.

The simple definition of alarm periods as "times of increased probability with respect to normal conditions", which are not associated to a specific value of probability for the occurrence of a strong earthquake, is imposed by the fact that any attempt to quantify precisely the probability increase during TIPs would require several a priori assumptions (i.e. Poissonian recurrence, independence of TIPs and functions, etc.). Most of these assumptions would be poorly constrained by the available observations and hence below any critics. An approximate estimate of the probability for an incumbent strong earthquake during a declared TIP (i.e. the probability of a TIP to be a success), however, may be given based on very simple arguments. Taking into account the accuracy of CN predictions in the global tests (about 80% of the time is correctly recognised) and the low rate of occurrence of the strong earthquakes (MATTHEWS, 1996 and 1997), it is possible to estimate the conditional probability for a TIP to be about 40%. Hence, as shown by PERESAN *et al.,* (1999) a declared TIP has approximately 60% of probability to be a false alarm, while if no TIP is indicated, at 96% probability no strong earthquake will occur.

The algorithm CN is applied in Italy since 1990 (KEILIS-BOROK *et al.,* 1990). A regionalization (fig. 2), strictly following the seismotectonic zoning (MELETTI *et al.,* 2000) and taking into account the main geodynamic features of the Italian area, is currently used for the application of the algorithm. The forward prediction is performed every two months, using the CCI1996 (PERESAN *et al.,* 1997) catalogue updated with the NEIC Preliminary Determinations of Epicenters (PERESAN & ROTWAIN, 1998). The thresholds M_0 for the selection of the events to be predicted are fixed, according to their average return period, to $M_0 = 5.4$ for the Northern region and to $M_0 = 5.6$ for the Central and Southern regions. Details about CN application in Italy can be found in PERESAN *et al.,* (1999). Results of predictions are routinely provided since January 1998; the results updated to May, 1 2001, are shown in figure 3.

Pattern recognition of earthquake prone areas

The methodology developed by GELFAND *et al.* (1972, 1976) for the recognition of earthquake-prone areas has been succesfully tested in many different regions of the world (e.g GORSHKOV *et al.*, 2000 and references therein).

The methodology is based on the assumption that strong events are likely to occur at the nodes, specific structures that are formed around intersections of lineaments. According to this technique, a hierarchical block structure of the studied region is delineated, independently from seismicity information, by means of the MZS (ALEXEEVSKAYA *et al.*, 1977). The territory is thus divided into a system of blocks with decreasing rank (mountain countries, megablocks and blocks), separated by boundary zones, called lineaments. The lineaments are identified using tectonic and geological data, with special care to present-day topography. The rank of the lineaments depends on the rank of the delimited structure. Lineaments can be distinguished into longitudinal and transverse, depending on their orientation, respectively parallel or intersecting the regional predominant trend of topography and tectonic structures. The nodes are formed at the intersections of lineaments. Among the defined nodes, those prone to strong earthquakes are then identified by pattern recognition on the basis of the parameters characterising indirectly the intensity of neotectonic movements and fragmentation of the crust at nodes (e.g. elevation and its variations in mountain belts and watershed areas; orientation and density of linear topographic features; type and density of drainage pattern).

A revision of the earthquake prone areas recognised by CAPUTO *et al.* (1980) has been performed by GORSHKOV *et al.* (2001) in peninsular Italy and Sicily, updating on a more detailed scale, the identification of the sites where events with magnitude larger or equal to 6.0 or 6.5 may occur.

The morphostructural map of peninsular Italy and Sicily (fig. 4) has been compiled (GORSHKOV *et al.,* 2001) at the scale of 1:1,000,000 by the combined analysis of topographic, tectonic, geological maps and satellite photos. The large-scale tectonic domains that compose the region have been defined as first-rank areas and correspond to the Apennines, Calabria and Sicily, which differ in present-day topography (physiography), tectonic style, lithology (stratigraphy), and geological history. These areas are bordered by first-rank lineaments corresponding to the prominent faults. The first-rank units are divided into megablocks, which differ mainly in the topography; their boundaries (second-rank lineaments) mark zones where the topography changes sharply and are traced along rectilinear topographic features and partially along the faults. Third-rank lineaments bounding blocks, control local changes of elevation and/or orientation of mountain ranges.

