A STRONG MOTION NETWORK IN NORTHERN ITALY: DETECTION CAPABILITIES AND FIRST ANALYSIS

Paolo Augliera, Ezio D'Alema, Simone Marzorati and Marco Massa

Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Milano-Pavia, via Bassini 15, 20133 Milano, Italy

Abstract

The necessity of a dense network in Northern Italy started from the lack of available data after the occurrence of the 24^{th} November 2004, Ml 5.2, Salò earthquake. Since 2006, many efforts have been made by the INGV (*Italian National Institute for Geophysic and Vulcanology*), Department of Milano-Pavia (hereinafter INGV MI-PV), to improve the strong-motion monitoring of the Northern Italy regions. This activity led to the installation of a strong-motion network composed by 20 accelerometers, 4 coupled with 20-bits Lennartz Mars88 recorders, 12 coupled with 24-bits Reftek 130 recorders and 4 coupled with 24-bits Gaia2 recorders.

The network allow us to reduce, in the area under study, the average inter-distances between strong-motion stations from about 40 km (at November 2004) to 15 km. At present the network includes nine 6-channels stations where velocity sensors work together the strong-motion ones. The data transmission is assured by modem-gsm, with the exception of 4 stations that send data in real time through a TCP/IP protocol. In order to evaluate different site responses, the stations have been installed both in free field and near (or inside) public buildings, located in the center of small villages. From June 2006 to December 2008 a dataset of 94 events with local magnitude range from 0.7 to 5.1 has been collected. An ad-hoc data-processing system have been created in order to provide, after each recorded event, engineering parameters such as peak ground acceleration (PGA) and velocity (PGV), response spectra (SA and PSV), Arias and Housner intensities. Data dissemination is achieved through the web site http://rais.mi.ingv.it, while the waveforms are distributed through the Italian strong motion database (http://itaca.mi.ingv.it).

Key words North Italy - strong motion station - data acquisition system - seismic networks

Introduction

The strong-motion data are fundamental for earthquake engineering studies such as advanced structural analyses, seismic hazard evaluation, site effects and calibration of ground motion attenuation relationships.

In Italy the strong-motion monitoring is assured since 1972 by the *National Accelerometric Network* (RAN) managed up to 1998 by ENEA (*Italian energy and environment organization) and* ENEL (*Italian electricity company)* and then by DPC (*Department of Italian Civil Protection*). At present RAN network is composed by 119 analogical stations and 269 digital ones. At the same time the Italian regions are monitored by a velocimetric national network managed by the *Italian Institute for Geophysics and Vulcanology* (*National Earthquake Center* INGV-CNT, http://cnt.rm.ingv.it/). The latest represents the official organization in charge of providing focal parameters in case of an earthquake. At present the national velocimetric network (Delladio et al., 2006) consists of about 300 seismic stations (80 of them coupled with strong-motion sensor) equipped with 3-component broadband sensors able to send data in real-time both by satellite or terrestrial cable links (http://iside.rm.ingv.it/).

Due to the low level of seismic hazard (Gruppo di Lavoro, 2004), the lowest density of installation is detectable in Northern Italy. Since 2003, the INGV (Department of Milano Pavia) started the installation of a regional velocimetric network in the area of Central-North Italy with the main scope of studying the propagation effects in a very deep sedimentary basin (Po plain). At present 9 velocimetric sensors, characterized both by broad-band (40s) and long-period sensors (5s), are installed in this area and work coupled to 9 strong-motion sensors of RAIS (see column 8 in Table 1).

It is worth noting that although if Northern Italy is an area with relatively low seismicity (with the exception of the Friuli region), both for the energy release and rate of strong events, it is an area which can be affected by energetic events. This is highlighted by not well constrained historical earthquakes such as the 1117, Mw 6.49, Verona earthquake (Galadini et al. 2001; Guidoboni et al. 2005), or the 1222, Mw 6.05, Brescia earthquake (Guidoboni et al. 1986), or by better defined events such as the 1695, Mw 6.61, Asolo earthquake (Galadini et al. 2005; Burrato et al. 2008) or the more recent 1901, Mw 5.67 (Io=VIII MCS; Camassi and Stucchi 1996), Salò earthquake. All information related to the estimated moment magnitude Mw are obtained from the CPTI04 earthquake parametric Italian catalogue (Gruppo di Lavoro

CPTI 2004). The 24^{th} November 2004, Ml 5.2 (Mw 5.0) Salò earthquake (Augliera et al., 2006) was the strongest event that shocked the Northern Italy in the last 30 years (see black square in figure 1). On the bases of the official data provided by the Lombardia Region authorities, this earthquake, felt in Northern Italy, strongly affected 66 municipalities close to the epicentral area, damaging about 3700 buildings and 300 churches, for an approximate damage evaluation of 215 million euros. In the epicentral area only one analogue strong-motion station of the RAN network, recorded the mainshock. The peak ground horizontal acceleration, recorded at an epicentral distance of 14 km, was 0.071 g (http://itaca.mi.ingv.it). Due to the lack of stations installed in the epicentral area, the first not saturated data was recorded, by a INGV-CNT velocimetric station, at an epicentral distance of 88 km.

In order to avoid the lack of recordings in the case of future earthquakes in Northern Italy, since June 2006, the INGV MI-PV has been starting the installation of a dense strong-motion network named RAIS (*Strong Motion Network in Northern Italy;* in italian: **R**ete **A**ccelerometrica in **I**talia **S**ettentrionale, http://rais.mi.ingv.it, figure 1 and table 1).

The main goals of the RAIS is both to collect data with a wide range of magnitude, allowing us to increase the knowledge on the area, and to assure high quality dataset in case of strong events. In seismology the measured range of amplitudes is very large: the natural background noise, highly frequency dependent, sets the limit for the smallest amplitude at about 1nm of displacement at 1 Hz, while the largest displacement due to an event is of the order of 1 m (Clinton 2004). This represents a dynamic range of 10^9. The seismological frequency band of interest ranges from 10^{-5} to 1000 Hz (in the most cases up to 100 Hz). The challenge is therefore to use instruments which can record energy over a wide frequency/amplitude range.

In the past, analog instruments were usually made to record one type of ground motion like velocity or acceleration. Traditionally, seismologists focus their studies on data recorded by velocity sensor, for the easier interpretation of seismic phases, while engineers use accelerograms to evaluate seismic performance on structures. Today, thanks to the progress of technology, weak-motion instruments can measure rather strong motions and strong-motion sensors are sensitive as the weak-motion sensors. Finally the digital recordings make easier the conversion from acceleration to velocity and vice versa (Havskov and Alguacil 2004).

Planning and detection models

After the 2004 Salò earthquake, the lack of digital strong-motion stations, in the central sector of Northern Italy, forced the INGV and, in particular the department of Milano-Pavia, to plan the installation of a dense strong-motion network.

RAIS arose thanks to a project namely "Stazioni accelerometriche in Italia Settentrionale" included in the framework of the 2004-2006 agreement between INGV and DPC. The main goals were both to improve earthquake detection in the area and to ensure the collection of high-quality data in the case of strong events.

As shown in figure 1 the studied area includes mainly the Lombardia and Veneto regions. The first installation of strong-motion sensors exploited the sites where nine INGV-MI PV velocimetric station ware already present. At the end of December 2008 20 strong-motion stations (blue triangles in figure 1) were installed in the area of interest. In agreement with INGV-CNT (on the basis of their station present in North Italy, see figure 1) others 4 installations have been planned for 2009 (yellow triangles in figure 1). The RAIS network reduces, in the area surrounding the 24th November 2004 Salò event, the average inter-distances between strong-motion stations from about 40 km (at November 2004) to less than 15 km.

