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PATTERN RECOGNITION TECHNIQUES AND NEO-DETERMINISTIC SEISMIC HAZARD: TIME DEPENDENT SCENARIOS FOR NORTH-EASTERN ITALY

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Abstract

An integrated neo-deterministic approach to seismic hazard assessment has been developed that combines different pattern recognition techniques, designed for the space-time identification of strong earthquakes, with algorithms for the realistic modeling of seismic ground motion. The integrated approach allows for a time dependent definition of the seismic input, through the routine updating of earthquake predictions. The scenarios of expected ground motion, associated with the alarmed areas, are defined by means of full waveform modeling. A set of neo-deterministic scenarios of ground motion is defined at regional and local scale, thus providing a prioritization tool for timely prevention and mitigation actions.

Constraints about the space and time of occurrence of the impending strong earthquakes are provided by three formally defined and globally tested algorithms, which have been developed according to a pattern recognition scheme. Two algorithms, namely CN and M8, are routinely used for intermediate-term middle-range earthquake predictions, while a third algorithm allows for the identification of the areas prone to large events. These independent procedures have been combined to better constrain the alarmed area. The pattern recognition of earthquake-prone areas does not belong to the family of earthquake prediction algorithms since it does not provide any information about the time of occurrence of the expected earthquakes. Nevertheless, it can be considered as the term-less zero-approximation, which restrains the alerted areas (e.g. defined by CN or M8) to the more precise location of large events.

Italy is the only region of moderate seismic activity where the two different prediction algorithms CN and M8S (i.e. a spatially stabilized variant of M8) are applied simultaneously and a real-time test of predictions, for earthquakes with magnitude larger than 5.4, is ongoing since 2003. The application of the CN to the Adriatic region (s.l.), which is relevant for seismic hazard assessment in the North-Eastern part of the Italian territory, is also discussed. Examples of neo-deterministic scenarios are provided, at regional and local scale and for the cities of Trieste and Nimis (Friuli Venezia Giulia region), where the knowledge of the local geological conditions permitted a detailed evaluation of the expected ground motion.
1. Introduction

The vulnerability of mankind to catastrophic earthquakes and related disasters keeps increasing along with understanding the role and need for effective prevention strategies. A strategy for the mitigation of earthquakes impact, in fact, should be oriented to cost effective preventive measures, aimed at creating knowledge-based hazard resilient public assets, rather than to highly expensive post-disaster rescue and relief operations, that currently prevail in many countries. Time dependent hazard scenarios, by providing basic knowledge of expected earthquake occurrence (location, time and magnitude) and related ground motion, can be helpful in reorienting the current strategies toward increased earthquake preparedness.

Unlike other areas of timely warning (e.g. tropical cyclones, some kinds of flood or drought emergencies), earthquake warning has just reached its “adolescence” in science. In fact, the complex nature of the seismic phenomenon does not seem to allow for deterministic predictions; therefore, we cannot know in advance location, magnitude, and time of occurrence of an earthquake, all within narrow limits, so that a planned evacuation can take place. Nevertheless the accuracy of earthquake warnings is improving and the ability to spatially define and map the zones of highest risk is advancing rapidly. Different time intervals, from decades to seconds, are required to undertake different measures. Having different costs, they can be realistically maintained during different time periods and over territories of different size. The key to damage reduction in an area of concern is the timely escalation or de-escalation of preparedness measures, depending on the current state of alert. In general, the alarm for an earthquake of a certain magnitude may extend in time from the zero-approximation of seismic zoning (no time information), through the long-term (decades), intermediate-term (months to years) and short-term ones (hours to days), while in space it may vary from long-range territories (thousands kilometers) to the exact location of the earthquake source (tens of kilometers). Accordingly, the preparedness measures range from the definition of adequate building codes, to intermediate-term alarm declaration and reinforcement of high-risk facilities, to imminent "red alert". The theoretical advances in the selection of the optimal strategy (Molchan, 1996), based on a trade-off between total volume of alert and rate of failures-to-predict on one side and cost-benefit function on the other, create a bridge between predictions and application to natural hazards policy. The capability to construct realistic scenarios of hazard provides a practical tool for decision-making, thus allowing for an optimization of timely warning strategies.

The relevance of developing neo-deterministic time-dependent seismic hazard maps for use in prioritizing mitigation policies from a mid-term anticipatory perspective is evident in view of the basic shortcomings of most of the traditional probabilistic approaches (see Castaños and Lomnitz, 2002; Klügel, 2007, and references therein), as well as of their very unsatisfactory performances proved by recent destructive earthquakes, like Kobe (17.1.1995) Japan, Gujarat (26.1.2001) India, Bam (26.12.2003) Iran, and Boumerdes (21.5.2003) Algeria (Panza et al., 2004) that, among the others, motivated an ongoing revision of safety rules for nuclear power plants. The seismic zonation adopted by the current regulations in many countries has been defined according to a well-established and popular but inadequate, conventional probabilistic approach and hence it is basically affected by the limitations of such methodology. Specifically, probabilistic seismic hazard maps are: a) strongly dependent on the available observations, unavoidably incomplete due to the long time scales involved; b) do not adequately consider
the site effects, since they resort to convolutive techniques (e.g. attenuation relationship) which cannot be rigorously applied when dealing with complex geological structures; c) time-independent, being based on the assumption of the random occurrence of earthquakes. Moreover the mathematical model of the probabilistic seismic hazard analysis is inaccurate and introduces systematic errors in the calculation process that leads to unrealistic results (Klügel, 2007).