For recognition purposes, the nodes have been defined as circles of radius R=25 km surrounding each point of intersection of lineaments (GORSHKOV *et al.*, 2001). Such node dimension is comparable with the nodes observed in the Pamirs-Tien Shan region (RANTSMAN, 1979), with the size of the earthquake source for the magnitude range considered in this work (WELLS & COPPERSMITH, 1994) and with the smoothing window used in the deterministic hazard computation (COSTA *et al.,* 1993).

Under the assumption that the future strong events will occur at the nodes, the seismic potential of each node has been evaluated, by the pattern recognition technique, for two magnitude thresholds, $M \geq 6.0$ and $M \geq 6.5$.

The results of the classification of the nodes for both magnitude thresholds are in good agreement with the recorded seismicity, in fact almost all (more than 90%) of the past strong earthquakes occurred at the recognised nodes (GORSHKOV *et al.*, 2001). The nodes prone to $M \geq 6.5$ events are shown in figure 4.

Integrated Deterministic Seismic Hazard

The deterministic hazard modelling (COSTA *et al.,* 1993) employed in this integrated approach allows for a first-order seismic hazard mapping, based on the computation of complete synthetic seismograms with parameters defined from a wide geophysical and geological data set. The procedure uses regional polygons that limit the area of validity of the different structural models and of the parameters, such as focal mechanisms, seismogenic areas and earthquake catalogues, necessary to characterise the seismic sources and the anelastic properties of the medium. In this analysis, performed at a regional scale, local site effects are clearly neglected.

The steps of the deterministic procedure are summarised below:

1. seismic sources are grouped into homogeneous seismogenic zones and for each group the representative focal mechanism is assigned;
2. the scalar seismic moment associated with each source is estimated considering the maximum observed magnitudes in the epicentral area, eventually integrated with other available information on the seismic potential of active faults;
3. a database of synthetic seismograms is computed by modal summation (PANZA, 1985; FLORSCH *et al.,* 1991), to model ground motion making use of the available knowledge of the earthquake generation and wave propagation processes;
4. seismic hazard maps are compiled, considering maximum displacement, velocity, design ground acceleration (DGA), or any other parameter that can be extracted from the complete synthetic seismograms, which blend information from geology, historical seismicity and observational seismology.

Thus, given a set of expected sources and the average properties of the structural model, a zoning can be performed at a regional scale, identifying areas prone to the heaviest seismic input. This procedure led to theoretical peak values estimates (PANZA *et al.,* 1996) for the Umbria-Marche region that are well in agreement with the peak values observed during the 1997 earthquake sequence (AOUDIA *et al.,* 2000).

In the present study we make use of such methodology, in order to generate scenarios of expected ground motion that can be considered, in case of a declared TIP, to increase earthquake preparedness. According to the flow chart shown in figure 1, the space information provided by CN can be used directly with the deterministic hazard procedure, to associate to each CN region a hazard scenario (space: level 1). Local scenarios (space: level 2) can be computed for each earthquake prone node capable of the strongest events, within a given CN region. The obtained maps (space: levels 1 and 2) provide a useful tool for decision-makers in order to optimise safety measures.

CN for deteministic hazard

The algorithm CN indicates if an event, with magnitude larger or equal than a fixed threshold M_0, is likely to occur within a given region and time interval. In order to describe what should be expected, in terms of ground shaking, when a TIP is declared, we apply the procedure for the deterministic evaluation of seismic hazard following closely PANZA *et al.* (1999), considering only the set of possible sources included in the CN region.

The grouping of sources and the definition of the representative focal mechanism is provided by the seismogenic zones independently defined by GNDT (CORSANEGO *et al.,* 1997).

To derive the distribution of the maximum observed magnitudes, we consider the catalogue NT4.1 (CAMASSI & STUCCHI, 1996). Since each CN region represents an individual seismic domain, as assumed by the regionalization based on the seismotectonic model, only the sub-catalogue of events which occurred inside the region is considered. The seismicity is then discretized into 0.2°x0.2° cells, assigning to each cell the maximum magnitude M recorded within it; a smoothing procedure (PANZA *et al.,* 1999) is then applied to account for the spatial uncertainty and for source dimensions. Only the cells located within a seismogenic zone and within the CN region are retained, and a double-couple point source, with a representative focal mechanism, is placed at the centre of each cell. If the assigned magnitude M is lower than the CN threshold M_0, we put $M = M_0$.