The first phase of the project concerned the choice of the sites for installations: the selection criteria are generally based on off-site and in-field studies (Trnkoczy et al. 2002).

The site selection has been generally a compromises between the network geometry, which depends on the purpose of the monitoring, and the criteria that a given site presents in order to be suitable for an installation.

The installations have been preceded by microtremors analyses performed using horizontal to vertical spectral ratio (HVNR) computed for each site by Nakamura technique (figure 2, left panel). In some stations additional Pseudo Spectral Density (PSD) analyses, coupled with Probability Density Functions (PDF), have been performed. In particular, we investigated the variation of seismic noise by computing the PDF for a set of PSD (McNamara and Buland 2004). In the example of Figure 2 (right panel), following the procedure used in Marzorati and Bindi (2006), to investigate the characteristics of background seismic noise in North-central Italy, we processed seismic noise windows of at least 30 minutes recorded by a broad band sensor with a sampling rate of 100 sps. The data have been processed by removing mean and linear trend and then applying a digital Butterworth filter in the frequency

range 0.1-25 Hz. The time-series have been divided into segments of 60 s with an overlapping of 75% in order to reduce the variance in the PSD computation.
Several strong-motion stations have been installed in the Po Plain, the area of Italy with highest density of both civil and industrial structures. The main goal of the noise measures, performed during the sites selection, was to detect anomalous peaks (i.e. coming from industrial plants) that might avoid the spectra of seismic recordings. As demonstrated by Marzorati and Bindi (2006) the whole area of North Italy is characterized by a man-made background seismic noise that represents the dominant sources of high-frequency noise (> 1Hz), generated by the coupling of soil with traffic and machinery energy.
In some cases, stations have been installed inside buildings (i.e. ASO7 inside a medieval fortress) and in this case the influence of the structure on the recordings has been evaluated (Massa et al., 2009).
The influence of both noise and acquisition levels of each recorder with respect to a detection threshold is exemplified in figure 3. The spatial variability of magnitude, corresponding to the magnitude detection threshold, has been estimated by comparing the average noise levels, measured at each site, with a synthetic spectrum. The synthetic spectrum is computed by considering the ω-square source model (Brune 1970) for a distribution of earthquakes located at each node of a regular grid with step of 1 km in the inner zone of the network (8250 points) and 5 km outside (1200 points). The moment magnitude ranges from 1.5 to 4.5 with step 0.1, for a total of 9450 simulated earthquakes for each magnitude value. The source spectrum is propagated to each station assuming the 1/R geometrical spreading term. We assumed that an earthquake is detected by the network when the signal-to-noise ratio, computed in the frequency range 1-10 Hz, is larger than 10 at least for 3 stations. In this configuration the analysis shows a detection threshold roughly above magnitude 2 in the inner zone of the network and about magnitude 3.0 outside (figure 3).

Acquisition system and data processing

With the aim to check the performance of the strong-motion sensors, the first nine accelerometers were coupled to the velocity sensors. After simple numerical conversions, performed on the same signals recorded by different systems, comparisons have been made in order to verify the goodness of strong-motion records both in time and in frequency domains.

The RAIS network is equipped with Kinemetrics Episensors (FBA ES-T) characterized by 155 db of dynamic range and a full scale of 2.0 g. At present 12 sensors are coupled with Reftek 130-01 24-bits digital recorders, 4 with Gaia2 24-bits digital recorders (produced by INGV-CNT laboratories) and 4 with Lennartz Mars88-MC 20 bits digital recorders.

For 16 stations the transmission of data is assured by modem-GSM, while the stations MILA (wi-fi connection), EUCT, MER2 and CONC (Table 2) are able to send the data in real time through a TCT/IP protocol by using SeisComP software (http://geofon.gfz-potsdam.de/geofon/seiscomp).

The stations equipped with Reftek-130 and Gaia2 record signals in continuous mode with a sampling rate of 100 Hz, and an ad-hoc system has been created in order to download each seismic event into central system (D'Alema 2007). On the contrary for the stations equipped by Mars88-MC the softwares provided by Lennartz (http://www.lennartz-electronic.de/) are used.

At present the event detection is made using the Mars88 recorders, that are equipped by an automatic system able to trigger the events on the basis of a multi-stations coincidence scheme (D'Alema and Marzorati, 2004). In the future, the 4 Mars88 stations with lower dynamic will be replaced, and a new procedure (now in progress) will include the following steps:

a) for the event detection the location given by INGV-CNT will be used.
b) the new location (point *a*) will be consider as a warning signal for data acquisition and as input to start an automatic procedure to download data.
c) every 5 minutes the file containing the list of locations (provided by INGV-CNT) will be downloaded.
d) In case of a new event the ratio between the theoretic signal, in a fixed frequency band, and with the average noise level is evaluated for each site.
e) if the ratio estimated in point *d* will exceed a fixed threshold for almost 3 station, the event ID will be memorized and the procedure for data download at the RAIS stations will start.

At present the system is in the test phase, in order to define the best values for frequency band and threshold values.

Nowadays data from different datalogger are acquired in their native format and later converted in SAC format. All data are then collected in a common workstation where the processing starts.

A first phase of pre-processing, in order to remove the so called non-standard errors (multiple events in the same records and presence of spikes), is made. In a second phase a first-order baseline operator is applied to the whole record, in order to have a zero-mean of the signal, then, a simple baseline correction is applied by removing the linear trend, computed with a least square method. Digital data were filtered using an acausal 4th order Butterworth filter.

Using codes ad-hoc developed, for each strong-motion waveform PGA (peak ground acceleration), PGV (peak ground velocity), SA (acceleration response spectra), PSV (pseudo-velocity response spectra), Rd (displacement response spectra), IA (Arias Intensity; Arias 1970) and IH (Housner intensity; Housner 1952) are automatically calculated.

Finally, for each site, the HVSR (horizontal to vertical spectral ratio on earthquake) is calculated after the selection of the first 10 s of the S phase. To calculate HVSR the mean and the linear trend are removed and then a 4th order band-pass Butterworth filter between 0.2 and 25 Hz is applied; then the FFT is calculated and then smoothed using the Konno and Ohmachi (1998) window; the spectral ratio between the root-mean square average spectrum of the horizontal components and the spectrum of the vertical component is so calculated. For each event with Ml > 3.0, PGA, PGV and SA values (for period of 0.3 s, 1.0 s and 3.0 s) are sent to the INGV-CNT with the aim to improve the calculation of the shake maps of the event (http://earthquake.rm.ingv.it/shakemap/shake/index.html).

First Results

Since June 2006 the strong-motion network allowed us to start a detailed monitoring of the central area of northern Italy. In figure 4 a comparison between the spectra related of events recorded by RAIS and spectra computed on a large number of observed records is reported (Clinton 2004). In the example we have considered 2 events, the first with magnitude 1.5 recorded at a distance of 12 km (CONC) and the second with magnitude 2.6 recorded at a distance of 116 km (ASO7) (as described in table 2). The results reported in figure 4 highlights the good agreement between acceleration spectra.

The minimum resolution due to different dynamic range and setting used for the Reftek 130 and Mars88 digitizers is also reported. In particular for frequencies lower than 10 Hz the difference is due to the different dynamic of the recording system, while for frequencies higher than 10 Hz the difference is due to the different level of background seismic noise of the considered sites.

