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Experiment in Intermediate-term middle-range earthquake prediction in Italy and surrounding regions

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Algorithms for middle-range intermediate-term prediction

Algorithms fully formalized and globally tested for prediction are:

- **CN algorithm** (*Gabrielov et al., 1986; Rotwain and Novikova, 1999*)
- **M8 algorithm** (*Keilis-Borok and Kossobokov, 1987; Kossobokov et al., 1999*)

They allow to identify the TIPs (Times of Increased Probability) for the occurrence of a strong earthquake within a delimited region

Algorithms for middle-range intermediate-term prediction

The algorithms are based on a set of empirical functions to allow for a quantitative analysis of the premonitory patterns which can be detected in the seismic flow:

- **Variations in the seismic activity**
- **Seismic quiescence**
- **Space-time clustering of events**

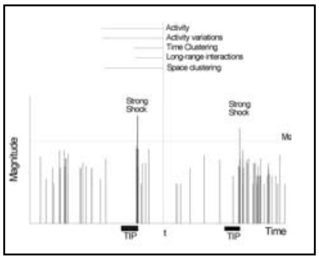
These methods are designed according to a pattern-recognition scheme, to define space and time limits where a disastrous earthquake has to be expected based on detectable inverse cascade of seismic process, at different space and time ranges.

Functions of the seismic flow

The functions of the seismic flow are computed over the sequence of main shocks within a predefined region.

Functions are normalized by minimal magnitude cutoff M_{min}, defined by one of the two conditions:

- **$M_{min} = M_0 - C$, C: constant**
- **M_{min} such as $N(M_{min}) = A$, A: constant rate of activity**



Normalization is necessary to ensure uniform application with the same set of adjustable parameters in regions of different seismic activity.

Functions of the seismic flow: magnitude ranges

CN algorithm

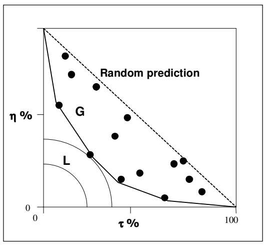
	N2	N3	K	G	Sigma	Smax	Zmax	q	Bmax
Mmin	m3	m2	m2	m2	m1	m1	m1	m2	-
Mmax	-	-	-	-	Mo-1	Mo-1	Mo-1	-	-

Magnitude cutoff for normalization of functions, based on rate of activity: m1(a=3.0) m2(b=1.4) m3(c=0.4)

M8 algorithm

	N1	L1	Z1	N2	L2	Z2	Bmax
Mmin	M(10)	M(10)	M(10)	M(20)	M(20)	M(20)	-
Mmax	-	-	Mo-0.5	-	-	Mo-0.5	Mo-0.2

Evaluation of prediction results



The quality of prediction can be characterised by using two prediction parameters:

$\eta=n/N$: the rate of failures-to-predict

$\tau=t/T$: the rate of alarm times

N is the number of strong earthquakes occurred during the time period T covered by prediction

The alarms cover altogether the time t and they have missed n strong events

- **The performance of the prediction algorithm is characterized by its error curve G, which shows how far from a random guess are the resulting predictions.** (*Molchan, 1997*)

CN algorithm in Italy

Rules for CN application and selection of target events

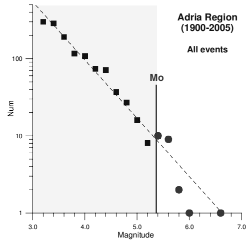
Area: 5L-10L (L is the source linear dimension)

Magnitude of completeness:
- $M_o - \Delta M \geq M_c$ where $\Delta M \approx 3$
- Yearly average number of events with $M \geq M_c$ must be>3

Magnitude threshold M_o:
- M_o corresponds to a minimum of N(M)
- The return period for events with $M \geq M_o$ is ≈6-7 years

➡ CN makes use of the information given by small and moderate earthquakes, following the GR law (having quite a good statistic), to predict the stronger earthquakes, which are anomalous events (i.e. do not follow the GR law) for the same area.