In the present study we apply an integrated neo-deterministic approach (Peresan et al., 2002) that allows for an effective estimation of seismic hazard. The neo-deterministic method capably addresses the above-mentioned limitations of the probabilistic hazard assessment as follows: a) it is obviously based on experimental observations, but it overcomes the correlated problems (e.g. deviation from Gutenberg–Richter (GR) law) by means of advanced physical modelling techniques, which are very important for the design of civil infrastructures (Klügel et al., 2006); b) it allows to consider the complexity of the source and the site effects without using convolutive methods; c) it is time dependent in the sense that it produces maps associated with the areas alarmed by the prediction algorithms, which vary in time.

In the neo-deterministic method, the constraint about the space and time of occurrence of impending strong earthquakes is provided by the intermediate-term middle-range earthquake prediction, performed by means of the algorithms CN or M8, and by the pattern recognition of the areas prone to large events. The algorithms M8 and CN belong to a family of formally defined procedures for intermediate-term middle-range earthquake prediction, based on the observed variations in the background seismicity, which obeys the GR law, preceding large earthquakes. They allow for a diagnosis of the periods of time (TIP: Time of Increased Probability for the occurrence of a strong earthquake) when a strong event is likely to occur inside a given region. The results of the global real-time experimental testing of M8 and CN algorithms (Kossobokov et al., 1999; Rotwain and Novikova, 1999) indicate the possibility of practical earthquake forecasting, although with limited accuracy (i.e. with a characteristic alarm-time ranging from a few months to a few years and a space uncertainty of hundreds of kilometers). A reduction of space uncertainty is feasible through the combined use of seismological, geological and morphostructural information. In fact, pattern-recognition can be used to identify the sites capable of generating strong events inside the alerted areas, independently from any transient seismic information.

Among the possible developments towards a more accurate identification of the area of the impending earthquake, the analysis of real-time deformation patterns within alerted earthquake prone areas is expected to play a relevant role, where the newly available high quality positioning data (e.g., GPS and InSAR) would permit to compile real-time displacement/deformation maps (e.g. Dalla Via et al., 2007; Marotta and Sabadini, 2004) within the alerted areas and combine them with routinely updated seismic information.

We illustrate in the following the time dependent scenarios of earthquake ground motion considering the application of the mentioned methodologies to North-Eastern Italy. Pattern recognition techniques have been applied in Italy with the aim to contribute to seismic (Caputo et al., 1980, 1983) and volcanic hazard assessment (Mulargia et al., 1991). Italy nowadays is the only region of moderate seismic activity where a real-time test of the two different prediction algorithms CN and M8S (i.e. a spatially stabilized variant of M8) is ongoing since 2003 (Peresan et al., 2005). Along with the results obtained from the
intermediate-term middle-range earthquake prediction experiment, we discuss the extension of CN algorithm application to a new region, namely the Adria region, which turns out to be relevant for seismic hazard assessment in the North-Eastern part of the Italian territory. Examples of neo-deterministic scenarios are provided at regional and local scale considering the cities of Trieste and Nimis (Friuli Venezia Giulia region, NE Italy) where the knowledge of the geological conditions permitted a detailed evaluation of the expected ground motion, taking into account site effects.

2. Intermediate-term middle-range earthquake prediction in Italy and surrounding areas

To predict an earthquake means to indicate the main features (time, space and expected minimum magnitude) of an impending event, usually on the basis of the observation of a precursory signal. Special attention must be paid to validate precursors, because earthquakes are too infrequent and each phenomenon has its own non-seismic natural variations, and to establish a reliable precursory connection requires observations of many cases. Up to now, most of the proposed precursors have either failed or are, at best, unproven, mainly due to the lack of prolonged and systematic records. To assess the effectiveness of a prediction method, even accepting an intrinsic proportion of missed events or false alarms, the forecasts must demonstrate to be more effective than a random guess. In this framework, retrospective analysis of past earthquakes is essential to set up a prediction tool. Nevertheless the ultimate experimental validation of the considered method can be provided only through real-time tests, accumulating a collection of correct and wrong predictions that will eventually permit to assess its predictive capability.

Nowadays, one of the most promising approaches seems to be represented by the intermediate-term middle-range earthquake predictions (i.e. with a characteristic alarm-time from a few months to a few years and a space uncertainty of hundreds of kilometers) based on the detection of certain variations in the background seismicity preceding large earthquakes. In fact, the analysis of the seismic flow has evidenced that some specific seismicity patterns, in the events below some magnitude threshold, may prelude to an incumbent strong event, with magnitude above the same threshold. This observation is supported by the consideration that to initiate an earthquake a certain stress level is necessary that will maintain slow fracture growth; the latter tends to be discrete and manifests itself as background seismicity (Knopoff, 1996).

Several possible scenarios of precursory seismic activity have been proposed; nevertheless, only a few formally defined algorithms allow for a systematic monitoring of seismicity, as well as for a widespread testing of their performances. In this study two algorithms are considered, namely CN and M8 algorithms (see Keilis-Borok and Soloviev (2003) and references therein) that belong to a family of middle-range intermediate-term earthquake prediction algorithms based on a quantitative analysis of the seismic flow. The algorithms are based on a multiple set of premonitory patterns and have been designed following the general concepts of pattern recognition, which automatically imply strict definitions and reproducible prediction results. CN and M8 algorithms allow for a diagnosis of the Times of Increased Probability (TIPs) for the occurrence, inside a given region and time window, of earthquakes with magnitude greater than a fixed threshold $M_0$. Quantification of the seismicity patterns is obtained through a set of empirical
functions of time, evaluated on the sequence of the main shocks which occurred in the analysed region, each representing a reproducible precursor.