A good opportunity to check the efficiency of the RAIS has been the occurrence of the 20th October 2006, Ml 3.7, event (Table 2, ID 061020001112). This event, occurred in the center of the network, had epicentre located about 10 km West of the source of the 24th November 2004 Salò event. The maximum peak ground horizontal acceleration (18 cm/s^2) was recorded at CONC station (hypocentral distance of 17 Km).

Figure 5 shows the improvement in the monitoring of the area provided by the installation of the RAIS: considering a total of 13 stations, with hypocentral distances lower than 100 km, 8 stations are those of RAIS. The difference in the peak values, observed in the first 20 km, might be associated to different site conditions.

To illustrate the benefit produced by the new installations we have made hypothetical examples considering some of the stronger historical events (catalogue data from Gruppo di Lavoro CPTI 2004) occurred in the area under study.

As shown in figure 6, the 1802 Oglio Valley earthquake (Imax=VIII-IX MCS) would have been recorded by 6 strong-motion stations (4 belonging to RAIS) in the first 30 km. Similarly, the 1891 Illasi Valley earthquake (Imax=IX MCS) would have been recorded by 7 stations (5 belonging to RAIS) in the first 30 km and the 1932 Mount Baldo earthquake (Imax=VII/VIII MCS) would have been recorded by 11 stations (belonging to RAIS) in the first 30 km.

Considering a repeat of the 24th November 2004, Ml 5.2, Salò event, we can observe that an earthquake with identical focal parameters would be at present recorded by 10 strong-motion stations (5 of the RAIS) in the first 30 km.

In the time period from June 2006 to December 2008 the RAIS network recorded 94 seismic events, with local magnitude ranging from 0.7 to 5.1 (for a total of 1678 digital strong-motion waveforms). In figure 7 is reported the distribution of data recorded by RAIS since June 2006 versus magnitude and hypocentral distances. In figure 8 we show the peak ground accelerations (both vertical and horizontal components) relative to these events. The plots, presented for different classes of magnitude, show an increasing of event detection (with distance) with increase magnitude; in particular it is possible to note that events with magnitude less than 2.0 are recorded at hypocentral distance up to 100 km.

Data dissemination and conclusion

The data recorded by RAIS are disseminated through the web site http://rais.mi.ingv.it, where the metadata related to records and stations are included. The web site has been developed on the basis of World Wide Web Consortium recommendation standard (W3C, URL: http://www.w3c.it). On the web site each recorded event is described by the focal parameters, coming from the official site of INGV-CNT, and tables containing amplitude, frequency and duration parameters of the records. For each site detailed geological and geophysical information, based on noise analysis, are reported.

In case of relevant events (i.e. 23th December 2008 15:24:21, Ml 5.1 Parma earthquake, http://cnt.rm.ingv.it/~earthquake/index2.html) the data recorded by the RAIS are converted in an ad-hoc formats (sac and ascii) and included in the **IT**alian **AC**celerometric **A**rchive (ITACA) where the waveforms can be downloaded (Luzi et al., 2008).

At present the data recorded by RAIS are collected and processed also to improve the production of ShakeMaps® (http://earthquake.rm.ingv.it/shakemap/shake/) for events recorded in Northern Italy with Ml larger than 3.0.

The main restriction of the RAIS is represented by the modem-gsm data transmission system, that does not allow a real-time acquisition of waveforms for 16 stations. At present MILA, MERA, CONC and EUCT are connected to the acquisition center in real-time mode and they are managed by SeisComP software. In particular, we use a wi-fi connection for MILA and TCP-IP link for the other three stations.

The future developments will concern both the transmission system, through the upgrade of the modem-gsm system, and the data sharing with INGV-CNT, in order to provide parameters (PGA, PGV and SA) and waveforms through automatic and real-time solutions.

Acknowledgements

The first developments of the network has been supported by INGV department of Milano-Pavia, INGV-CNT (Earthquake National Centre) and Department of Italian Civil Protection (DPC), in the framework of the 2004-2006 agreement between *Istituto Nazionale di Geofisica and Vulcanologia* and *Department of Italian Civil Protection*. The authors thank all people, both institutional and private citizen, that have cooperated in the phases of installation of the RAIS.

Thanks to the anonymous reviewers for useful suggestions.

REFERENCES

ARIAS, A. (1970) A measure of earthquake intensity, in *Seismic Design of Nuclear Power Plants*, R. Hansen (Editor), M.I.T. press, Cambridge.

AUGLIERA, P., E. D'ALEMA, S. MARZORATI, M. MASSA, P. DE GORI and A. MARCHETTI (2006) Data set Garda 2004: elaborazione dati, installazione stazioni sismiche (2004 Garda dataset: data processing, installation of seismic stations), Convenzione ProCiv-INGV 2004-2006 - Progetto DPC-S3: scenari di scuotimento in aree di interesse prioritario e/o strategico, DPC-S3: Deliverable12, DVD, (in italian).

BURRATO, P., M.E. POLI, P. VANNOLI, A. ZANFERRARI, R. BASILI and F. GALADINI (2008) Sources of Mw 5+ earthquakes in northeastern Italy and western Slovenia: an updated view based on geological and seismological evidence, Tectonophysics, 453, 157-176.

BRUNE, J. N. (1970) Tectonic stress and the spectra of seismic shear waves from earthquakes, J. Geophys. Res., 75, 4997–5009.

CAMASSI, R. and M. STUCCHI (1996) NT4.1, un catalogo parametrico di terremoti di area italiana al di sopra della soglia del danno (a parametric catalogue of damaging earthquakes in the Italian area), CNR-GNDT, *Zincotecnica Nuova*, 66 pp.

CLINTON, J. F. (2004) Modern Digital Seismology: Instrumentation, and Small Amplitude Studies in the Engineering World. *Technical Report: Caltech EERL-2004-10*. Earthquake Engineering Research Laboratory, Pasadena, CA.

D'ALEMA, E. (2007) Stazioni accelerometriche con REFTEK-130/modem GSM: note tecniche sui softwares in ambiente Linux per la Rete Accelerometrica dell'Italia Settentrionale. Rapporti Tecnici INGV, 37, 24 pp. (in italian).

D'ALEMA, E. and S. MARZORATI (2004) Metodologie per l'installazione e la gestione delle stazioni sismiche Mars88 modem control, Rapporti Tecnici INGV, 21, 32 pp. (in italian).

DELLADIO, A., A. AMATO, L. BADIALI, M. CATTANEO, F. DOUMAZ and F. MELE (2006) The real-time earthquake monitoring system in Italy, Géosciences, 4, 70-75.

GALADINI, F, M.E. POLI and A. ZANFERRARI (2005) Seismogenetic sources potentially responsible for earthquake M > 6 in the eastern Southern Alps (Thiene-Udine sector, NE Italy), Geophys. J. Int., 161, 739-762.

GALADINI, F., P. GALLI, D. MOLIN and D. CIURLETTI (2001) Searching for the seismogenic source of the 1117 earthquake in northern Italy: a multidisciplinary approach, In: Glade, T., Albini P., Frances, F. (Eds.), “The use of historical data in natural hazards assessment”, 3-27, Kluver Ac. Publ., Dordrect, The Netherlands.

GRUPPO DI LAVORO (2004) Redazione della mappa di pericolosità sismica prevista dall’ordinanza PCM 3274 del 20 Marzo 2003, Rapporto conclusivo per il Dipartimento della Protezione Civile, INGV, Milano-Roma, 65 pp. (in italian).