Synthetic seismograms are then computed with receivers placed at the nodes of a grid with step 0.2°x0.2°, covering the studied area; at each receiver the sum vector of the radial, vertical and transverse components of ground motion is computed. To reduce the amount of computations, the maximum source-receiver distance is set to 25, 50 and 90 km, depending on the magnitude associated with the source ($M < 6, 6 \leq M < 7$ and $M \geq 7$, respectively). The lateral heterogeneity of the medium is taken into account by making use of different regional structural models: each synthetic seismogram is computed considering the average structural model associated to the regional polygon that includes the receiver. More details about the procedure can be found in PANZA *et al.* (1999).

Each receiver is thus associated to recordings of many different sources and any parameter of interest can be extracted from such complete time series, therefore different maps can be produced. To provide an example of the possible scenarios associated with CN TIPs, the maps of horizontal velocities produced for the three

Italian regions are shown in figure 5. The corresponding maximum intensities at some Italian cities along the monitored regions, are then estimated (Table I), considering the relations among the parameters of ground motion and the ISG maximum observed intensities (MOLIN *et al.,* 1996), derived by PANZA *et al.* (1997).

The integrated CN-deterministic hazard approach allows us to observe, for example, that a TIP in the Northern region mainly concerns the north-eastern part of Italy. Meanwhile, comparing fig. 5a and fig. 5b, it is possible to notice that along the coast of the Adriatic sea, between latitudes 40°N and 42°N, the highest hazard is associated to alarms in the Central region. This is mainly due to the lower level of the past seismic activity in such part of the compressive belt composing the Northern region, with respect to the higher magnitude seismicity associated with the extensional belt in the Central region.

Earthquake-prone areas for deterministic hazard

Scenarios associated with CN regions provide information about the whole area which may be concerned by a declared TIP; nevertheless a single earthquake does not generate such an extended damage, nor every point within the alerted region is capable to generate the strongest events ($M \geq 6.0$ or $M \geq 6.5$). Since the space uncertainty of CN predictions is intrinsically quite large, an attempt to better constrain the expected sources is done through the pattern recognition of earthquake-prone areas. When a TIP is declared, the strongest events should nucleate at the identified nodes inside the alerted region; hence, it is possible to associate each of these nodes (fig. 4), corresponding to circles with radius R=25 km (GORSHKOV *et al.*, 2001), to a scenario with dimensions comparable to the area which may be realistically affected by a single strong event.

To provide an example of such pattern recognition and deterministic hazard integrated approach, we consider the particular case of Central region and the nodes prone to earthquakes with $M \geq 6.5$, that have been identified by GORSHKOV *et al.* (2001) for peninsular Italy (fig. 4). The procedure is the same we followed in the previous section, except that only the subset of sources (discretized into 0.2°x0.2° cells) included in a node are retained now, considering each circle separately. Moreover if the magnitude M assigned to a representative source, based on historical data, is lower than the magnitude expected according to the seismogenic potential indicated by the morphostructural analysis, then we set $M = 6.5$. The pattern recognition of earthquake prone areas, however, does not provide an upper limit for the magnitude to be expected at a given node. Hence, special attention should be paid to those areas identified as prone to strong earthquakes, but characterised only by moderate seismic activity in historical time, in order to assess their effective maximum seismogenic potential.

A set of scenarios is then obtained through the realistic modelling of ground motion, for the earthquake-prone areas within the CN Central region (fig. 6d). From these scenarios it is possible to select, for example, those associated with places of special interest (e.g. large cities or some special industrial areas). Here we provide the maps of horizontal velocities for the nodes giving the maximum ground motion in the cities of Assisi, Roma and Napoli (fig. 6). The maximum intensities, as obtained from the regression (PANZA *et al.,* 1997) of estimated velocity, displacement and DGA, are provided in Table II. The observed maximum intensities drawn from ISG data are reported for comparison.