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, etc.), most of which would be poorly constrained by the available observations and hence below any critics.

The tests of predictions, performed on a global scale, allowed a first statistical assessment of the predictive capability of M8 and CN algorithms (Kossobokov et al., 1999; Rotwain and Novikova, 1999). Specifically, for the M8 algorithm the results obtained in real-time prediction mode since 1992 have already demonstrated the high confidence level (above 99%) of the prediction of the world’s largest earthquakes, in the magnitude range 8.0 – 8.5 (Keilis-Borok and Soloviev, 2003; Kossobokov et al., 1999). For the algorithm CN a preliminary estimate of the significance of the achieved prediction results, obtained for the period 1983-1998 in 22 regions of the world, gives a confidence level around 95% (Rotwain and Novikova, 1999).

Italy is the only region of moderate seismic activity where the two algorithms CN and M8S are currently applied simultaneously for the routine intermediate-term middle-range earthquake prediction (Peresan et al., 2005). Significant efforts have been made to minimize the intrinsic space uncertainty of predictions and the subjectivity of the definition of the areas where precursors should be identified (Peresan et al., 1999; Kossobokov et al., 2002). For the application of the algorithm CN, a regionalization strictly based on the seismotectonic zoning, and taking into account the main geodynamic features of the Italian area, is currently used as the result of a set of optimization tests (Keilis-Borok et al., 1990; Costa et al., 1996; Peresan et al., 1999). For the application of the M8S algorithm, that is a spatially stabilized variant of M8, the seismicity of the study region is analysed within a dense set of overlapping circles, with radius increasing with the magnitude of the target events and covering the monitored area. Several experiments have been dedicated to assess the robustness of the methodology against the unavoidable uncertainties in the data (Peresan et al., 2000; 2002). With these results acquired, an experiment was launched in July 2003, aimed at the real-time test of M8S and CN prediction for earthquakes with magnitude larger than 5.4 in the Italian region. The results of the intermediate-term middle-range predictions in Italy are routinely updated and made accessible to a number of scientists.

The goal of the experiment was to accumulate a collection of correct and wrong predictions (the latter include the false alarms and/or the failures to predict encountered in the test) permitting to verify and assess the predictive capability of the considered methodology.

2.1 The algorithm CN in Italy and surrounding areas

According to CN rules, the region for the algorithm application is selected taking into account the spatial distribution of seismicity and the geometry of fault systems and its linear dimensions must be greater or equal to 5L-10L, where L = L(M0) is the rupture size of the target earthquake (Keilis-Borok, 1996). In agreement with the Multiscale Seismicity model (Molchan et al., 1997), when seismicity is analysed over
relatively small regions, the frequency-magnitude relation is linear only up to a certain magnitude, while for the larger events it usually exhibits an upward bend. When applying the algorithm CN, in order to guarantee a certain stability of the results (Molchan et al., 1990), the magnitude threshold $M_0$ is selected as close as possible to the minimum in the histogram of the number of events versus magnitude, which separates the linear portion of the frequency-magnitude distribution from its upward bend. Consequently, within the areas delimited for prediction purposes, the number of earthquakes with $M > M_0$ (whose source size becomes comparable with the region size) generally exceed the estimation based on the extrapolation of the GR law and hence they can be considered abnormally strong within the given region. At the same time the Multiscale model guarantees the self-similarity condition for the small and moderate events ($M < M_0$), considered for the analysis of the premonitory patterns, and hence the log-linearity of the frequency-magnitude relation in the magnitude range of interest. In such a way the algorithms make use of the information carried by small and moderate earthquakes, statistically characterised by the GR law, to predict the strong earthquakes, which are anomalous and often arbitrarily interpreted as characteristic events inside the regions delimited for prediction purposes.

The algorithm CN has been applied in Italy since 1990 (Keilis-Borok et al., 1990). A regionalization (Fig. 1), 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 borders of each region have been traced including only adjacent zones with similar seismogenic behaviour and the transitional zones connected to them, compatible with the cinematic model (Peresan et al., 1999).

The forward CN prediction is updated every two months, using the UCI2001 catalogue (Peresan and Panza, 2002), which is composed by the Italian catalogue CCI1996 (Peresan et al., 1997) for the period 1900-1985 and updated with the NEIC Preliminary Determinations of Epicentres since 1986. The thresholds $M_0$ for the selection of the events to be predicted are fixed, taking into account their average return period, $M_0=5.4$ for the Northern region and $M_0=5.6$ for the Central and Southern regions. Details about CN application in Italy can be found in (Peresan et al., 2005). Starting from January 1998, predictions are regularly updated every two months. Since July 2003 current predictions are made accessible to a number of scientists and a complete archive of predictions can be viewed at the following web site: http://www.ictp.trieste.it/www_users/sand/prediction/prediction.htm. The results obtained up to 1 March 2008, either by retrospective analysis or in real time prediction, are shown in Figure 1 and are briefly summarised in Table 1. The space-time volume occupied by alarms is estimated following Kossobokov et al. (1999), taking into account the space distribution of epicentres in the monitored territory.