GRUPPO DI LAVORO CPTI (2004) Catalogo Parametrico dei Terremoti Italiani, versione 2004 (CPTI04), INGV, Bologna, http://emidius.mi.ingv.it/CPTI04.

GUIDOBONI E., A. COMASTRI and E. BOSCHI (2005) The "exceptional" earthquake of 3 January 1117 in Verona area (northern Italy): a critical time review and detection of two lost earthquakes (Lower Germany and Tuscany), J. Geophys. Res., 110, B12309.

GUIDOBONI, E. (1986) The earthquake of December 25, 1222: analysis of a myth, in "Engineering Geology Problems in seismic areas", V. Cotecchia editor, vol. III, Bari 1986, pp. 413-24.

HAVSKOV, J. and G. ALGUACIL (2004) Instrumentation in Earthquake Seismology, Springer Ed., Netherlands, 337 pp.

HOUSNER, G.W. (1952) Spectrum intensities of strong-motion earthquakes, in: *Proc. Symp. on Earthquake and Blast Effects Structures*, C. M. Feigen (editors), Univ. California, Los Angeles, 21-36.

KONNO, K. and T. OHMACHI (1998) Ground-motion characteristics estimated from spectral ratio between horizontal and vertical components of microtremors, Bull. Seism. Soc. Am., 88, 228-241.

LUZI, L., S. HAILEMIKAEL, D. BINDI, F. PACOR and F. MELE (2008) ITACA (ITalian ACcelerometric Archive): a web portal for the dissemination of Italian strong motion data. Seism. Res. Lett. Doi:10.1785/gssrl.79.5.

MARZORATI, S. and D. BINDI (2006) Ambient noise levels in North-central Italy, Geochem. Geophys. Geosyst., 7, Q09010.

MASSA, M., S. MARZORATI, C. LADINA and S. LOVATI (2009) Urban seismic stations: soil-structure interaction assessment by spectral ratio analyses, *Bull. of Earthquake Eng.*, preliminary accepted.

MASSA, M., S. MARZORATI, E. D'ALEMA, D. DI GIACOMO and P. AUGLIERA (2007) Site classification assessment for estimating empirical attenuation relationships for Central-Northern earthquakes, Jour. Earthquake Engineering, 11, 943-967.

McNAMARA, D.E. and R. P. BULAND (2004) Ambient noise levels in Continental United States, Bull. Seism. Soc. Am., 94, 1517-1527.

PETERSON, J, (1993) Observation and modeling of background seismic noise, Open File Report 93-322, USGS, Albuquerque, New Mexico.

TRNKOCZY, A., P. BORMANN, W. HANKA, L. G. HOLCOMB and R. L. NIGBOR (2002) Site selection, preparation and installation of seismic station, In: P. Bormann (Ed) IASPEI New Manual of Seismological Observatory Practice (NMSOP), Vol 1, ch. 7, 1-108.

Table Captions

Table 1 - Station code and geographical coordinates for the RAIS strong motion network. In table are reported the number of bits of the recorder (column Bits), the time signal used by digitizer (Time), a simplified classification of soils (Soil; R: rock, H: hard soil; S: soft soil) and the type of installation (Site; FF: free field, Bmn: instrument in building with m equal to number of stories of the building including ground floor and +/-n equal to the floor where the instrument is installed, 0 for ground floor). The velocimetric sensor installed in the nine 6-channel stations are also reported (column Veloc.).

Table 2 - Focal parameter of the earthquakes used in this work. In column LOC. REF. the code CNT is referred to official Earthquake Bulletin of the National Earthquake Center (INGV-CNT, Rome) focal solutions. The complete list of the earthquakes recorded by RAIS is available on web site http://rais.mi.ingv.it.

Code	Lat (°)	Lon (°)	Elev (m)	Installation	Recorder	Bits	Veloc	Time	Soil	Site
MER8	45.6725	9.4182	350	25/10/2005	Gaia2	24	Trillium 40	GPS	S	FF
MILA	45.4803	9.2321	125	01/06/2006	Gaia2	24	Trillium 40	GPS	S	B20
EUCT	45.2026	9.1349	82	26/06/2006	Gaia2	24	Trillium 40	GPS	S	B10
CTL8	45.2763	9.7622	66	07/06/2006	Mars88/MC	20	Trillium 40	DCF	S	B2-1
BAG8	45.8228	10.4664	807	15/06/2006	Mars88/MC	20	Le3D-5s	DCF	R	B3-1
CONC	45.6060	10.2170	126	03/05/2006	Gaia2	24	-	GPS	H	B2-1
CAPR	45.6372	9.9345	215	31/05/2006	Reftek 130	24	-	GPS	S	B1-1
VOBA	45.6429	10.5040	292	28/06/2006	Reftek 130	24	-	GPS	S	B3-1
NEG8	45.4976	10.9482	167	29/06/2006	Mars88/MC	20	Le3D-5s	DCF	R	FF
ZEN8	45.6378	10.7319	596	30/06/2006	Mars88/MC	20	-	DCF	H	B4-1
ASO7	45.8049	11.9180	221	03/08/2006	Reftek 130	24	Le3D-1s	GPS	R	B30
BORM	46.4694	10.3764	1235	29/11/2006	Reftek 130	24	-	GPS	R	B10
MLCO	46.2918	9.8638	2030	30/11/2006	Reftek 130	24	-	GPS	R	FF
MANT	45.1495	10.7897	36	14/12/2006	Reftek 130	24	Trillium 40	GPS	S	B3-1
ZOVE	45.4536	11.4876	376	28/06/2007	Reftek 130	24	-	GPS	R	B10
MRNE	45.7397	10.1175	600	10/07/2007	Reftek 130	24	Trillium 40	GPS	R	B10
LEON	45.4582	10.1234	92	18/07/2007	Reftek 130	24	-	GPS	S	FF
VOLT	45.3132	10.6606	107	09/11/2007	Reftek 130	24	-	GPS	S	FF
SAND	45.6399	11.6099	51	19/12/2007	Reftek 130	24	-	GPS	S	FF
ORZI	45.4056	9.9307	83	24/04/2008	Reftek 130	24		GPS	S	FF

Table 1

EVENT_ID	Y M D	H M S	LAT (N)	LON (E)	DEPTH (km)	ML	LOC. REF.
041124225800	2004 11 24	22 59 38	45.685	10.521	5.4	5.2	CNT
061020001112	2006 10 20	00 11 58	45.716	10.339	1.50	3.7	CNT
061020002648	2006 10 20	00 28 57	45.670	10.350	12.40	1.5	CNT
070122193856	2007 01 22	19 39 24	46.696	11.126	8.50	2.6	CNT

Table 2

Figure Captions

Fig. 1 - Map of the strong-motion stations presented in this study. Triangles indicate the RAIS stations (planned in yellow), red squares indicate the INGV-CNT stations and grey circles indicate the RAN stations (without distinction between digital or analogue). The empty squares indicate both the the 3 historical earthquakes (1802, 1891 and 1932) and the 2004 Salò event analyzed in Figure 6.

Fig. 2 - Horizontal to vertical spectral ratio (left panel) and Probability Density Function (PDF) of power spectral density (PSD) (right panel) related to about 30 minutes of microseismic noise measured with a broad-band velocity sensor located very close to VOBA strong-motion station.

Fig. 3 - Magnitude Detection Threshold for RAIS in the actual configuration (see text for explanation).