Choice of M_o



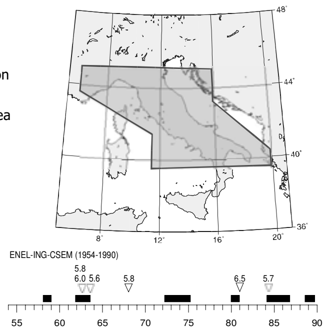
M_o=5.4 (17 events)
Return Period: about 6 years

First application of CN algorithm in the Italian area

Italian Region

(Keilis-Borok et al., 1990, Pageoph, 134)

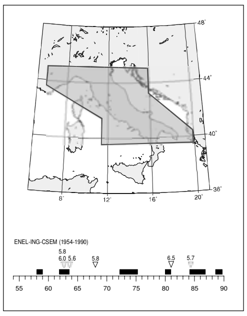
- Regionalization defined based on the completeness of the used catalog ENEL-ING-CSEM, partially covering the Adriatic sea
- Prediction of the events with M≥5.6
- TSP:1954-1986; TIP diagnosis: 1954-1990
- Results: 80% predicted events (4 out of 5) TIP: 26.0% of total time



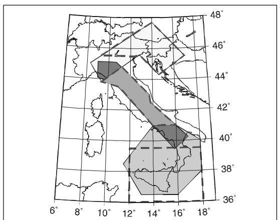
▽ Strong Earthquakes with M≥5.6

▬ TIPs

Evolution of the regionalization for the Italian territory



(Keilis-Borok et al., 1990)



	NORTH		CENTRE		SOUTH	
	Area 1	Area 2	Area 1	Area 2	Area 1	Area 2
Events Predicted/total	2/2	2/2	3/3	3/4	3/3	1/2
False alarms	1	2	2	4	5	2
TIP %	27	34	23	38	33	25

(Costa et al., 1995; 1996)

Rules for the definition of CN regions according to the seismotectonic model

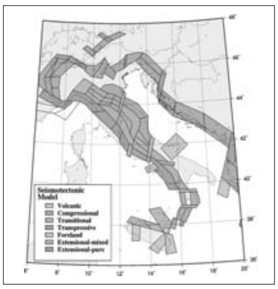
A single region includes:

1. **adjacent zones with the same seismogenic characteristics (e.g. only compressive or only extensive);**
2. **zones with transitional properties.**

A transitional zone is included in a region if:

1. **it is between zones of the same kind;**
2. **it is at the edges of the region and the space distribution of the aftershocks reveals a possible connection.**

(Peresan, Costa & Panza., 1999, Pageoph, 154)



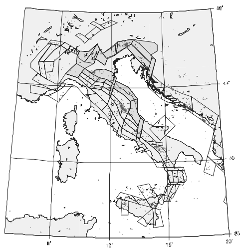
Seismotectonic zoning of Italy defined by GNDT (Gruppo Nazionale per la Difesa dai Terremoti)
(Meletti et al., Pageoph, 2000)

Intermediate-term middle-range earthquake prediction CN

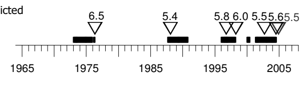
NORTHERN REGION

Prediction of the events with M≥5.4
Updated to 1-9-2007
(next update: 1-11-2007)

TIP: 29.0% of total time



▬ TIPs
▽ Strong Earthquakes predicted
▽ Failure to predict



Intermediate-term middle-range earthquake prediction CN

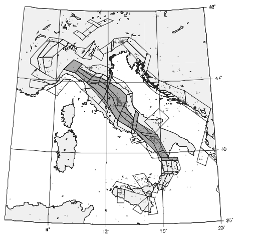
CENTRAL REGION

Prediction of the events with M≥5.6

Updated to 1-9-2007

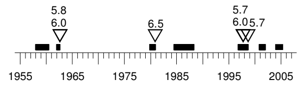
(next update: 1-11-2007)

TIP: 22.2% of total time



TIPs

Strong Earthquakes predicted



Intermediate-term middle-range earthquake prediction CN

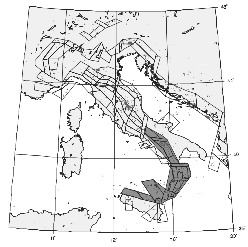
SOUTHERN REGION

Prediction of the events with M≥5.6

Updated to 1-9-2007

(next update: 1-11-2007)

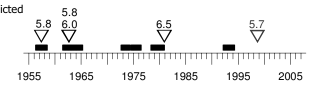
TIP: 27.3% of total time



TIPs

Strong Earthquakes predicted

Failure to predict



Intermediate-term middle-range earthquake prediction

Space-time volume of alarm in CN application in Italy

Experiment	Space-time volume of alarm (%)	n/N	Confidence level (%)
Retrospective* (1954 – 1963)	41	3/3	93
Retrospective (1964 – 1997)	27	5/5	>99
Forward (1998 – 2007)	36	4/5	94
All together (1954 – 2007)	30	12/13	>99

