CN EARTHQUAKE PREDICTION ALGORITHM AND THE MONITORING OF THE FUTURE STRONG VRANCEA EVENTS*

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The preparation process of the strong subcrustal events originating in the Vrancea region, Romania, is monitored using an intermediate-term medium-range earthquake prediction method – the CN algorithm (Keilis-Borok, Rotwain, 1990). We present the results of the monitoring of the preparation of future strong earthquakes for the time interval from January 1, 1994, to January 1, 2003 using the updated catalogue of the Romanian local network. The data base considered for the CN monitoring of the preparation of the future strong earthquakes in Vrancea covers the period from 1966.3.1 to 2003.1.1 and the geographical rectangle 44.8^0–48.4^0N, 25.0^0–28.0^0E. The algorithm correctly identifies, by retrospective prediction, the TIPs for all the three strong earthquakes (Mo = 6.4) that occurred in Vrancea during this period. The cumulated duration of the TIPs represents 26.5% of the total interval of time considered (1966.3.1–2003.1.1). The monitoring of current seismicity using the algorithm CN is carried out since 1994. No strong earthquakes occurred from 1994.1.1 to 2003.1.1 but the CN declared an extended false alarm from 1999.5.1 to 2000.11.1. There is no alarm currently declared in the region (on January 1, 2003), as can be seen from the TIPs diagram shown in Figure 1.

Key words: earthquake prediction, CN monitoring, Vrancea.

INTRODUCTION

The strong earthquakes originating at intermediate depths in the Vrancea region (located in the SE corner of the highly bent Carpathian arc) are among the most important natural disasters that induce heavy effects (high number of casualties and extensive damage) on the Romanian territory. The occurrence of these earthquakes is irregular, but not infrequent (2–5 events with magnitude $M_w > 7$ per century). Their effects are felt over a large territory, from Central Europe to Moscow and from Greece to Scandinavia. The largest cultural and economic centre exposed to the seismic risk due to the Vrancea earthquakes is Bucharest. This

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metropolitan area (230 km^2 wide) is characterized by the presence of 2 million inhabitants (on 01.01.1998) (9% of the country's population and 15% of the urban one) and by a considerable number of high-risk structures and infrastructures.

The best way to face strong earthquakes is to mitigate the seismic risk using the two possible complementary approaches, represented by: (a) the antiseismic design of structures and infrastructures (able to stand strong earthquakes without significant damage) based on reliable seismic microzonation studies (Moldoveanu *et al.*, 2000; Moldoveanu, Panza, 2001; Cioflan *et al.*, 2002; Panza *et al.*, 2002) and (b) the strong earthquake prediction (in terms of alarm intervals declared for long, intermediate or short-term space- and time-windows).

The intermediate-term medium range earthquake prediction represents the most realistic target to be reached at the present state of knowledge. The alarm declared in this case extends over a time window of about one year or more, and a space window of a few hundreds of kilometres. In the particular case of Vrancea events the spatial uncertainty is much lesser, being of about 100 km. The main measures for the mitigation of the seismic risk allowed by the intermediate-term medium range prediction are: (a) verification of the buildings and infrastructures stability and reinforcement measures when required, (b) elaboration of emergency plans of action, (c) schedule of the main actions required to restore the normality of the social and economic life after the earthquake.

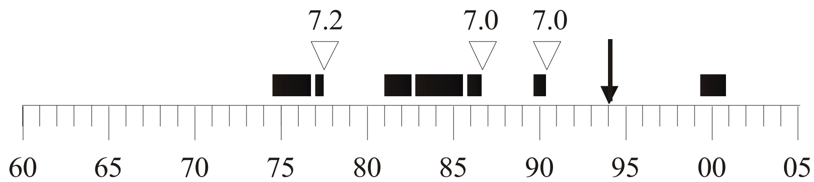

Fig. 1 – CN monitoring for the Vrancea region. Diagnosis of TIPs from 1966.03.01 to 2003.01.01 using the local catalog. The 3 strong earthquakes (Mo > 6.4) are preceeded by TIPs. The total duration of the TIPs represents 26.5% of the total time considered. The monitoring of current seismicity using the CN algorithm is carried out since 1994 (see arrow indication). No strong earthquake occurred from 1994.1.1 to 2003.1.1 but the CN declared an extended false alarm (18 months) from 1999.5.1 to 2000.11.1.