Fig. 4 - Comparison between average recordings of earthquake spectra (Clinton 2004; blue and red thin lines) and acceleration spectra as obtained by the RAIS recordings (20th October 2006, Origin Time 00:28:57.41, M 1.5, station CONC and 22th January 2007, M 2.6, station ASO7; blue and red thick lines). In the picture the high noise model (NHNM, Peterson 1993; gray dotted line), the minimum resolution for the Episensor coupled both with Mars88/MC (black dotted line) and Reftek 130 digitizer are also reported (black dashed line).

Fig. 5 - Plot of peak ground horizontal acceleration vs hypocentral distance for all stations that recorded the 20th October 2006, Ml 3.7, event (Origin Time 00:11 58.10). RAN station is plotted in magenta (stars), INGV-CNT stations are plotted in blue (diamonds) and RAIS stations are plotted in red (circles). For RAIS also the station code and the soil type (R: rock, H: hard soil; S: soft soil) are reported. The gray line represents the regional (central-north Italy) ground motion prediction equation for horizontal PGA calibrated for rock in Massa et al. (2007).

Fig. 6 - Number of stations, in current network configurations, that would record a given historical event vs distance for RAIS (black), RAN (grey) and INGV-CNT

(white). From top to bottom: 12th May 1802, Oglio Valley earthquake; 07th June 1891, Illasi Valley earthquake; 19th February 1932, Mount Baldo earthquake and 24th November 2004, Salò earthquake.

Fig. 7 - Top panel: dataset collected by RAIS from June 2006. Data are plotted as a function of magnitude and hypocentral distance. Middle panel: histograms of the recordings of the RAIS versus hypocentral distance and (bottom panel) magnitude.

Fig. 8 - Peak ground acceleration (both vertical and horizontal) related to the 94 earthquakes recorded by RAIS from June 2006 to December 2008 grouped for different classes of local. For Ml > 2.9 (bottom panels), the records around 100 km with higher values are related to 23th December 2008, Ml 5.1 and 4.7, Parma earthquakes.

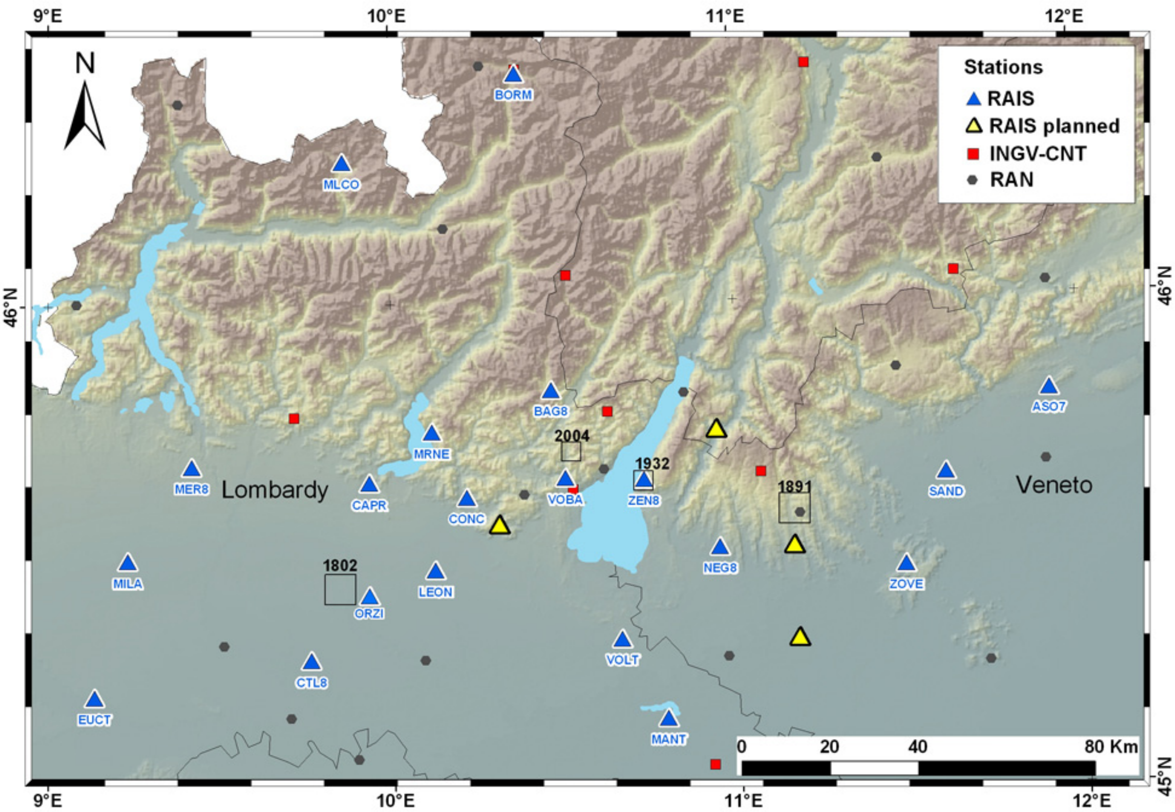

Stations
RAIS
RAIS planned
INGV-CNT
RAN
Lombardy
Veneto
BORM
MLCO
BAG8
MRNE
MER8
CAPR
CONC
VOBA
ZEN8
NEG8
SAND
ASO7
ZOVE
MILA
LEON
ORZI
CTL8
VOLT
MANT
EUCT
2004
1932
1891
1802
9°E
10°E
11°E
12°E
46°N
45°N
0 20 40 80 Km

Fig. 1

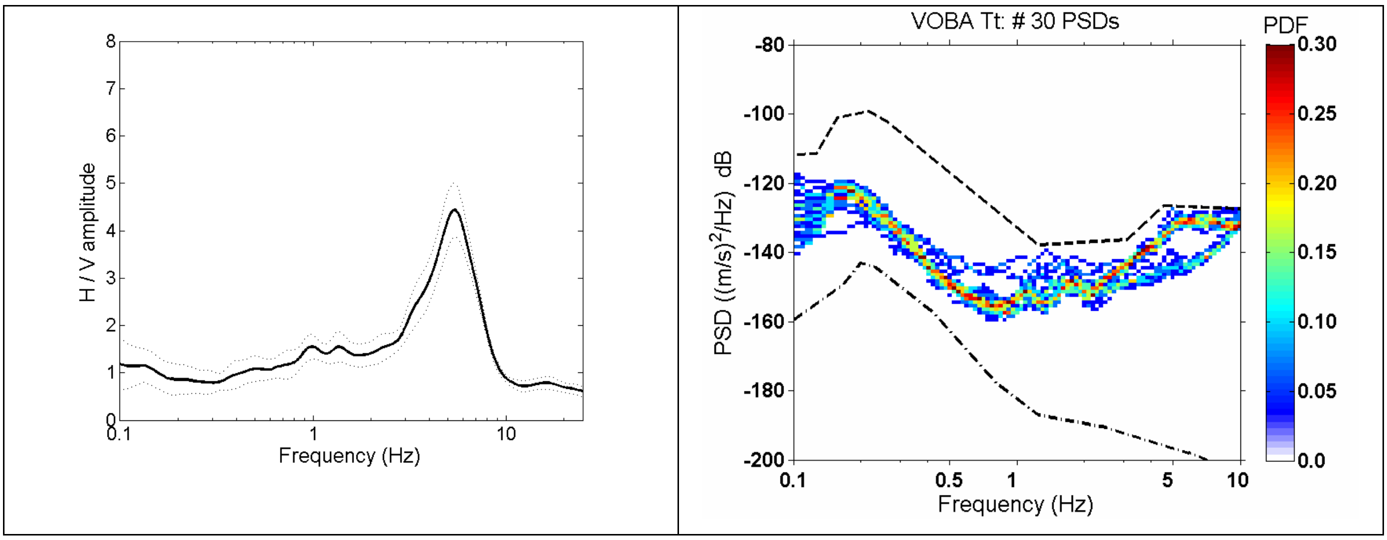

H / V amplitude
Frequency (Hz)
VOBA Tt: # 30 PSDs
PSD ((m/s)²/Hz) dB
Frequency (Hz)
PDF