Altogether, CN algorithm predicted twelve out of the thirteen strong earthquakes that occurred inside the monitored regions, with a space-time volume occupied by alarms of about 30% of the total considered space-time volume. The confidence level of such predictions is above 99%. When taking into account the results obtained in forward predictions for Italy, together with those obtained on a global scale up to 1998 (Rotwain and Novikova, 1999), the estimate of the confidence level of CN predictions increases up to 99%. 
The three regions currently used for the routine monitoring of earthquakes occurrence cover a large part of the Italian territory (Fig. 1), including the most seismically active zones located along the north-western boundary of the Adria plate. Based on the successful and stable results obtained so far (Tab. 1), a region suitable for CN application in the Adriatic region (s.l.) has been defined (Peresan et al., 2006; Rotwain et al., 2008), following the same rules controlling the definition of the three regions identified in the Italian territory. The new area, the Adria region, is composed of the foreland zones extending from the Adriatic Sea to Southern Sicily, through the Ionian Sea (Fig. 2) and is bordering, along its north-western boundary, the regionalization defined for the Italian peninsula. The southern boundary of the Adria region corresponds to a minimum in the distribution of the epicentres of recorded earthquakes and to the east the boundary of the region coincides with the border of the compressional belt located along the Dinarides. CN application to the Adria region has been performed using the same catalogue UCI2001 (Peresan and Panza, 2002) considered for the Italian peninsula. The results obtained in retrospective and real-time analysis (starting January 2003) can be summarized as follows: seven out of nine earthquakes, with magnitude $M_\geq M_0=5.4$, which occurred during the time interval 1964-2008 are correctly preceded by TIPs, with a total alarm duration covering about 36% of the considered time (Fig.2). The successful results obtained for the Italian territory, including the real-time prediction test for earthquakes with magnitude larger than 5.4, indicate that the seismotectonic model may provide a useful guide in the selection of the fault systems involved in the preparation of strong earthquakes, leading to a general reduction of the space-time uncertainty of predictions.

### 2.2 The algorithm M8S in Italy

Algorithm M8 was designed for the prediction of the strongest earthquakes worldwide, with magnitude 8.0 and above (Keilis-Borok and Kossobokov, 1987), and was later adapted for the prediction of earthquakes with smaller magnitudes (Keilis-Borok and Kossobokov, 1990). The M8 algorithm analyzes the seismic activity inside a set of Circles of Investigation, CIs, with a radius proportional to the linear size of the events to be predicted, i.e. proportional to the magnitude threshold, $M_0$. The choice of $M_0$ is determined by the condition that the average recurrence time of strong earthquakes is sufficiently long in the territory considered. A hierarchy of predictions is usually delivered for different magnitude ranges $M_0+$, considering values of $M_0$ with an increment of 0.5 (i.e. $M_0+$ indicates the magnitude range: $M_0 \leq M \leq M_0+0.5$). Since the area of the CIs scales with the magnitude $M_0$ of target earthquakes, as for CN algorithm, similar considerations on the frequency-magnitude of events apply. Specifically, in agreement with the Multiscale model (Molchan et al., 1997) the M8S algorithm makes use of the information carried by small and moderate earthquakes to predict the strongest events, generally exceeding the estimation based on the extrapolation of the GR law and often arbitrarily interpreted as characteristic earthquakes.

For the monitoring of seismicity in the Italian territory, a spatially stabilized variant of M8, namely the M8S algorithm, is considered, where the seismicity is analysed within a dense set of overlapping CIs...
covering the monitored area (Kossobokov et al., 2002). The M8S algorithm is less subjective and less sensitive to the position of the CIs than the standard variant of the M8 algorithm. In Italy predictions are performed in the three different magnitude ranges defined by $M_0 = 6.5, 6.0$ and $5.5$ (i.e. M6.5+, M6.0+ and M5.5+), with CIs of radius $R=192$ km, $R=138$ km and $R=106$ km respectively, centred at the nodes of a grid with spacing approximately equal to the linear dimension of the target earthquakes. The catalogue used for the M8S application is the UCI2001 (Peresan and Panza, 2002), that is the same used by the algorithm CN; according to the worldwide M8 tests the operating magnitude considered is $M_{\text{max}}$. Details about M8S application in Italy are given in (Peresan et al., 2005). In Figure 3 we provide, as an example, the maps showing the results of M8S application in the Italian territory (predictions issued January 1, 2008).

The performances of the M8S algorithm in Italy are summarised in Table 2. As for CN algorithm, the space-time volume occupied by alarms is estimated following Kossobokov et al. (1999). In the retrospective simulation of predictions, during the period 1972-2001, twelve out of eighteen large earthquakes, with magnitudes from 5.5 to 7.0, occurred in the alarmed areas, with an average space-time volume occupied by alarms of about 34-39% of total space-time volume (for details see Kossobokov et al., 2002; Peresan et al., 2005). With these results acquired, the M8S algorithm is applied for the real-time monitoring of seismicity since January 2001; the predictions are routinely updated every six months and a complete archive of predictions is given at the web site: www.ictp.trieste.it/www_users/sand/prediction/prediction.htm. Altogether, the algorithm M8S predicted about 63% of the strong earthquakes which occurred within the monitored territory (i.e. 17 out of 27 events with $M \geq 5.5$), with a space-time volume occupied by alarms of about 37% of total space-time volume and a confidence level of about 97%.

