SITE EFFECTS IN THE EASTERN PO PLAIN BY MEAN OF WEAK AND STRONG EARTHQUAKES

C. Barnaba[1], G. Laurenzano[1], L. Moratto[1], A. Vuan[1], M. Romanelli[1], D. Pesaresi[1], M. Plasencia Linares[1], E. Priolo[1]

[1]*OGS (Istituto Nazionale di Oceanografia e di Geofisica Sperimentale) – Sezione Scientifica Centro di Ricerche Sismologiche (CRS), Italy*

Introduction

We present the activities carried out within the S2 2012-2013 Project, funded in the frame of DPC-INGV Agreement, that concerns the mid-long term Seismic Hazard Assessment in Italy on two priority areas, the Po Plain and the Southern Italy. The Po Valley, an area hitherto considered of low seismological interest, has attracted the attention of the seismological community following the events of May 20, 2012. The day after the main shock that stuck eastern Emilia in 2012, the OGS - Istituto Nazionale di Oceanografia e di Geofisica Sperimentale deployed a temporary seismographic network in the Ferrara area. All the investigated locations were set on soft soils. The large amount of collected data allowed comparison between observed PGA and theoretical predictions, ShakeMaps and attenuation laws, but the lack of a reference site during the 2012 recordings did not allow for estimating the amplification factor. In order to accomplish this task, in February 2013, a new 5 stations recording array acquired data at four of the 2012 network sites and at the Casaglia reference site, north of Ferrara, where a borehole Very Broad-Band station is coupled with a mid-period sensor at the surface. This borehole reference station made possible the estimation of site amplification of the 2013 array sites. The reference methods allowed an easier identification of the resonance frequency, which peaks appear sharper than what displayed by single-station methods (both H/V on ambient noise and earthquakes), and relative soil amplification. A large amount of original seismological data has been recorded in a poorly instrumented area, including significant events of the 2012 Emilia and 2013 Lunigiana sequences. The entire dataset of continuous waveforms has been made available on the OGS web based OASIS Database, from the earliest stages of the project. For the largest events strong-motion parameters were calculated and published on the OASIS database. Event time series and metadata (site monographs) are available similarly to the ITACA Database.

OGS Temporary Network

The OGS temporary network (Fig. 1), consisting in eight stations equipped with velocimetric and accelerometric sensors, was deployed on May 21, 2012. A ninth site was set up one month later, on June 25, 2012, as a replacement for a no-longer-available site (OG003). Recording stopped for all stations on July 25, 2012.

Since February 2013, four sites of the previous network have been occupied again with the same configuration of 2012 to extend the observation, and a new seismic station is acquiring data at the Casaglia site, which surface sensor integrates the Very Broad-Band station installed in a 135m deep borehole.

Stations were installed in the building basement or in the free field. Two sites were set up east of Ferrara: OG001 in the new city hospital at Cona and OG007 in Aguscello village. Site OG002 in the Ferrara municipality, in front of the chemical-industry district. OG003 and OG009 were set up near sites with moderate and strong liquefaction phenomena in the towns of Sant'Agostino and San Carlo. OG005, OG006, and OG008 were set up in the towns of Poggio Renatico, Vigarano Pieve, and Mirabello, which suffered damage that was moderate, but more severe than neighbouring villages according to the macroseismic survey (Tertulliani et al., 2012). OG004 was deployed in Ficarolo village, north of the seismic sequence events. Site OG012, installed during the 2013, is very close to OG002, but it was not set exactly in the same place. More information on the temporary network can be found in the OGS Archive System of Instrumental Seismology (OASIS; http://oasis.crs.inogs.it) under network code ZR; for each site, monographs giving a geological and geotechnical description of the recording site are available.
The Casaglia surface site, OG010, is a free field station installed at the top of the borehole FERB station. The instrumentation installed is a Lennartz velocimeter with a natural period of 5 seconds. The Casaglia borehole station (FERB) uses a Guralp 360 seconds coupled with an accelerometer CMG-5T (Pesaresi et al., 2012).
All the instrumented sites can be classified as C soil, according the EC8 (soft soils, with Vs in the range 180-360 m/s). Downhole seismic test at the Casaglia site gave the opportunity to constrain the empirical shear waves profiles deduced by empirical methods (e.g. ESAC). The velocity profiles deduced by ESAC method at three sites of the OGS network (Priolo et al., 2012) are very similar, with a very low value at the surface (120-150 m/s), and increases with depth (215-250 m/s). One site shows slower Vs values, so that it stands on the edge with soil type D (Vs < 180 m/s). This site experienced severe liquefaction phenomena during the main shock of May, 20 2012. The Casaglia site, where direct measurements are available in the first 80 m (Margheriti et al, 2000), shows the main discontinuity at 15 m, related to the water table, with sharp velocity increase of shear waves (higher than 200 m/s), while down to 80m velocity increases gently with depth.