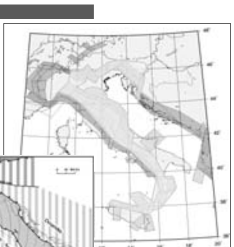
* Central and Southern regions only

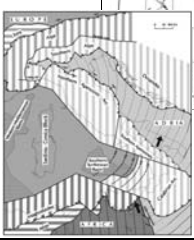
Algorithm CN predicted 12 out of the 13 strong earthquakes occurred in the monitored zones of Italy, with 30% of the considered space-time volume occupied by alarms.
(updated to September 1 2007)

The regionalization based on the seismotectonic model

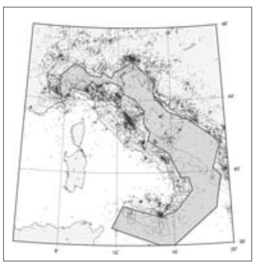
- **The seismotectonic model, supported by kinematic arguments, can be viewed as a useful tool that permits to optimise the selection of the fault systems involved in the generation of strong earthquakes.**

Adriatic Region





CN region



(Meletti et al., Pageoph, 2000)

CN application to the Adriatic region

ADRIA REGION

Prediction of the events with M≥5.4

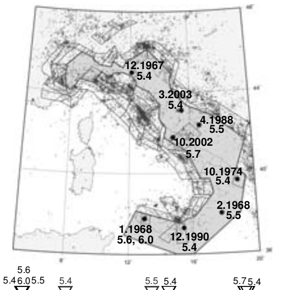
UCI catalog

Updated to 1-9-2007

(next update: 1-11-2007)

TSP: 1.1 1999

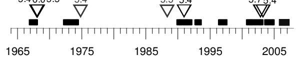
75% predicted events (6 out of 8)
TIP: 34.9% of total time
6 false alarms



TIPs

Strong Earthquakes predicted

Failure to predict



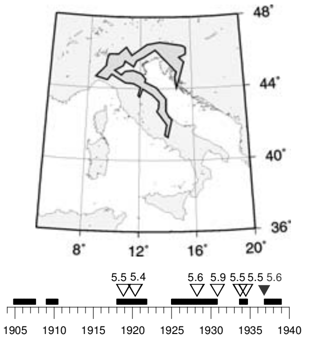
CN algorithm in Italy: stability experiments

CN algorithm in Italy: stability experiments

Experiment "seismic history" Northern Region

Prediction of the events with M≥5.4
TSP:1964-1998
TIP diagnosis: 1904-1940

86% predicted events (6 out of 7)
TIP: 48.0% of total time

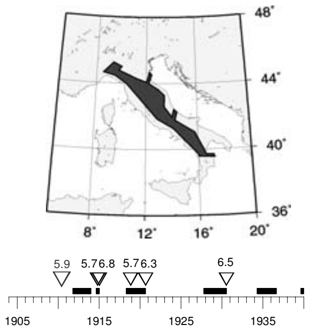


CN algorithm in Italy: stability experiments

Experiment "seismic history" Central Region

Prediction of the events with M≥5.6
TSP:1954-1998
TIP diagnosis: 1904-1940

84% predicted events (5 out of 6)
TIP: 28.7% of total time

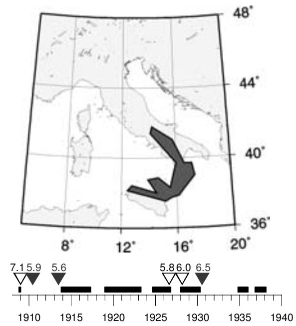


CN algorithm in Italy: stability experiments

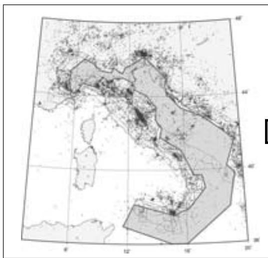
Experiment "seismic history" Southern Region