Apart from Roma and Napoli, which are the largest cities in the study area, we consider the case of Assisi since the corresponding node hosted at least three strong earthquakes with $M \geq 6.0$ in the past millennium (M=6.3 in 1279 and M=6.1 in 1832, according to BOSCHI *et al.,* 1995) and the most recent one which occurred in 1997 (M=6.0). The synthetic scenario appears reasonably comparable with the available macroseismic observations and experimental strong motion records (AOUDIA *et al.,* 2000); from Table II we can observe that the computed intensity can be slightly higher than the observed one, and that the city is surrounded by a large number of nodes.

The scenarios associated to the cities of Roma and Napoli (fig. 6b, 6c) involve a wider area than that associated to Assisi, according to the large magnitudes reported for this part of the Italian peninsula.

Conclusions

In this work we provided an example showing how different methodologies can be integrated, blending together the available information in a set of realistic scenarios, to supply a useful tool for decision-makers in order to increase earthquake preparedness.

The retrospective analysis of the case of the Umbria-Marche earthquake, which occurred in Central Italy on September, 26 1997, seems to support the adequacy of the proposed procedure. According to CN, the M=6.0 event was preceded by a TIP declared for the Central region (fig. 3b). Furthermore, the epicentre is localised within one of the nodes recognised to be prone to earthquakes with both $M \geq 6.0$ and $M \geq 6.5$. Finally, the scenario associated to the corresponding node, by the deterministic hazard procedure, appears reasonably comparable with the experimental strong motion records and the available macroseismic observations (AOUDIA *et al.,* 2000).

Deterministic hazard and recognition of earthquake prone areas procedures are especially useful as a mean of prevention in areas that have not yet been struck, but are potentially prone to earthquakes. In fact, they are based on a wide geophysical and geological data set, as well as on the current knowledge of the physical process of earthquake generation and wave propagation in realistic anelastic media, and not only on the available macroseismic observations. Moreover, the procedure for seismic hazard assessment based on the computation of synthetic seismograms provide a realistic modelling of ground motion instead of a less specific upper bound for the maximum possible ground shaking. According to FIELD *et al.*, (2000), "waveform modelling represents our best hope for making more accurate estimates of ground motion at a site" and "is also in line with the trend toward dynamic analysis in the engineering community".

The advantage of the proposed integrated deterministic hazard procedure consists in the time information provided by predictions, useful to increase preparedness of safety measures and to indicate a priority for detailed seismic risk studies to be performed on a smaller scale.

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City	CN region	Imax (observed)	Imax(computed)		
			Displacement	Velocity	DGA
Trieste	**north**	VII	VI	VII	VI
Bologna	**north**, centre	VIII	VIII	VIII	IX
Assisi	**centre**	VIII	VIII	IX	IX
Firenze	**centre**	VIII	VII	VIII	VIII
Roma	**centre**	VIII	IX	VIII	IX
Napoli	**centre**, south	VIII	X	IX	IX
Messina	**south**	X	X	X	X

Tab. I - Maximum intensities at some cities along the CN monitored area (fig. 5) estimated, using the relations derived by PANZA *et al.,* (1997) for the parameters of ground motion and the ISG observed intensities (MOLIN *et al.,* 1996). The CN region providing the maximum ground shaking is evidenced in bold. Design Ground Acceleration (DGA) has been obtained using the design spectra of EC8 for soil A (EUROCODICE 8, 1993).

City	Number of nodes	Imax (observed)	Imax(computed)		
			Displacement	Velocity	DGA
Assisi	9	VIII	VIII	IX	IX
Roma	5	VIII	IX	IX	IX
Napoli	3	VIII	X	IX	IX

Tab. II - Maximum intensities at some cities in Central Italy (fig. 6), corresponding to the nodes prone to earthquakes with $M \geq 6.5$, and maximum observed intensity from ISG (MOLIN *et al.,* 1996). Only the scenarios for the nodes providing the maximum ground shaking are considered and the number of nodes, which may interest each city, is indicated.