3. Pattern recognition of earthquake prone areas
The space uncertainty typical of the intermediate-term middle-range predictions is quite large. An attempt to better constrain the location of the impending events is possible through the combined use of seismological, geological and morphostructural information. In fact, the pattern-recognition technique can be used to identify the sites capable to generate the strongest events. The method for the pattern recognition of earthquake-prone areas is based on the assumption that strong events nucleate at the morphostructural nodes (Gelfand et al., 1972), specific structures that are formed at the intersections of lineaments. Lineaments can be identified by the Morphostructural Zonation (MZS) Method (Alekseevskaya et al., 1977), which delineates a hierarchical block structure of the study region, using tectonic and geological data, with special care to present-day topography. 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 neo-tectonic 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). The methodology developed for the recognition of earthquake prone areas has been successfully tested in many different regions of the world (e.g. Gorshkov et al., 2000, and references therein).
This methodology has been applied to peninsular Italy and Sicily by Gorshkov et al. (2002), revising and updating, on a more detailed scale, the analysis performed by Caputo et al. (1980). Later on a similar analysis was performed for the Alps and the Dinarides (Gorshkov et al., 2004). The morphostructural map has been compiled at the scale of 1:1,000,000 by the combined analysis of topographic, tectonic, geological maps and satellite photos. Under the assumption that 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 $M \geq 6.5$. 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. 2002). Such node dimension is comparable with the size of the earthquake source for the magnitude range considered in this work (Wells and Coppersmith, 1994). 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. The lineaments and nodes prone to $M \geq 6.5$ and $M \geq 6.0$ events are shown in figure 4.

The possibility of identifying the structural boundaries of a node has been proved by extensive field-work in the Pamir-Tian Shan and the Greater Caucasus (Rantsman, 1979; Gvishiani et al., 1986). The analysis, by defining the boundaries of the earthquake prone areas with more detail than the standard circles routinely considered in the large scale analysis (e.g. (Gorshkov et al., 2002; 2004), may eventually permit to narrow down the location of potential strong earthquakes and thus reduce the related hazard (Gorshkov et al., 2008). Therefore a refined analysis, at regional scale, is currently in progress for the Alps-Dinarides junction (Gorshkov et al., 2008) with the aim to delineate the geometry of node boundaries based on morphostructural lineaments of lower rank, outlined using large-scale cartographic sources, including topographic and geological maps at the scale of 1:150,000.

The identification of earthquake prone areas is especially important in areas where historical and instrumental information is scarce. In fact these areas can be used as input sources in any deterministic seismic hazard assessment, thus allowing an effective estimate of the seismic risk, more realistic than that based on the unavoidably incomplete seismological observations, contained in earthquake catalogues.

4. Time-dependent neo-deterministic seismic hazard scenarios for North-Eastern Italy

Predicting the intensity of shaking associated to a declared TIP plays a key role in preventing damage. Several probabilistic seismic hazard maps have been produced for the Italian territory, based on different assumptions for the definition of seismogenic zones, recurrence relations, maximum magnitudes and attenuation relationships (Slejko et al., 1998; Gruppo di Lavoro, 2004). The resulting maps, however, appear quite dependent on the made assumptions (especially on the geometry of the seismogenic zones), thus evidencing a certain subjectivity of the obtained results. In this study the time information provided by predictions is used to produce appropriate scenarios of ground motion, useful to increase the preparedness measures and to indicate a priority for the necessary detailed seismic risk studies. Maps are produced by the neo-deterministic procedure for the evaluation of seismic hazard, which is based on the computation of complete synthetic seismograms (Panza et al., 2001) following the laws of physics and avoiding standard convolutive approaches that have a questionable validity (e.g. Paskaleva et al., 2007).
Different kinds of scenarios can be computed at different space level:
- level 1: scenarios at bedrock associated with the alerted regions;
- level 2: scenarios at bedrock associated with each seismogenic node within the alerted region;
- level 3: detailed scenarios, that take into account local soil conditions, associated with each seismogenic node within the alerted region.

4.1 Time dependent scenarios of ground motion associated with alerted regions

Ground shaking scenarios associated with the alerted regions are computed, considering altogether the set of possible sources included in the alerted regions. In this paper we provide examples from the CN Adria region and the M8S alerted areas as at 1 January 2008 (Figs. 2, 3), focussing on the North-Eastern part of Italy. The proposed procedure represents a development of that illustrated in Peresan et al. (2008).

We analyse the seismic flow as contained in the Italian (CPTI04, Gasperini et al., 2004), Slovenian (Zivcic et al., 2000) and Croatian (Markusic et al., 2000) earthquake catalogues. The observed seismicity is discretized into 0.2°x0.2° cells, assigning to each cell the maximum magnitude $M_{\text{obs}}$ recorded within it.

The database of the sources used for the computation of seismograms is compiled in two steps that take into account the different source models defined by the seismogenic zones (Meletti and Valensise, 2004) and the seismogenic nodes (Gorshkov et al., 2002; 2004), which supply complementary information.

Step 1. Only cells located in the seismogenic zones associated with a maximum magnitude $M_{ZS}$ greater than the magnitude threshold $M_0$ of the alarmed area (as given by the prediction algorithms) are included in the analysis. The maximum magnitudes $M_{ZS}$ associated with the different seismogenic zones are estimated from the information contained in Meletti and Valensise (2004). A further selection is performed retaining only the cells that belong to an alerted region. A smoothing procedure is then applied to account for the spatial uncertainty and for source dimensions (Panza et al., 1999) and again only the cells that belong to the intersection of the seismogenic zones and the alarmed region are finally considered. To be conservative, if the smoothed magnitude $M_{\text{smooth}}$ is lower than the prediction threshold $M_0$, the operating value $M$ is set equal to $M_0$, otherwise $M= M_{\text{smooth}}$.