Prediction of the events with M≥5.6
TSP:1954-1998
TIP diagnosis: 1908-1940

50% predicted events (3 out of 6)
TIP: 46.8% of total time



CN algorithm: stability test for the Adria region



TIP diagnosis: 1964-2006.11

M_0=5.4	UCI catalog				
End of TSP	*n/N*	η	τ	ξ	κ
2003-01	6/8	25.0%	31.3%	56.3%	45.0%
1999-01	6/8	25.0%	31.3%	56.3%	45.0%
1991-01	6/8	25.0%	28.2%	53.2%	40.0%
1988-05	6/8	25.0%	34.4%	59.4%	45.0%

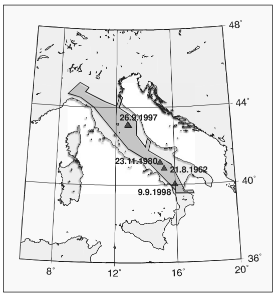
n = number of predicted earthquakes with M≥5.4
N = total number of main shocks with M≥5.4
η = n/N statistic of failures to predict
τ= τ_Σ /T statistic of alarm time
κ= k/K statistic of false alarms

To evaluate the stability of prediction results, the time period (TSP) used to adjust the algorithm thresholds, is progressively reduced.

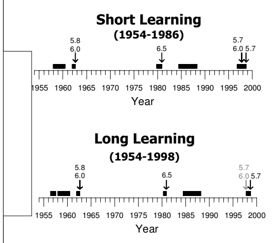
The results of the experiment show that the *(η+τ)* is well below the value (η+τ)=100% corresponding to the results of a random guess.

The total error is comparable with that obtained on a global scale (about 50%)

CN algorithm in Central Italy: results obtained with the original catalog



Prediction of the events with M≥5.6



TIPs obtained with the original catalog with a different length of the "thresholds setting period" (Learning)

Randomised Magnitude

$$M_R = M_C + \Delta M_I + \Delta M_D$$

M_c : operating magnitude

ΔM_I : measurement error ΔM_D : error of discretisation

Measurement random errors

$P(\Delta M_I) = F^{TR}(\Delta M_I)$

Truncated normal probability distribution with: $\sigma = \Delta M_{max} / 3$

$F^{TR}(\Delta M_I) = F(\Delta M_I)/[2F(\Delta M_{max})-1]$

ΔM_{max} = maximum assumed error on magnitudes

$$|\Delta M_I| \leq \Delta M_{max}$$

Errors of magnitude discretisation

$P(\Delta M_D)$ = Uniform probability distribution

Interval: [-d/2; d/2)

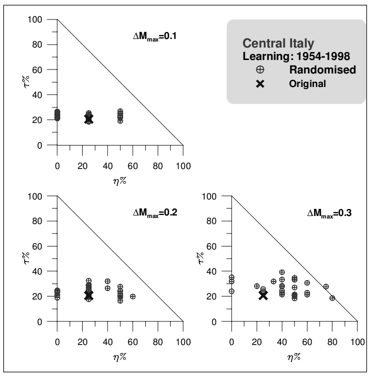
d=discretization step=0.1

Stability of TIPs diagnosis with respect to random errors in magnitude

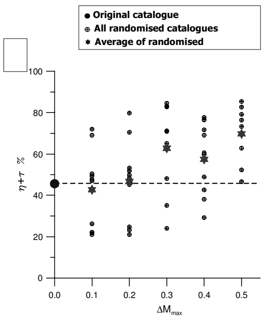
Central Italy

***$\eta=n/N$*:**
the rate of failures-to-predict

***$\tau=t/T$*:**
the rate of time of alarms



Results obtained with the randomised catalogue



Event date	M	N_S %	N_P %
23.11.1980	6.5	100.0	66.7
21.8.1962	6.0	100.0	93.3
26.9.1997	6.0	100.0	40.0
9.9.1998	5.7	83.3	56.0
19.9.1979	5.5	23.3	0.0
5.5.1990	5.5	12.0	0.0
7.5.1984	5.4	0.0	0.0

List of earthquakes with M≥5.6
Central Italy: 1950-1999

N_S : percentage of times each event is a strong event ($M \geq M_s = 5.6$)

N_P : percentage of times each event is predicted (catalogues randomised with $\Delta M_{max} = 0.3$)

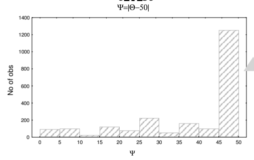
Stability of TIPs diagnosis with respect to random errors in magnitude