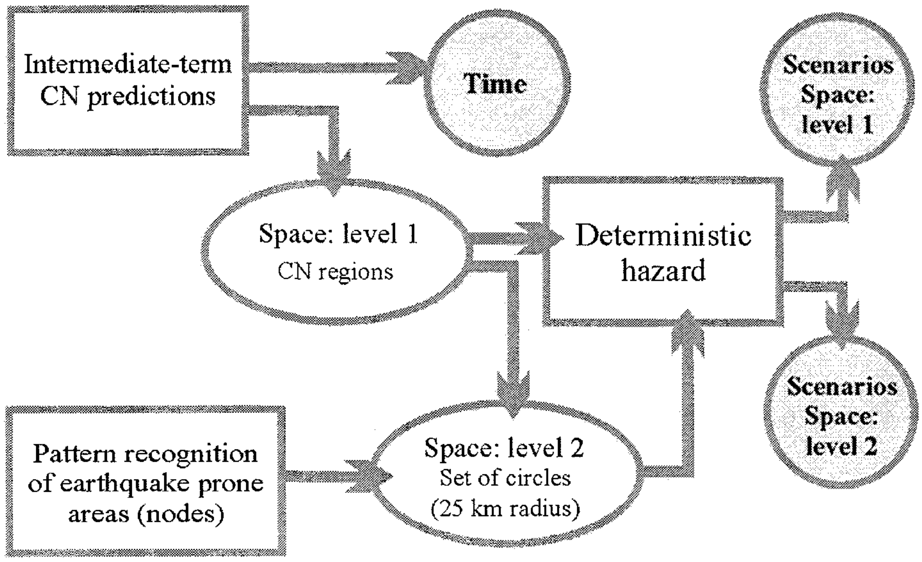

Fig. 1 - Flow chart of the proposed procedure: CN+deterministic hazard → Scenarios (space level 1); CN+pattern recognition+deterministic hazard → Scenarios (space level 2). The information provided by such integrated procedure is given in the grey circles.

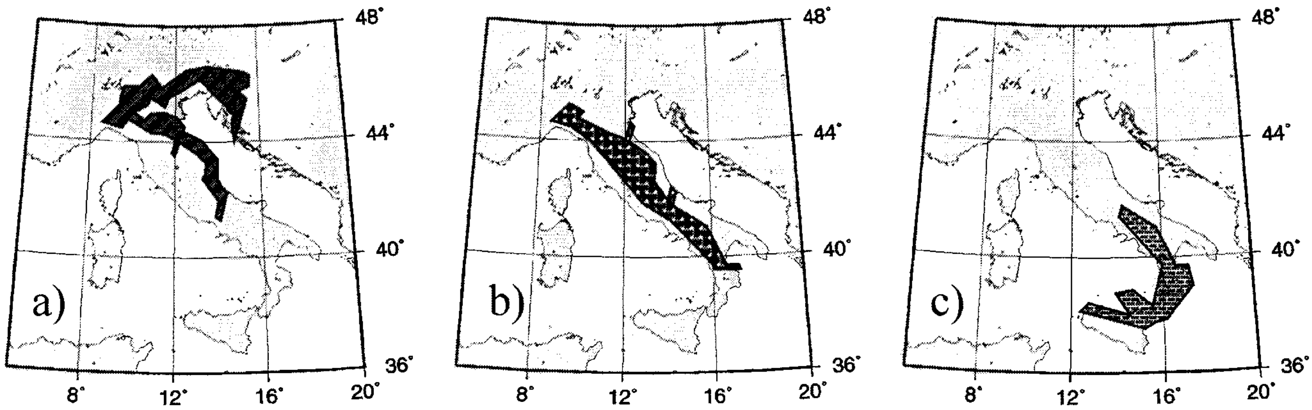

Fig. 2 - Regionalization defined, on the basis of the seismotectonic model, for CN application to the Italian territory: a) Northern Region; b) Central Region; c) Southern Region (PERESAN *et al.,* 1999).