Fig. 2

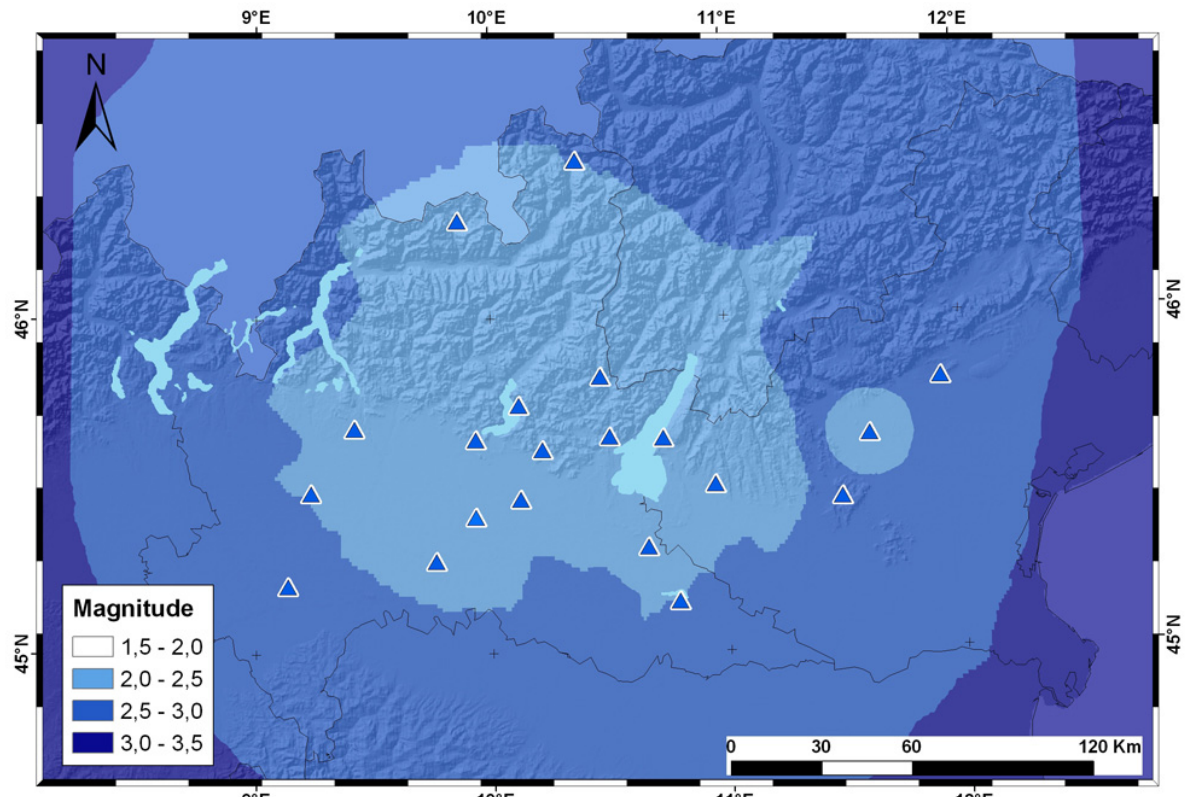
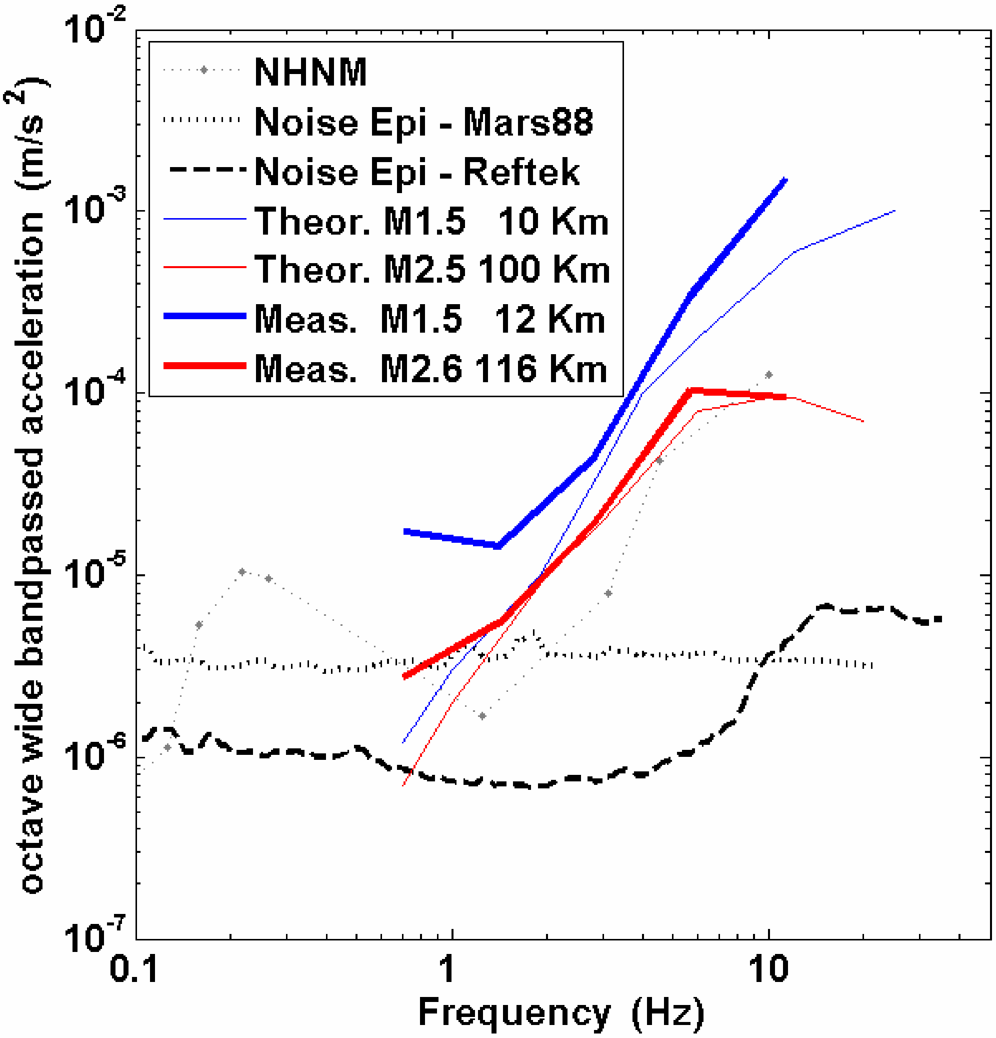
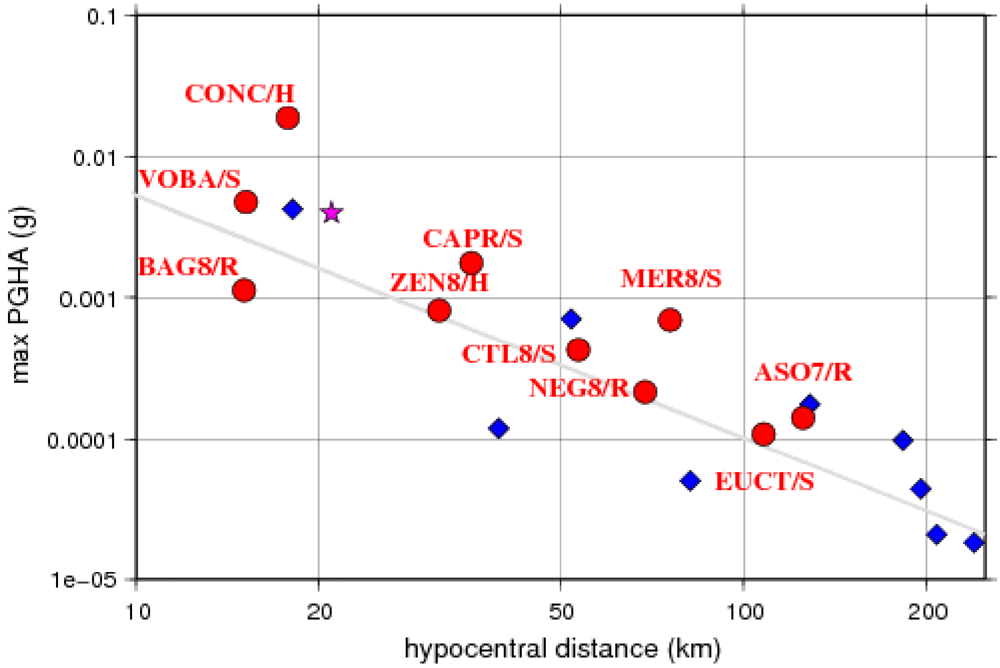