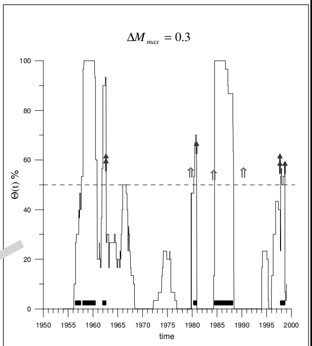
Central Italy

Ψ: percentage of tests for which the recognition of the time *t* does not change with respect to its average value

0≤Ψ≤50

$\Psi = |\Theta - 50|$





$\Theta(t)$: percentage of tests for which the time *t* belongs to a TIP

Peresan, Rotwain, Zaliapin, Panza , PEPI, 130 (2002)

Stability of CN predictions with respect to random errors in magnitude

- **The results of prediction remain stable for ΔM_{max}<0.3.**
- **The quality of predictions is mainly controlled by the percentage of failures to predict, which depends on the changes in the number of strong earthquakes.**
- **The identification of TIPs is very stable during most of the time and the randomisation does not introduce spurious alarming patterns associated with the occasionally strong events.**

Peresan, Rotwain, Zaliapin, Panza , PEPI, 130 (2002)

M8S algorithm in Italy

Algorithm M8S

- **The M8 algorithm, analyses the seismic activity inside a set of Circles of Investigation, CIs, with radius normalized by the linear size of the events to be predicted, i.e. proportional to magnitude threshold M_0.**
- **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: $M_0 \le M \le M_0+0.5$).**

Algorithm M8S

- **A new spatially stabilized variant of the algorithm M8 has been proposed , namely M8s algorithm, where the seismicity is analysed within a dense set of overlapping circles covering the monitored area** **(*Kossobokov et al., JSEE 2002*).**
- **The territory is scanned with a set of small circles distributed over a fine grid, with the radius of the small circles approximately equal the grid spacing and to the linear dimensions of the source of target events.**

Algorithm M8S : steps of the analysis

1. **The seismically active grid points are then selected by the condition that the average annual rate of seismic activity, within the small circle, is above a given threshold.**
2. **The grid points where data are insufficient for the application of M8 algorithm and isolated grid points are excluded.**
3. **The M8 algorithm is then applied with the circles of investigations, CIs, centred at each of the selected grid points.**
4. **An alarm is declared for a CI only if the overwhelming majority (more than 75%) of the CIs centred at the neighbouring grid points are also in state of alarm.**

M8S algorithm in Italy

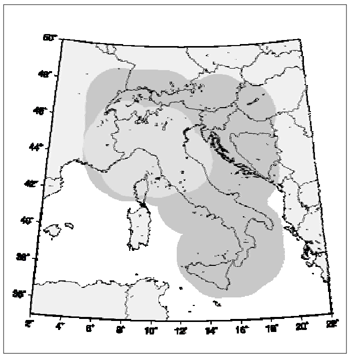
Magnitude:
M≥ 6.5

Radius of CI:
192 Km

Monitored region

Alerted region

Predictions as on: 1-7-2004



M8S algorithm in Italy

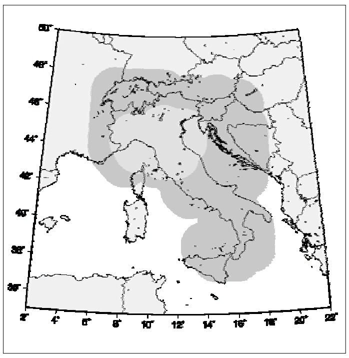
Magnitude:
M≥ 6.0

Radius of CI:
138 Km

Monitored region

Alerted region

Predictions as on: 1-7-2004



M8S algorithm in Italy

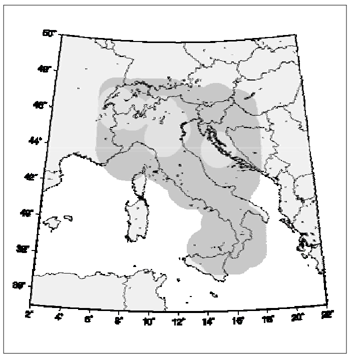
Magnitude:
M≥ 5.5

Radius of CI:
106 Km

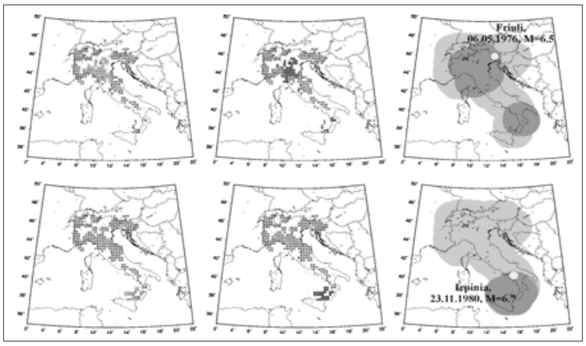
Monitored region

Alerted region

Predictions as on: 1-7-2004



Scheme of M8S algorithm prediction of earthquakes Friuli, 06.05.1976 and Irpinia, 23.11.1980.