Step 2. The smoothing procedure is performed on the entire set of cells. The coordinates of the centre of the nodes given by Gorshkov (2002, 2004) are rounded to 0.2 degrees, in order to be consistent with the grid resolution. If the smoothed magnitude $M_{\text{smooth}}$ assigned to the cells that belong to a node is lower than the magnitude threshold of the node indicated by the morphostructural analysis, $M_N$, the operating magnitude is raised to the magnitude threshold of the node. This choice allows us to consider strong earthquakes for areas where they are not yet observed but which are recognized prone to strong earthquakes. A class of nodes ($M_N \geq 6.0$ or $M_N \geq 6.5$) is considered only if the corresponding magnitude threshold $M_N$ is within the magnitude range of the predicted impending earthquakes. The selection of the class of nodes according to the magnitude threshold of the alarmed area is done as reported in Table 3. Again, only the cells located within the alarmed regions are retained.

In the case of the M8S algorithm, where predictions are delivered for consecutive ranges of magnitude $M_0^+$, if the magnitude $M$ computed, according to the steps just described, exceeds the considered magnitude range, then the operating magnitude is set equal to the upper bound of the range $M_0^+$ (e.g. for
M6.0+ scenarios the maximum operating magnitude is 6.4). In fact, if an alarm is declared for M6+\(^+\), we do not expect an earthquake larger than the upper boundary of the range M6+\(^+\), which would be eventually associated with the predictions issued for a higher magnitude range.

A double-couple point source, with a representative focal mechanism, consistent with the seismotectonic model and the available database of fault plane solutions (Meletti et al., 2004) is placed at the centre of each cell, at a depth which is a function of magnitude (10 km for M < 7; 15 km for M ≥ 7). The sources associated with the seismogenic zones are merged with those associated with the seismogenic nodes to create a single database.

Synthetic seismograms are then computed by the modal summation technique (Panza et al., 2001) for receivers placed at the nodes of a grid with step 0.2°x0.2°, covering the study area. The lateral heterogeneity of the medium is taken into account by making use of polygons with different structural models: each synthetic seismogram has been computed considering the average structural model associated with the regional polygon that includes the site. At each site the sum vector of the radial and transverse components of ground motion is computed. Seismograms are calculated for a maximum source-site distance of 150 km. The synthetic signals are computed for an upper frequency limit of 1Hz, and are properly scaled according to a smoothed magnitude distribution using the moment-magnitude relation given by Kanamori (1977) and the spectral scaling law proposed by Gusev (1983) as reported in Aki (1987).

Each site is thus associated with seismograms of many different sources and any parameter of interest can be extracted from such complete time series, therefore different maps can be produced. The neo-deterministic results are extended to frequencies higher than 1 Hz by using design response spectra (Panza et al., 1996). As an example the Eurocode 8 (1993), which defines the normalized elastic acceleration response spectrum of the ground motion, for 5% critical damping, can be used. Since the available regional structural models for Italy are all of type A, we can immediately determine the design ground acceleration (DGA) using the EC8 parameters for soil A (EC8, 1993).

The scenario of DGA (Design Ground Acceleration) associated with a TIP in the Adria region is shown in Fig. 5, while those associated with the M8S alarms are shown in Fig. 6. During the TIP a strong earthquake may occur at any point in the alerted area; therefore these maps represent the maximum DGA values associated with all of the possible events during the declared TIPs. Their validity lasts until the alarm expires, that is, at least up to the next upgrading of predictions (i.e. after two months for CN and after six months for M8S).

### 4.2 Scenarios of ground motion associated with seismogenic nodes

Ground shaking scenarios associated with the alerted regions provide information about the whole area that may be affected by a declared TIP. All the sources inside the alerted region are supposed to be active at the same time. This is a very conservative assumption, and in order to have a picture of what should be expected if a strong earthquake occurs during a TIP, the scenario associated with a single node prone to a strong earthquake must be calculated.
We supply examples of scenarios corresponding to two nodes that are of particular relevance for two cities of the Friuli Venezia Giulia region, Trieste and Nimis, where the knowledge about the local geology, topography and geotechnical properties permits to make a detailed ground motion modeling (Vaccari et al., 2005; Zuccolo et al., 2008) superseding the results obtained at the bedrock. These two nodes, indicated as D15 ($M_N \geq 6.0$) and D1 ($M_N \geq 6.5$) nodes (Gorshkov et al., 2004), are located at the Alps-Dinarides junction.

The procedure for the computation of scenarios at the bedrock is the same followed to define the integrated scenarios associated with the alarmed regions, treating each of the two nodes separately. After the gridding and the smoothing of seismicity, only the sources inside the node are considered. The coordinates of the centre of the node are rounded to 0.2 degrees so that the centre of the node coincides with one source; this rounding is justified by the fact that the precision of the coordinates of the center of the nodes, given by Gorshkov et al. (2004), turns out to be higher than the grid resolution adopted for the discretization of the sources. If the magnitude $M_{\text{smooth}}$ assigned to the sources that belong to the node is lower than $M_N$, we put $M = M_N$ according to the seismogenic potential indicated by the morphostructural analysis. In order to obtain scenarios with dimensions comparable to the area that may be realistically affected by such a strong event, the maximum epicentral distance used in the computation of the seismograms is set equal to 200 km. According to the neo-deterministic procedure, the node can be associated with maps describing the seismic ground motion (e.g. peak values of displacement, velocity and acceleration, or any other parameter of interest for seismic engineering) caused by the potential sources contained in a seismogenic node. Figure 7 shows the DGA scenarios associated with the two considered nodes. The peak values of displacement and velocity are provided in Table 4.