The acquired data were converted from native format to miniSEED format, according to SEED Standard, and archived on OASIS database, where any piece of waveform can be downloaded. The OASIS Web page includes the extracted waveforms of the main events as well as the strong-motion parameters, which will be usable as search keys in the ITACA database. Data from FERB station are available in real time by accessing the portal EIDA (http://eida.rm.ingv.it).

Data

The dataset consists of recordings related to the events of 2012 Emilia sequence; the new data acquired in 2013, referred to the regional events of Lunigiana (mainshock June, 21), Central Adriatic (Ancona sequence following the mainshock of July, 21), some local events with a magnitude greater than 3 (Bondeno, Ml=3.8, April, 5; Bolognese, Ml=3.5, June, 14; Talbignano, Ml=3.5, June, 19) and the event of the Croatia, Ml=4.7, on July, 30, were recorded.
For the events of 2012, we extracted the waveforms according to the preliminary OGS Bulletin (July 2012) for magnitude Ml> 3.7. After the bulletin revision (March, 2013), some events have been corrected for the magnitude, which was less than 3.7, but the quality of the records was very good so that they are retained in the list of top events.
For the events of 2013, we considered the OGS preliminary bulletin (RTS, July 2013) for local events of low magnitude, and the INGV bulletin (ISIDE, July 2013) for regional events of

magnitude greater than 3.0. A total of 46 and 58 events were considered for 2012 and 2013, respectively. Details on selected events can be found in Barnaba et al. (2013). Extracted time series have been visually-inspected by the operator and the events considered are only those whose S-phase recognition is certain at least for two sites.
To obtain a homogeneous dataset from the recorded velocity and acceleration time series, the data were processed by removal of means and trends, instrument correction with poles and zeroes to obtain displacement time series, band-pass filtering between 0.2 and 45 Hz, and simple and double differentiation to obtain velocity and acceleration time series.

Site response

Site response is estimated considering the conventional spectral ratios both single-station, either by reference site, considering earthquakes and ambient noise. The Casaglia borehole station was taken as a reference site, after correction of the time series to take into account the up-going and down-going wave propagation.

Spectral ratios are calculated by three different techniques: the classical reference-site-spectral-ratio (RSSR, Borcherdt, 1970), between the site of interest and the reference site of Casaglia (FERB, after time series correction according to Bindi et al., 2013. The borehole time series are multiplied by the factor of 2, for the free-surface effects, assuming vertical incidence); the generalized inversion technique (GIT, Andrews, 1986), considering asynchronous events; the spectral ratio between the horizontals and the vertical components for each event, for each station (EHV , Lermo and Chávez-García, 1994) .
Horizontal to vertical spectral ratio of ambient noise according to Nakamura method (NHV, 1989) have been also considered to detect resonance frequencies. Data acquired at different hours of night and day, excluding possible seismic events, both local and teleseismic have been analysed. A common response can be observed at all investigating sites in Ferrara, with an amplification band at 0.6-1 Hz, in accordance with Martelli et al. (2011) investigation in the area of the right bank of the Po, between Modena and the mouth. Also the site OG004, near Ficarolo village, and place on the left bank of the Po river, the resonance frequency of 0.6-1 Hz is clearly recognisable and it has been interpreted as a stratigraphic discontinuities, intercepted by the Casaglia well at 135 m depth below ground level, and interpreted as the Quaternary basement (Cocco et al., 2001).