Intermediate-term middle-range earthquake prediction

Space-time volume of alarm in M8S application in Italy

Experiment	M6.5+		M6.0+		M5.5+	
	Space-time volume, %	n/N	Space-time volume, %	n/N	Space-time volume, %	n/N
Retrospective (1972-2001)	36	2/2	40	1/2	39	9/14
Forward (2002-2007)	49	0/0	43	0/0	25	5/9
All together (1972-2007)	37	2/2	40	1/2	38	14/23

Algorithm M8s predicted 63% of the events occurred in the monitored zones in Italy, i.e. 17 out of 27 events occurred within the area alerted for the corresponding magnitude range. The confidence level of M5.5+ predictions since 1972 has been estimated to be about 97%; no estimation is yet possible for other magnitude levels.
(updated to July 1 2007)

Real-time monitoring of the seismic flow: CN and M8S algorithms in Italy

Intermediate-term middle-range earthquake prediction experiment in Italy

CN algorithm (*Keilis-Borok et al., 1990; Peresan et al., 2005*)
M8S algorithm (*Kossobokov et al, 2002*)

Main features:

- **Fully formalized algorithms and computer codes available for independent testing;**
- **Use of published & routine catalogues of earthquakes;**
- **Worldwide tests ongoing for more than 10 years permitted to assess the significance of the issued predictions** (*Kossobokov et al., 1999; Rotwain and Novikova, 1999*)

Italy:

- **Stability tests with respect to several free parameters of the algorithms** *(e.g. Costa et al., 1995; Peresan et al., GJI, 2000; Peresan et al., PEPI, 130, 2002);*
- **CN predictions are regularly updated every two months since January 1998;**
- **M8S predictions are regularly updated every six months since January 2002;**

Real time prediction experiment started in July 2003

Intermediate-term middle-range earthquake prediction experiment in Italy

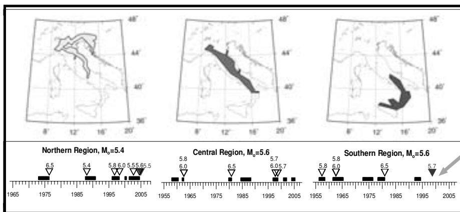
Prediction experiment: launched starting on July 2003, is aimed at a *real-time test* of CN and M8S predictions in Italy.

Updated predictions are regularly posted at:

"http://www.ictp.it/www_users/sand/prediction/prediction.htm"

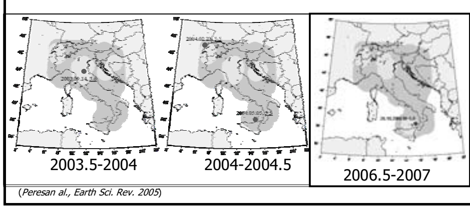
A complete archive of predictions is made accessible to a number of scientists, with the goal to accumulate a collection of correct and wrong predictions, that will permit to validate the considered methodology.

Current predictions are protected by password. Although these predictions are intermediate-term and by no means imply a "red alert", there is a legitimate concern about maintaining necessary confidentiality.



CN algorithm

Times of Increased Probability for the occurrence of events with M>Mo within the monitored regions



(*Peresan al., Earth Sci. Rev. 2005*)

M8S algorithm

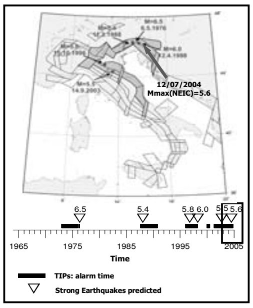
Monitored region

Alerted region

Events with M_{max} ≥5.5 occurred since July 2003

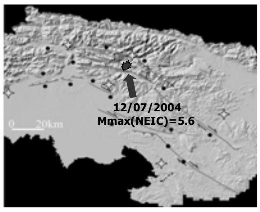
Updated to September 1 2007

The CN real-time monitoring of seismic flow

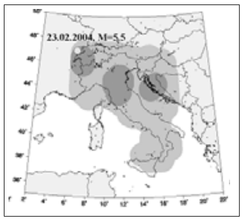


The Bovec earthquake - July 12 2004
Alarmed area for M≥5.4 by CN algorithm
(Peresan et al., ESR,2005)
(As on 1 July 2004)