The node D15, recognized prone for magnitude $\geq 6.0$ earthquakes, is the node that supplies the highest values for Trieste, even if two nodes with $M_N \geq 6.5$, D14 (analyzed in Peresan et al., 2008) and D16 are detected in the vicinity (Gorshkov et al., 2004). In fact D15 is the node closest to the city and its hazard is controlled by the smoothing operation, which assigns a magnitude 6.5 to some sources inside the node. For Nimis we choose the node D1 (recognized prone for both $M_N \geq 6.0$ and $M_N \geq 6.5$) because it includes the 1976 Friuli earthquake epicenter, which strongly hit the city of Nimis, and no other nearby node is capable to generate, for Nimis, values greater than those shown in Table 4.

In the ancient part of Trieste soft superficial sediments with poor geotechnical properties are present, while Nimis is located at the centre of a sedimentary valley. Therefore the site response is expected to play a relevant role in the ground shaking of the two test areas. We choose two sources inside the considered nodes (S1, within the node D15, and S2, within the node D1; Fig 8) to make a detailed ground motion modelling for Trieste and Nimis. To get a better constraint on the position of the sources we use the active fault map (Aoudia, 1998, Fig. 8) in order to select the sources in correspondence of the active faults. The aim of this analysis is to compute synthetic signals to be used as seismic input in subsequent engineering analysis for the definition of the seismic response of Palazzo Carciotti, a historical building completed in 1805, located in central Trieste, and the design of a residential seismic isolated building located in the municipality of Nimis.
This analysis is performed using a quite realistic definition of the mechanical properties of the sites, which are represented as local 2D sections (Fig. 9), and of the seismic sources (Fig. 8), which are modelled as extended sources. The rupture process at the source and the consequent directivity effect (i.e. radiation at a site depends on its azimuth with respect to rupture propagation direction) is modelled by means of the algorithm, developed by Gusev (Gusev and Pavlov, 2006), that simulates the radiation from a fault of finite dimensions, named PULSYN (PULse-based wide band SYNthesis). Along the profiles (local 2D sections) the ground motion is modelled with broadband synthetic seismograms (maximum frequency 5 Hz) computed by the hybrid technique described in detail by Panza et al. (2001).

From the computed accelerograms we obtain at Palazzo Carciotti a peak ground acceleration of about 0.2 g (~200 cm/s²), which corresponds to a macroseismic intensity as large as X (MCS) (Panza et al., 1997), while in the centre of Nimis the computed DGA value is about 1.2 g, that may correspond to a macroseismic intensity not less than XI (MCS) (Panza et al., 1997). Both values are greater than the corresponding values obtained at the bedrock and using the point source approximation (Fig. 7, Tab. 4).

Therefore the local soil conditions cannot be captured by the average values typical of bedrock modelling, but they must be the object of further detailed analysis at least for those sites where intensity values greater than VII (MCS) are calculated at the bedrock, as is the case of Nimis and Trieste (Tab. 4).

The importance of the detailed modelling is particularly evident in the case of Nimis, where it has been shown that the site conditions advise against the construction of a conventional fixed-base masonry. A valid alternative is supplied by the seismic isolation (e.g. Dolce et al., 2004; Martelli and Forni, 1998), which is achieved interposing between the building structure and its foundations some supporting devices, called isolators, that decouples the motion of the structure from that of the ground during an earthquake. For the case of Nimis, a seismically base-isolated building is advantageous not only from the safety point of view but also from the economical one.

Further details about the realistic modelling of seismic ground motion in Trieste can be found in Peresan et al. (2008) and Vaccari et al. (2005), while the study of Nimis is reported in Zuccolo et al. (2008). The review of the seismogenic nodes in the Friuli Venezia Giulia area, presently in progress (Gorshkov et al., 2008), could lead to a reduction of the seismic hazard in Trieste by one degree of the MCS scale.

5. Conclusions

The preparedness to the occurrence of an earthquake requires knowledge of the expected earthquake location, its size and the effects of the local site conditions on seismic ground motion. The described integrated approach blends together the available information in a set of realistic scenarios and supplies a useful tool for decision-makers to be used to increase the community preparedness to strong seismic events.

Amongst the many advantages of the time dependent neo-deterministic hazard assessment is the time information given by the intermediate-term middle-range earthquake prediction that is useful to plan preparedness and rescue actions (e.g. placement and survey of the first-aid resources) and to define priority criteria for the detailed studies required by a reliable seismic microzonation. Another particularly important advantage is the capability to incorporate, in a rather straightforward way, new information.
about seismic sources and structural models, progressively available to the scientific community. Additional information that permits to better constrain the potential sources, such as a more accurate definition of the maximum magnitude associated with a given fault system or a more precise definition of boundaries for the earthquake prone areas (Gorshkov et al., 2008), may eventually lead to a modest reduction of the estimated hazard.

The neo-deterministic hazard assessment makes use of formalized and robust procedures for the recognition of earthquake prone areas and it is especially useful as a prevention tool in areas that have not yet been struck, but are potentially prone to strong earthquakes. The procedure permits an optimum exploitation of the wide geophysical and geological data sets that are available, as well as the current knowledge of the physical process of earthquake generation and wave propagation in realistic anelastic media, and does not need to rely heavily, if not exclusively on macroseismic observations (catalogues of historical events). Moreover, the procedure for the seismic hazard assessment based on the computation of synthetic seismograms provides 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".

Acknowledgements

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References


Keilis-Borok V.I., Kutnetsov I.V., Panza G.F., Rotwain I.M., Costa, G., On intermediate-term


Table 1: Space-time volume of alarm for CN application in Italy. The total space considered corresponds to the union of the three monitored regions; during the period 1954-1963 only Central and Southern regions were analysed. Details about computation of space-time volume of alarm can be found in Peresan et al. (2005).