THE CN ALGORITHM

The CN algorithm (Keilis-Borok, Rotwain, 1990) is a formal intermediate-term medium range earthquake prediction algorithm, based on the quantitative analysis of the premonitory phenomena that can be detected in the seismic flow preceding the occurrence of strong earthquakes. This algorithm was originally developed considering the shallow seismicity of the California-Nevada region, and subsequently applied in many other parts of the world (Keilis-Borok, Rotwain, 1990; Novikova *et al.*, 1996; Costa *et al.*, 1996; Rotwain, Novikova, 1999).

The CN is structured according to a pattern recognition scheme, applied to the seismic flow of a selected region, to allow the identification of the Time of Increased Probability (TIP) of strong earthquakes with magnitude above a fixed threshold Mo. Two are the conditions which define Mo: (1) the average recurrence period of the strong events with M ≥ Mo is approximately 6-7 years, and (2) Mo is close to a minimum of the frequency-magnitude distribution of the earthquakes, occurred in the study region. The quantification of the seismicity patterns is based on phenomena that are observed in many non-linear systems before collapse (the response to a perturbation increases, becomes more chaotic, and acts at large distances). In our case, the non-linear system is the system of seismically active faults, the strong earthquakes are the catastrophic events that are responsible for a sudden variation of the dynamical properties of the system, whereas the small quakes are the sources of perturbation of the system and, at the same time, they reveal the escalation of the response of the system to the perturbation. Thus, before a strong earthquake, which represents the collapse of the system, we observe: (1) increase of the seismic activity, clustering of the earthquakes in time and space, and spatial concentration of sources; in other words, the escalation of the response to the perturbation; (2) increase of the variation of seismicity and its clustering, which reflects the chaotic response to the perturbation; (3) long-range interaction of earthquakes, which can be interpreted as an increase of the influence range of the perturbation. A set of nine empirical functions evaluate, within several sliding time windows, the seismic activity, seismic quiescence, space-time clustering of the seismic activity and spatial concentration of the earthquakes by considering the sequence of the main shocks which occurred in the analysed region. The flow of the earthquakes is represented, at each time, *t*, by a vector formed by the values of the different functions that define the algorithm CN. The functions are normalized, so that they can be applied to different territories, with different seismicity, without an *ad hoc* adjustment of the parameters.

The CN analysis identifies within the earthquake flow, along the time axis, three different categories of time intervals: D (Dangerous), N (Non-dangerous) and X (Undetermined). The D intervals extend for 2 years before each strong event. Intervals X extend for 3 years after each strong event. If a strong earthquake occurs within an X interval, the interval becomes a D interval. The remaining time intervals are N intervals. The division of the temporal axis into three types of time intervals is used at the stage of pattern recognition to choose the objects for learning. The intervals X (3 years after a strong event) are not used in the pattern recognition stage because they follow a strong shock.

The nine functions are discretized by defining the thresholds small, medium and large, on the basis of 33- and 66-percentile of the maximum value observed during the learning interval considered in the framework of the pattern recognition scheme. Then the algorithm estimates the combinations of the different discretized functions that are more typical for intervals D and N, respectively. Following the procedure of pattern recognition, features D are defined by the condition that they occur during most of the intervals D, and just in a few cases during the intervals N. Features N are defined by the opposite condition. Each feature corresponds to a discretized value of a function or to a combination of such values for two or three functions. At the stage of voting, each time *t* is tested regardless of its position with respect to the occurrence time of a strong earthquake.

A TIP for a strong earthquake is declared at the time *t* and for one year if: (1) the difference between the number of D and N features is greater or equal to a constant V, and (2) the total source area of the earthquakes occurred during the last 3 years before the time *t* is less than a constant E. These two conditions mean that there are many D features at the time *t* and that the seismic energy released is low. Consecutive TIPs may overlap and originate an alarm period exceeding one year. If during the TIP no strong event occurs – the alarm is false, while the occurrence of a strong event outside the TIP is a failure to predict.

The monitoring of current seismicity in different regions of the world using the algorithm CN is carried out since 1983 (Rotwain, Novikova, 1999). Up to present the CN algorithm identified correctly 16 strong earthquakes out the 21 that occurred within the 20 regions monitored. The total duration of the TIPs declared represents 24% of the entire time interval analysed while the statistical significance of the prognosis is about 95%.