9°E
10°E
11°E
12°E
46°N
45°N
N
Magnitude
1,5 - 2,0
2,0 - 2,5
2,5 - 3,0
3,0 - 3,5
0
30
60
120 Km

Fig. 3



10-2
10-3
10-4
10-5
10-6
10-7
octave wide bandpassed acceleration (m/s 2)
NHNM
Noise Epi - Mars88
Noise Epi - Reftek
Theor. M1.5 10 Km
Theor. M2.5 100 Km
Meas. M1.5 12 Km
Meas. M2.6 116 Km
0.1
1
10
Frequency (Hz)

Fig. 4



0.1
0.01
0.001
0.0001
1e−05
max PGHA (g)
10
20
50
100
200
hypocentral distance (km)
CONC/H
VOBA/S
BAG8/R
CAPR/S
ZEN8/H
MER8/S
CTL8/S
NEG8/R
ASO7/R
EUCT/S

Fig. 5

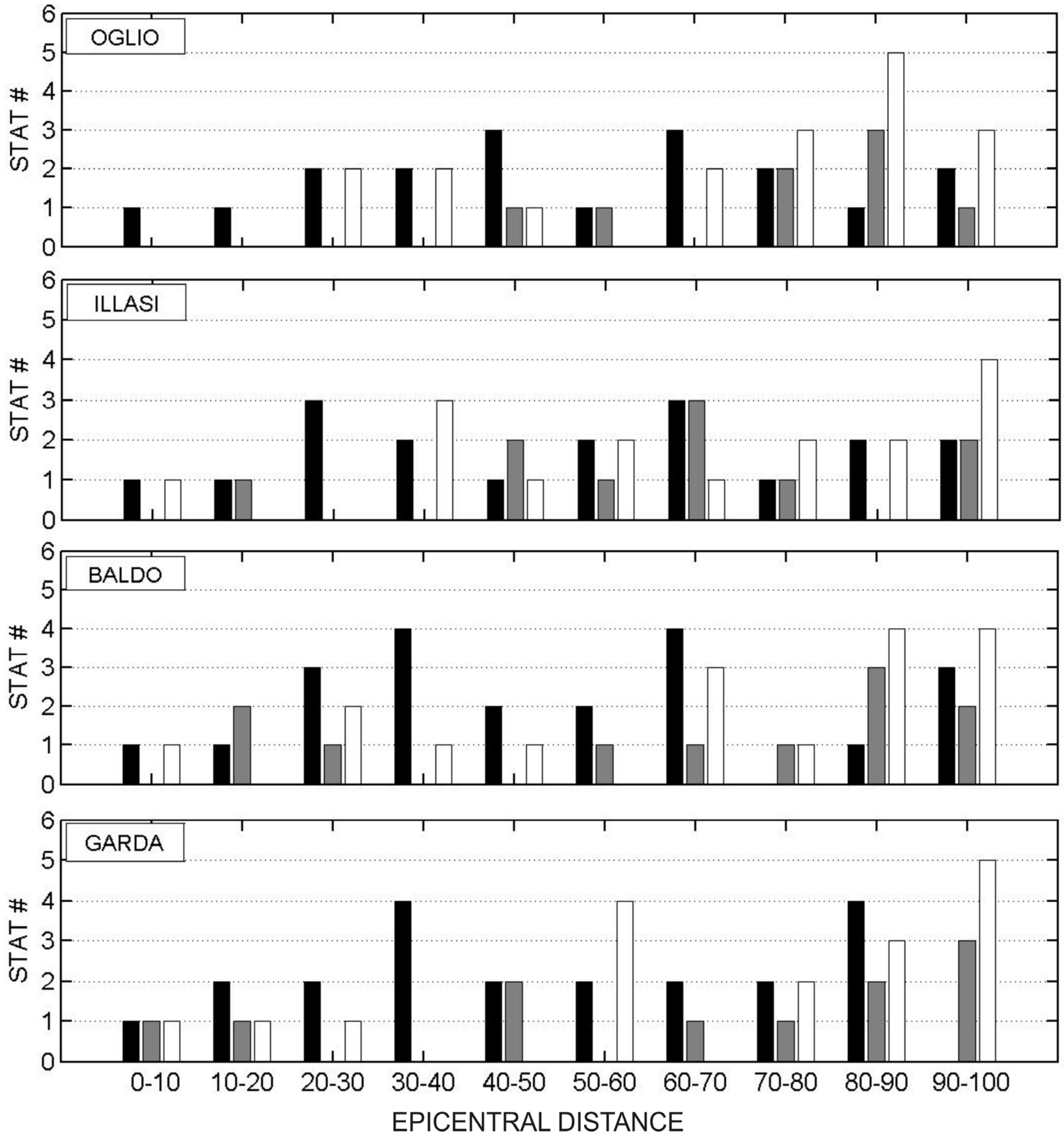
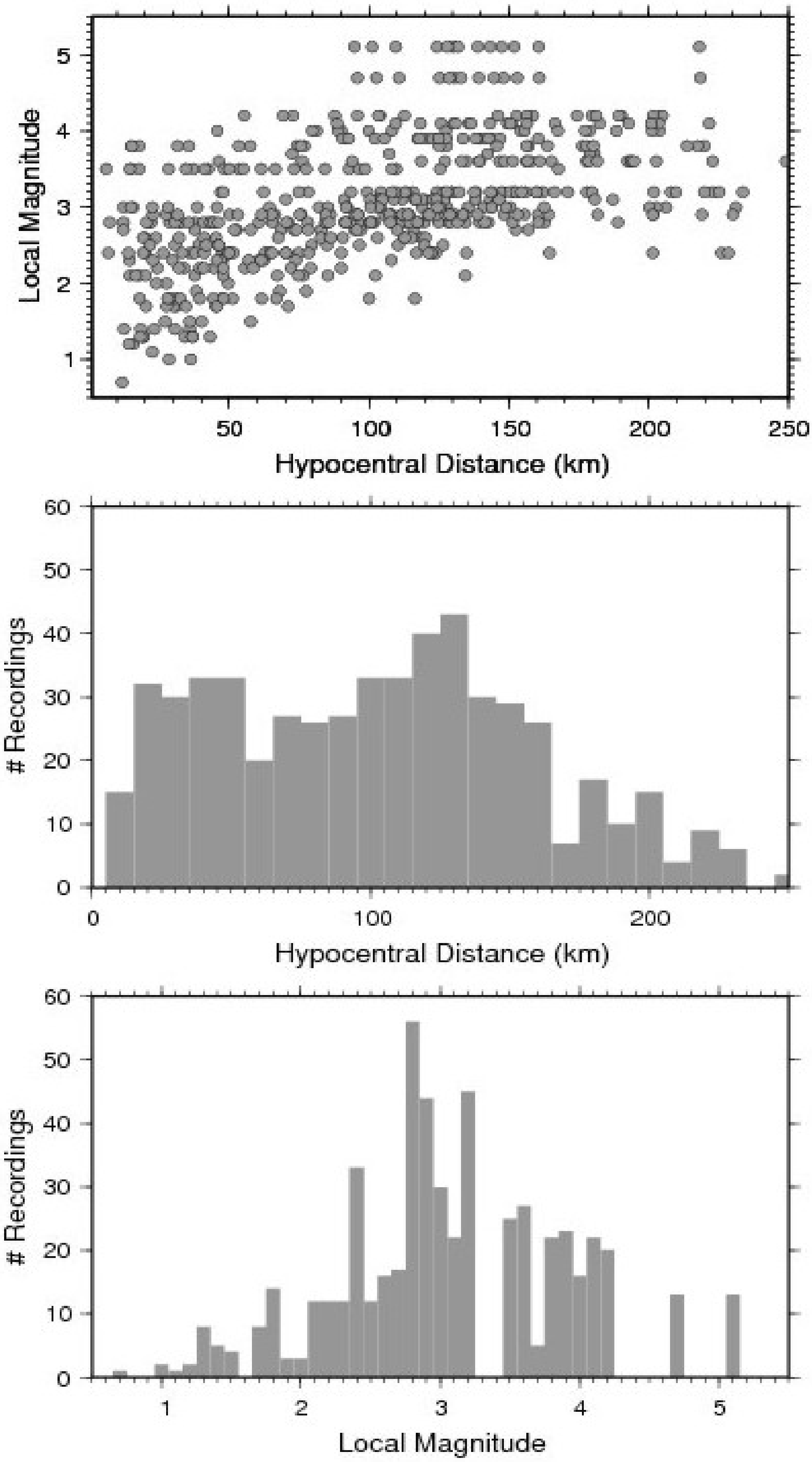