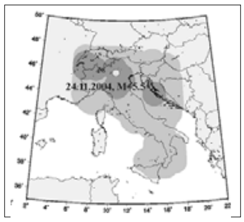
Southeastern Alps – External Dinarides
InSAR - CGPS - Campaign GPS monitoring



The M8S real-time monitoring of seismic flow

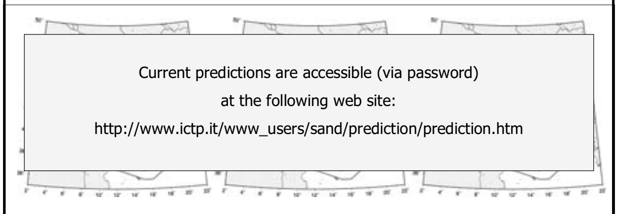


The Switzerland earthquake
February 23 2004
Alarmed area for M≥5.5 by M8S algorithm
(Peresan et al., ESR,2005)
(As on 1 January – 1 July 2004)



The Salò earthquake
November 24 2004
Alarmed area for M≥5.5 by M8S algorithm
(Peresan et al., ESR,2005)
(As on 1 July 2004 – 1 January 2005)

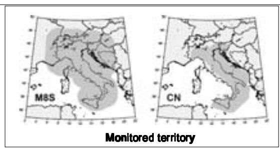
The current situation of alarms (since July 1 2007)



Current predictions are accessible (via password)
at the following web site:
http://www.ictp.it/www_users/sand/prediction/prediction.htm

Alarmed areas by:
- **M8S algorithm for M5.5+, M6.0+, M6.5+**
- **CN algorithm for M≥5.4**

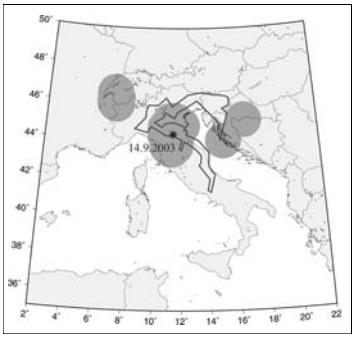
(Peresan , Kossobokov, Romashkova, Panza 2005, Earth Science Reviews, 69)



Monitored territory

(Subject to update on 1 November 2007)

Integrating CN and M8s prediction results



- **5 out of the 8 events with M ≥5.5, common to the 2 experiments (CN and M8s), are predicted by alarms declared by both algorithms.**
- **Space-time volume occupied by alarms around 16%.**
- **Space uncertainty reduced to about 15% of the common monitored area.**

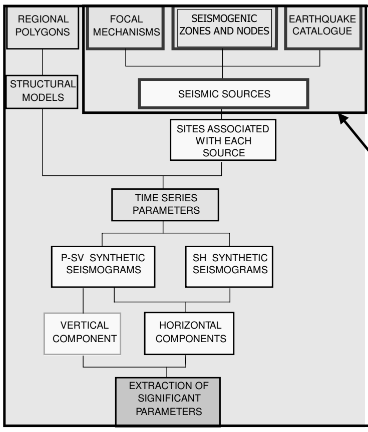
A review of the application of the algorithms CN and M8 to the Italian territory, about the input data, as well as detailed information about their performances is provided in:

"*Intermediate-term middle-range earthquake predictions in Italy: a review*" (2005), by A. Peresan, V. Kossobokov, L. Romashkova and G.F. Panza. Earth Science Reviews (69, 97-132, 2005).