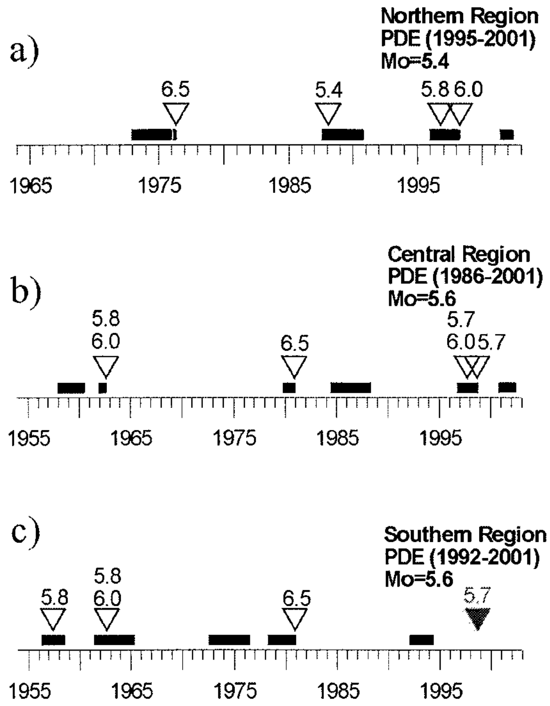

Fig. 3 - Diagrams of the Time of Increased Probability (TIPs) obtained for the three Italian regions in the monitoring of seismicity (updated: May, 1 2001). Black boxes represent the periods of alarm, while a triangle with a number above indicates the occurrence of a strong event together with its magnitude. Failures to predict are indicated by full grey triangles. The catalogue used for the monitoring is the CCI1996 (PERESAN *et al.,* 1997), updated with the Preliminary Determinations of Epicenters (PDE) from NEIC (PERESAN & ROTWAIN, 1998) during the period indicated in brackets.

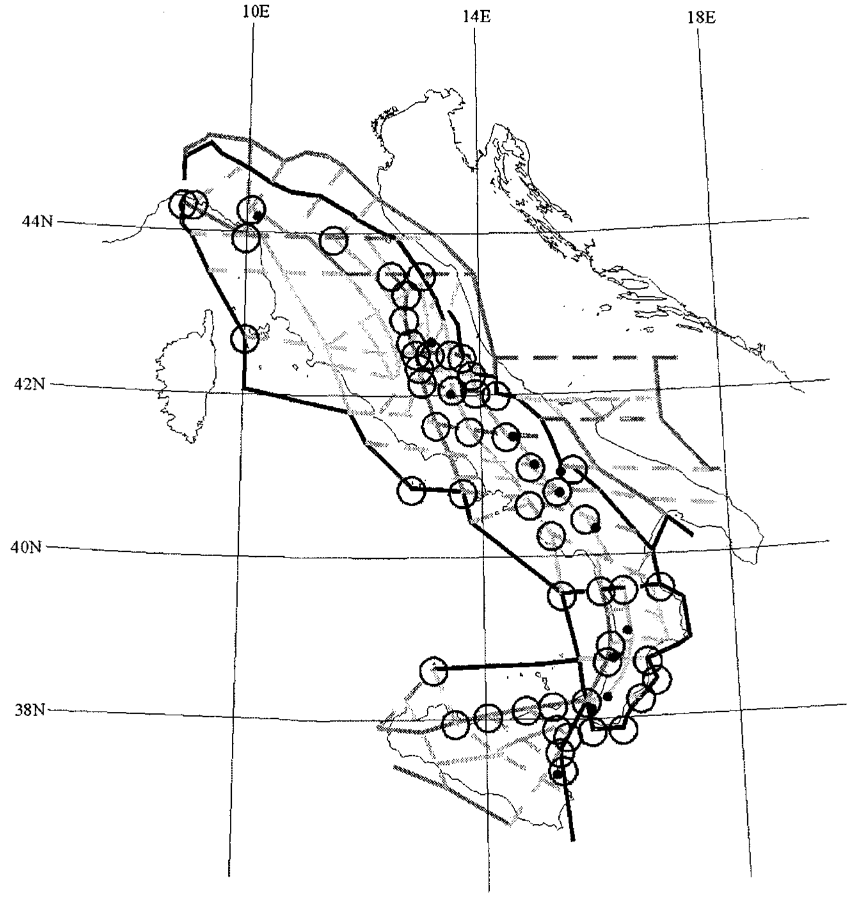

Fig. 4 - Morphostructural map of peninsular Italy and Sicily. Black lines are the lineaments of the first rank, dark grey lines are the lineaments of the second rank, light grey lines are the lineaments of the third rank; continuous lines are the longitudinal lineaments, discontinuous ones are the transverse lineaments. Circles indicate the nodes identified as prone to earthquakes with $M \geq 6.5$; the black dots denote the epicentres of the events with $M \geq 6.5$ reported in the considered catalogue (from GORSHKOV *et al.*, 2001).