INPUT DATA

Vrancea region, Romania, is one of the seismoactive areas where the seismic flow is currently monitored using the CN algorithm. A special attention is paid to this region because the consequences of its strong earthquakes can be disastrous over a very wide territory. The intermediate-depth events originating in Vrancea are confined in a well-defined volume, roughly delimited by a parallelepiped about 100 km long, 40 km wide, with a vertical extension from 50–60 km to 160–170 km of depth. The frequency of occurrence is about 10–15 events per month with local magnitude $M_L < 5.5$, and three to five strong events ($M_w \sim 7.0$) per century (Radulian *et al.*, 2000). The shallow activity is mainly located in the lower crust (depth > 15 km), often occurs in clusters, and the seismic energy released in the crust is substantially lower than the energy released at intermediate depths (the largest crustal earthquake ever recorded here has Ms = 5.3).

The data base obtained by merging the available catalogues for the Vrancea region (Novikova *et al.*, 1996) is continuously updated by adding the Vrancea events currently recorded by the Romanian seismic network (Moldoveanu *et al.*, 1995, continuously updated), and represents the input data for our study. The catalogue covers the rectangle $44.8^0 – 48.4^0$ N, $25.0^0 – 28.0^0$ E.

RETROSPECTIVE APPLICATION OF THE CN ALGORITHM TO THE VRANCEA REGION

One of the basic problems in the application of the CN algorithm is the choice of the regionalization to be used (Costa *et al.*, 1994, 1996; Peresan *et al.*, 1999). In this respect, the Vrancea region offers a special opportunity since a single zone of small linear dimensions is sufficient. For the time interval from 1932 to 1962, the Vrancea catalogue is complete for magnitudes above 4 only, thus it doesn't allow: (a) the determination of the algorithm parameters that depend on the smaller magnitudes and (b) the thresholds for the functions discretization that should be applied for the entire time interval covered by the catalogue. Nevertheless the catalogue offers the possibility to apply CN formally as a forward prediction. In fact, in analogy with what was done by Costa *et al.* (1994) for Italy, Novikova *et al.* (1996) applied the algorithm CN, to the period 1932–1962, using the parameters determined for the interval from 1962 to 1993. For the Vrancea seismicity the threshold magnitude of the strong earthquakes is found Mo = 6.4. Two strong shocks with M ≥ Mo occurred during the period 1932–1962, in 1940, with M = 7.4, and in 1945, with M = 6.4. The TIP is present before the earthquake of 1940, while the earthquake of 1945 is a failure to predict.

The retroactive simulation of the CN forward prediction made by Novikova *et al.* (1996) for the time interval from 1962.1.1 to 1994.1.1, using the intermediate-depth events from the Vrancea catalogue spanning the period from 1936.1.1 to 1994.1.1, correctly identifies the TIPs for the occurrence of three strong events above the threshold magnitude Mo = 6.4: (a) the M = 7.2 from March 4, 1977 is preceded by 2.1 months of alarm, (b) the M = 7.0 from August 30, 1986, is preceded by 12 months of alarm, and (c) the M = 7.0 from May 30, 1990, is preceded by 9 months of alarm. The duration of the TIPs registered before these three strong earthquakes is equal to 23.1 months. The algorithm also declared three false alarms with a cumulated duration of 76 months. The cumulated TIPs duration occupies 24.9% of the total time interval considered.

MONITORING OF VRANCEA SEISMICITY IN THE PERIOD 1994.1.1 – 2003.1.1

The strong Vrancea region seismicity has been continuously monitored since January 1994 using the CN intermediate-term medium-range algorithm. The values of the parameters used by the algorithm have been determined for the interval from 1962.1.1 to 1994.1.1. The TIPS diagnosis is performed from 1966.3.1. to 2003.1.1. On 1994.1.1 the "real time" monitoring starts.

No strong earthquakes (Mo ≥ 6.4) occurred in Vrancea from 1994.1.1 to 2003.1.1. but CN declared an extended false alarm (18 months) from 1999.5.1 to 2000.11.1. During this period the strongest recorded event has M = 5.0. The cumulated duration of the TIPs represents now 26.5% of the total period of time considered 1966.3.1–2003.1.1. There is no alarm currently declared in the region (on January 1, 2003), as can be seen from the TIPs diagram shown in Fig. 1.

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