Time dependent Neo-deterministic Hazard Scenarios

Regional seismic hazard scenarios
(ground motion at bedrock)

- Scenarios associated to alerted CN and M8S regions (+ time)
- Scenarios associated to seismogenic nodes

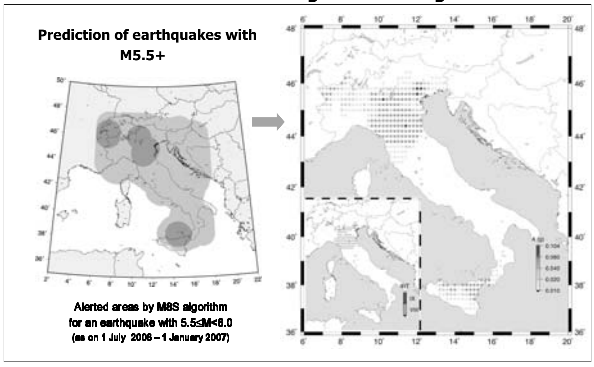


Flow-chart of the neo-deterministic hazard method

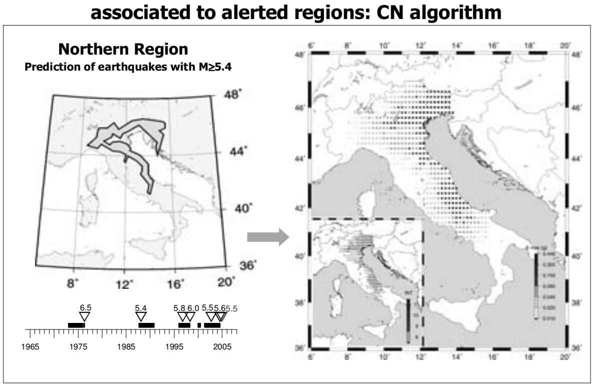
Seismic sources are defined based on seismic history, seismotectonic and seismogenic nodes.

Seismic sources are then selected within the alerted regions (CN or M8S) or within the earthquake prone nodes.

Neo-deterministic hazard scenarios associated to alerted regions: M8S algorithm



Neo-deterministic hazard scenarios associated to alerted regions: CN algorithm

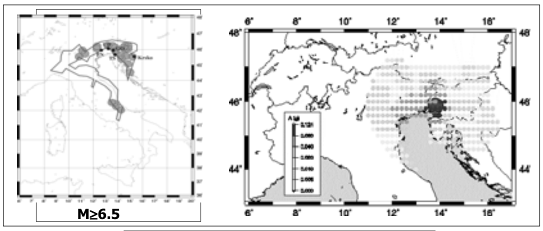


Scenario associated to earthquake prone nodes

Example: node determining the maximum ground motion in the city of Trieste

corresponding to an earthquake with M=6.5

(compatible with seismic history and seismotectonics)



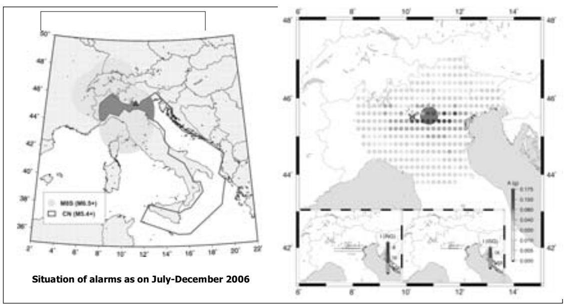
PGD (cm)	PGV (cm/s)	DGA (g)	I_{max} computed ING	I_{max} computed ISG	I_{max} observed
2.0 – 3.5	4.0 – 8.0	0.08-0.15	IX	VIII	VII

Peak Ground Displacement (PGD), Peak Ground Velocity (PGV), Design Ground Acceleration (DGA) and maximum computed intensity (I_{max} computed), estimated using the conversion tables proposed by Panza et al. (2001). The observed intensity in the city of Trieste is the same in the ING and ISG data sets.

Scenario associated to earthquake prone nodes

Example: earthquake with M=6.5 occurring at the node within the alerted region

(compatible with seismic history and seismotectonics)



Design Ground Acceleration (DGA) and maximum computed intensity (I_{max} computed), estimated using the conversion tables proposed by Panza et al. (2001) based on ING and ISG data sets.

ASI Pilot Project - SISMA
"Seismic Information System for Monitoring and Alert"

Development of a system, based on the neo-deterministic approach for the estimation of seismic ground motion, integrating the space and time dependent information provided by real-time monitoring of seismic flow and EO data analysis, through geophysical forward modeling.

DST

University of Milano

Politecnico di Milano

Positive steps towards implementation:

An agreement has been signed among the Abdus Salam International Centre for Theorethical Physics, **ICTP**, and the **Civil Defence** of the Friuli Venezia Giulia Region (NE Italy) for the practical implementation of the integrated neo-deterministic hazard procedure.

Routinely updated predictions and related seismic hazard maps are made available to the Civil Defence (end user).