Site responses are estimated considering spectral ratios for earthquakes of the Emilia sequence and for local and regional events. Each individual event has been analysed and examined manually. For the different methods used here, calculations assume the same input Fourier spectra of the S and coda waves. The window length is not less than 20 sec for events of Emilia sequence, for M>3.5; for events of 2013, the time length varies from a minimum of 10 sec to a maximum of 30 sec for regional events.
The events of the Emilia sequence were not recorded at FERB site; some tests were made to investigate the possibility of applying the generalized inversion technique, considering some events recorded in Casaglia in 2013. Closest events, which have epicentral distances similar to the Emilia sequence events, and the mainshock of Lunigiana sequence, have been analysed. These tests have demonstrated the non-applicability of the method of inversion when the average energy of the spectra at the site of interest and the reference is greater than three orders of magnitude, and there is at least one event synchronous for all sites.

Figure 2 shows the comparison of the two site-reference methods RSSR and GIT only for the sites working in 2013, when the records of FERB were available. The two methods show very similar results, while when they are compared with the horizontal-to-vertical ratio of earthquakes (EHV), some discrepancy arise, with the exception of the site OG010.
Reference site methods (RSSR and GIT) facilitate the identification of the resonance frequencies, both low-frequency (0.5-1 Hz) and at higher frequencies (1.8 Hz, 2.8 Hz); the adoption while of the single station method (EHV) is not always clearly interpretable, considering both ambient noise that seismic events as shown in figure 2, where there emerges a strong discrepancy between EHV and NHV. This difficulty to identify clearly the resonance frequency is not related to the energy of events: the sites OG006, OG007 and OG008 show that the results are practically identical, also considering different datasets and this observation verify the same site response in the case of both strong local earthquakes and regional events.
The amplifications of site OG010 considering the borehole ground motion corrected by multiplying the time series by a factor of 2 (according to Bindi et al., 2013) are in good agreement with those define by Margheriti et al. (2000) obtained multiplying spectral ratios by the coherence between surface and borehole recordings (following Steidl et al.1996). The main difference between the two computations is the level of amplification of the fundamental peak at about 0.8 Hz. While our analysis has the same values at all amplified frequency peaks (0.8, 1.8 and 3 Hz), Margheriti et al. show more amplification at higher values than at the fundamental one. These discrepancies could be related to the largest epicentral distance and magnitude of the 2013 dataset, compared to the local and weak 2000 dataset (Margheriti et al., 2000), that could not include events with enough energy to excite the low frequency of 0.8 Hz.

Comparison Observed-Predicted

The major events of the Emilia sequence were used to test the prediction of the ground-motion attenuation laws and ground shaking (ShakeMaps).
According to the present-day seismic hazard classification, the studied area is characterized by an expected horizontal peak ground acceleration (PGA) between 0.10 g and 0.15 g, with a 10% probability of being exceeded in 50 years. The observed PGA was compared with the values predicted by the ground-motion equations developed by Bindi et al. (2011). Assumptions were the geometric mean of horizontal components, a reverse fault mechanism, and that all the stations belonged to a soft-soil classification (class C, Vs < 360 m/s). From the dataset used, the PGA observed values are in good agreement with the predictions of the attenuation law.