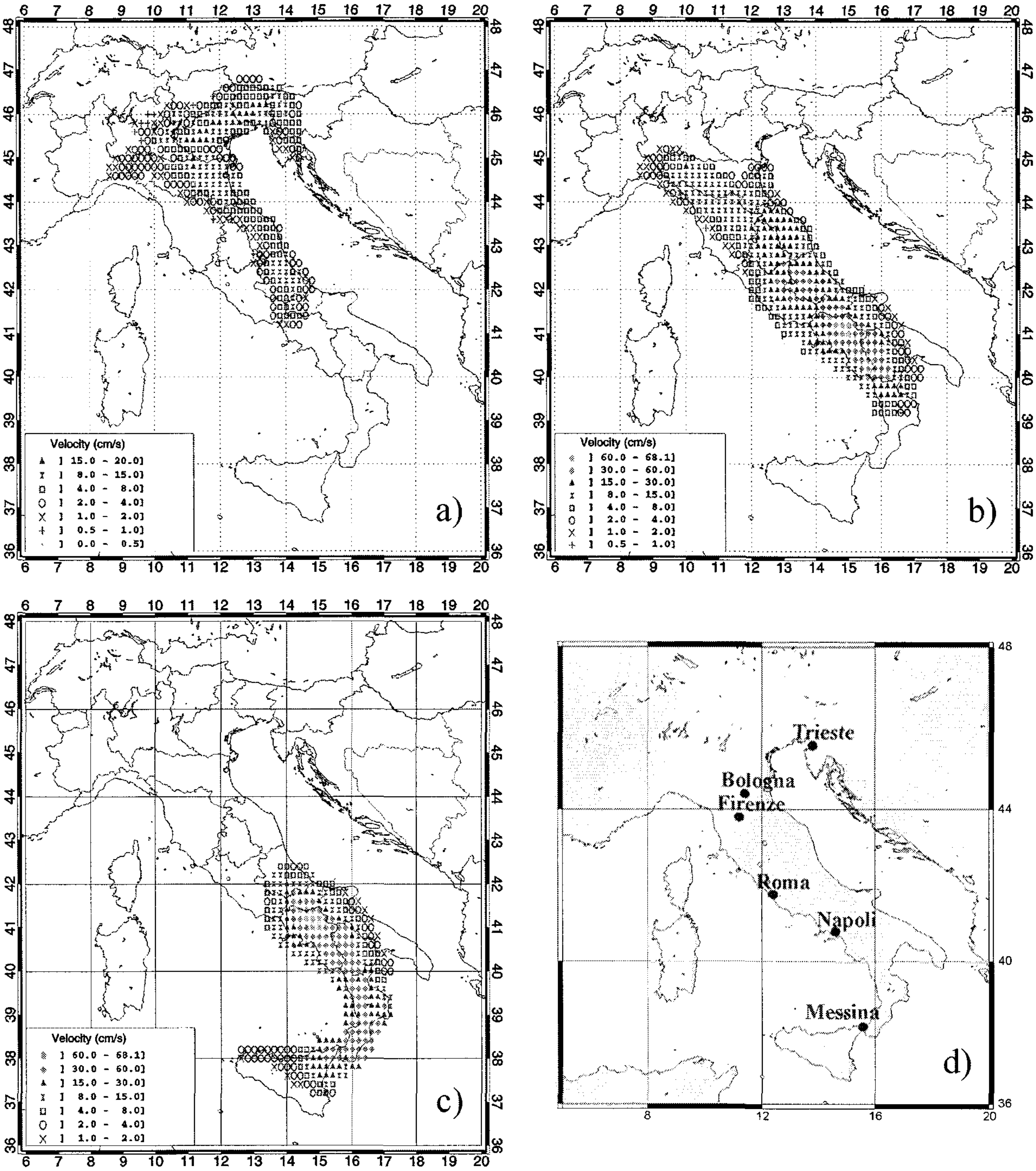

Fig. 5 - Maps of horizontal velocities computed, according to PANZA *et al.* (1999), for the a) Northern, b) Central and c) Southern regions. d) Map of the cities considered in Table I.