OGLIO
ILLASI
BALDO
GARDA
STAT #
0
1
2
3
4
5
6
0-10
10-20
20-30
30-40
40-50
50-60
60-70
70-80
80-90
90-100
EPICENTRAL DISTANCE

Fig. 6

Fig. 7



Local Magnitude
Hypocentral Distance (km)
Recordings
Hypocentral Distance (km)
Recordings
Local Magnitude

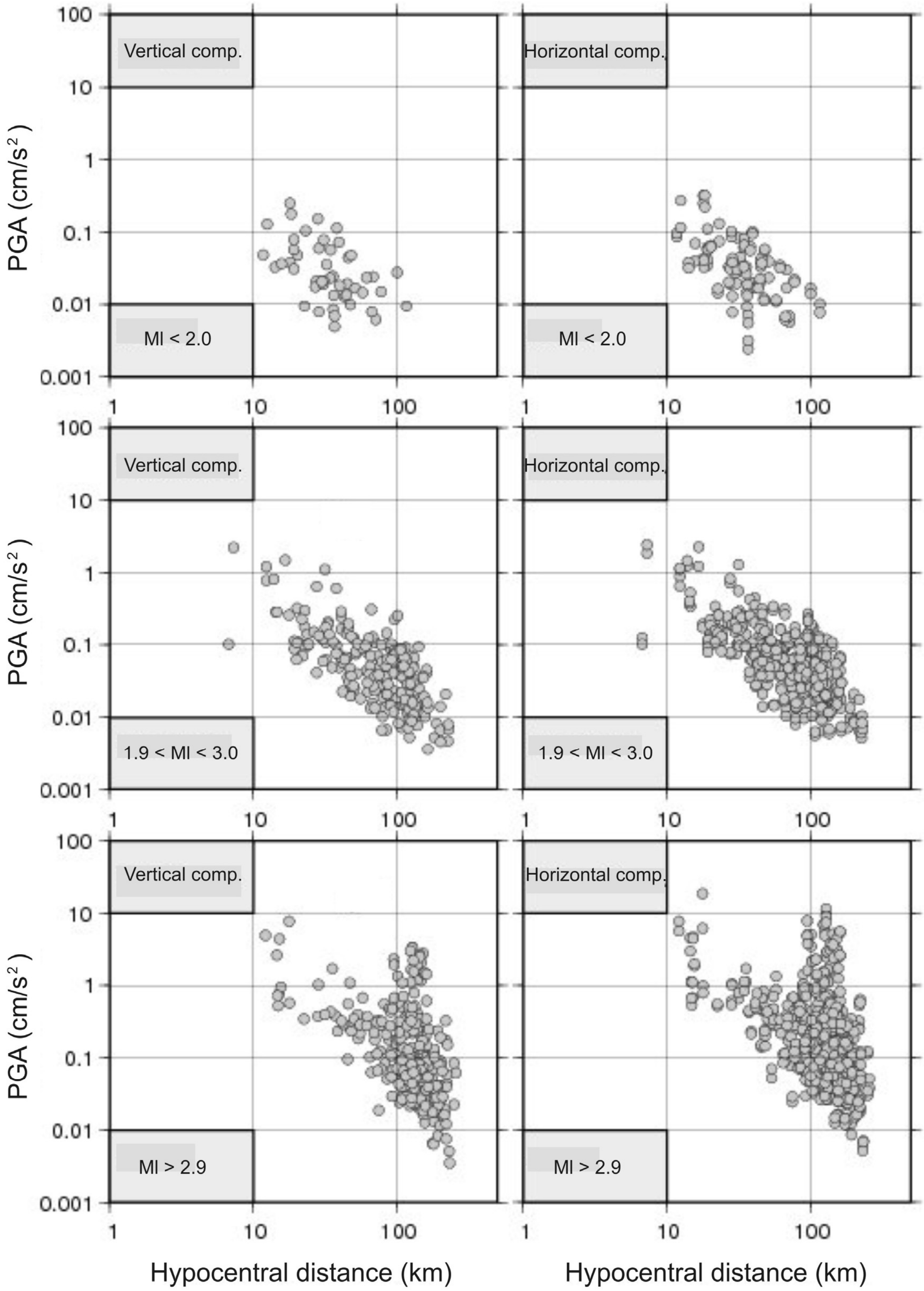

Vertical comp.
Horizontal comp.
Ml < 2.0
1.9 < Ml < 3.0
Ml > 2.9
PGA (cm/s²)
0.001
0.01
0.1
1
10
100
Hypocentral distance (km)

Fig. 8