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Space-time volume of alarm (%)</th>
<th>n/N</th>
<th>Confidence level (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Retrospective* (1954 – 1963)</td>
<td>41</td>
<td>3/3</td>
<td>93</td>
</tr>
<tr>
<td>Retrospective (1964 – 1997)</td>
<td>27</td>
<td>5/5</td>
<td>&gt;99</td>
</tr>
<tr>
<td>All together (1954 – 2008)</td>
<td>30</td>
<td>12/13</td>
<td>&gt;99</td>
</tr>
</tbody>
</table>

Table 2: Space-time volume of alarm for M8S application in Italy, obtained for the three subsequent magnitude ranges defined by M6.5+, M6.0+ and M5.5+. The space-time volume occupied by alarms is estimated according to Kossobokov et al. (1999).

<table>
<thead>
<tr>
<th>Experiment</th>
<th>M6.5+</th>
<th>M6.0+</th>
<th>M5.5+</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Space-time volume of alarm (%)</td>
<td>n/N</td>
<td>Space-time volume of alarm (%)</td>
</tr>
<tr>
<td>Retrospective (1972-2001)</td>
<td>36</td>
<td>2/2</td>
<td>40</td>
</tr>
<tr>
<td>Forward (2002-2008)</td>
<td>49</td>
<td>0/0</td>
<td>47</td>
</tr>
<tr>
<td>All together (1972-2008)</td>
<td>36</td>
<td>2/2</td>
<td>40</td>
</tr>
</tbody>
</table>
Table 3: Selection of the minimum magnitude associated with the nodes included in the computations, depending on the magnitude threshold of the alarmed area. A class of nodes ($M_N \geq 6.0$ or $M_N \geq 6.5$) is considered only if the corresponding magnitude threshold $M_N$ is within the magnitude range of predicted earthquakes. The “-” indicates that the corresponding class of nodes is not used.

<table>
<thead>
<tr>
<th>Prediction algorithm</th>
<th>Magnitude threshold for earthquakes prone nodes</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>$M_N \geq 6.0$</td>
</tr>
<tr>
<td>CN Northern region ($M_0=5.4$)</td>
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</tr>
<tr>
<td>M8S</td>
<td>M6.0+</td>
</tr>
<tr>
<td></td>
<td>M6.5+</td>
</tr>
</tbody>
</table>

Table 4: Peak ground displacement (PGD), peak ground velocity (PGV), design ground acceleration (DGA) and maximum estimated MCS intensity ($I_{\text{max}}$ computed), calculated for Trieste and Nimis considering the nodes D15 and D1 (Gorshkov et al., 2004), respectively. Intensities are computed using the conversion tables proposed by Panza et al. (1997), based on the observed intensities contained in ING (Boschi et al., 1995) and ISG (Molin et al., 1996) data sets.

<table>
<thead>
<tr>
<th>City</th>
<th>PGD (cm)</th>
<th>PGV (cm/s)</th>
<th>DGA (g)</th>
<th>$I_{\text{max}}$ computed</th>
<th>$I_{\text{max}}$ observed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ING</td>
<td>ISG</td>
</tr>
<tr>
<td>Trieste</td>
<td>3.5 – 7.0</td>
<td>8.0 – 15.0</td>
<td>0.08 – 0.15</td>
<td>IX</td>
<td>IX</td>
</tr>
<tr>
<td>Nimis</td>
<td>7.0 – 15.0</td>
<td>30.0 – 60.0</td>
<td>0.30 – 0.60</td>
<td>XI</td>
<td>X</td>
</tr>
</tbody>
</table>
Fig. 1 - Regionalization used for the application of CN in Italy. In the diagrams of TIPs, the black boxes represent periods of alarm, while each triangle surmounted by a number indicates the occurrence of a strong event ($M \geq M_0$), together with its magnitude. Full grey triangles indicate failures to predict.

Fig. 2 - Regionalization defined for the application of CN to the Adria region (Peresan et al., 2006; Rotwain et al., 2008).
Fig. 3 - Results of the application of the M8S algorithm in Italy for the prediction of earthquakes in three magnitude ranges: M6.5+ (Fig. 3a), M6.0+ (Fig. 3b) and M5.5+ (Fig. 3c). The light grey circles outline the territory where the algorithm M8S has been applied; the dark ones display the alarmed area (updated: January, 1 2008).
Fig. 4 – Morphostructural map of Italy and surrounding regions (after Gorshkov et al., 2002; 2004). Lines with different thicknesses indicate morphostructural lineaments of different rank: thick lines correspond to first order lineaments, medium lines to second order lineaments and thin lines to third order lineaments. Longitudinal lineaments are marked by continuous lines and transversal lineaments by dashed lines. Red circles represent the nodes prone to earthquakes with magnitude a) M≥6.0 and b) M≥6.5, respectively.
Fig. 5 - Map of DGA (Design Ground Acceleration) associated to an alarm in the Adria region. The minimum value reported in the map is 0.01 g.
Fig. 6 - Maps of DGA associated to the alarms (a) M5.5+, b) M6.0+ and c) M6.5+] in the M8S regions as on 1 January 2008. The minimum value reported in the maps is 0.01 g.
Fig. 7 - Maps of DGA generated for the nodes a) D15 and b) D1 (Gorshkov et al., 2004). In both maps, the large full circle represents the node, while the star indicates the location of a) Trieste and b) Nimis.
Fig. 8 – Sources, S1 and S2, used for the computation of seismic ground motion scenarios in Trieste and Nimis, respectively. Active faults mapped according to Aoudia (1998).
Fig. 9 - Cross-section used for the detailed modelling of ground motion in a) Trieste and b) Nimis, and the properties associated with the lithotypes.