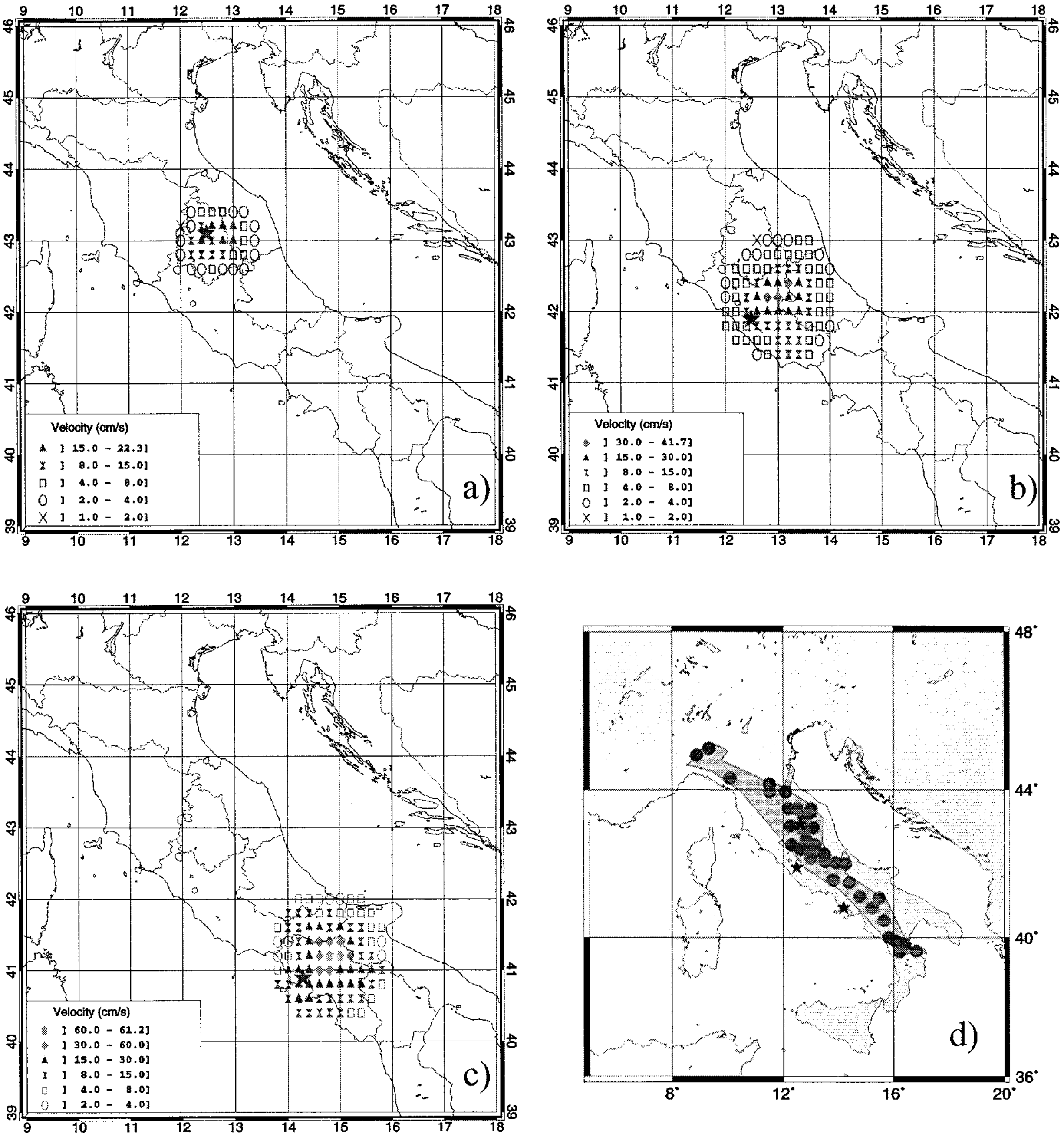

Fig. 6 - Maps of horizontal velocities generated for the nodes closest to the cities of a) Assisi, b) Rome and c) Naples and d) Map of the nodes prone to earthquakes with $M \geq 6.0$ (light gray) or $M \geq 6.5$ (dark gray), within the Central region. Cities are indicated by stars.