For the same dataset, the observed PGA values are compared with the data provided by ShakeMaps (Michelini et al., 2008).
INGV ShakeMaps (http://shakemap.rm.ingv.it/shake/archive) have been downloaded in grid.xyz file, containing a dense grid of geographic coordinates (latitude and longitude) and the shaking values, expressed in units of percent-g (g%).
For each event, the values closer to each OGS stations were extracted. The research was done with a radius of 500m from the station. ShakeMap values obtained were averaged and referred to the station. Figure 3 summarises the differences between the theoretical PGA of the ShakeMap and the PGA observed at the station. The greatest differences arise at OG003 site for stronger events, where the observed data are higher than the predicted data. At site OG004, on the contrary, the predict

values are in large part overestimated, in particular for mid PGA values, while for stronger events the accordance between the two values are good. Such differences observed at those sites may be related to geological peculiarity of the soils, which suffered strong liquefaction phenomena during the main events of May, 2012.
In the other sites, the observed PGA values are underestimated by the theoretical computations for weak events, while for the higher magnitudes more agreement can be observed.

Conclusions

The activities carried out within the project have provided a considerable amount of original seismological data in a poorly instrumented area, recording significant events of both the 2012 Emilia Sequence, and the regional events occurred in 2013. The entire dataset of continuous waveforms has been made available on the OGS web OASIS Database.
For the largest events of the Emilia Sequence strong-motion parameters were calculated and published on the OASIS web database. Event time series and metadata (site monographs) are available similarly to the ITACA Database. Since February 2013 the Casaglia station is operating, with a very broad-band borehole sensor and a mid-period surface sensor.
The referring borehole station makes possible the estimation of the site amplifications for those sites with instrumentation still operating in 2013. The reference methods allow an easier identification of the frequency of resonance, since peaks appear sharper than those displayed by single-station methods (both H/V on ambient noise and earthquakes). In particular, amplification in the range of 0.5-1 Hz, 1.8Hz and 2.8 Hz, are recognised in all the sites, even though with different levels. This suggests it is reasonable to consider the resonance frequencies and the values of amplification obtained by the single-station spectral ratio of earthquakes (EHV) as constraining values for the amplification of the site, where it was not possible to estimate an amplification factor (due to the lack of synchronous registrations with the reference site).
The recordings of the temporary network deployed in Ferrara area soon after the main event of May, 2012, were compared with the prediction of ground motion (GMPE and ShakeMaps). The analysis show that the theoretical data are in agreement or slightly overestimated compared to the observed data. Two sites (OG003 and OG004), show major discrepancies, probably related to soil liquefaction phenomena.

Acknowledgements

This research has been supported by the Dipartimento della Protezione Civile: Project S2, ProCiv-INGV (2012–2013). The authors wish to thank the Ferrara University colleagues R. Caputo, N. Abu-Zeid and G. Santarato for support in OGS temporary network deployment and our colleagues G. Durì, M. Bertoni, E. Del Negro for support in Casaglia site.

References

Andrews D.J.; 1986: *Objective determination of source parameters and similarity of earthquakes of different size*. In: Boatwright J., Scholz C.H. and Das S. (eds), *Earthquake Source Mechanics*, American Geophysical Union, Washington, DC, pp. 259-267.

Barnaba C., Laurenzano G., Moratto L. and Vuan A.; 2013: *Amplification factors for sample sites inside priority area "Po Plain"*. Progetto DPC-INGV-S2 *"Constraining observations into Seismic Hazard"*, Deliverable D2.2.

Borcherdt R. D.;1970: *Effects of local geology on ground motion near San Francisco Bay*. Bull. Seismol. Soc. Am. ,**60**, 29-61.

Bindi D., Parolai S., Picozzi M. and Ansal A.;2013: *Seismic input motion determined from a surface-dowhole pair of sensors: a constrained deconvolution approch.* Submitted to Bull. Seismol. Soc. Am.

Bindi D., Pacor F., Luzi L., Puglia R., Massa M., Ameri G. and Paolucci R.; 2011: *Ground-motion prediction equations derived from the Italian strong motion database*. Bull. Earth. Eng., **9,** 1899-1920.

Cocco M., Ardizzoni F., Azzara R.M., Dall'Olio L., Delladio A., Di Bona M., Malagnini L., Margheriti L. and Nardi A.; 2001: *Broadband waveforms and site effects at a borehole seismometer in the Po alluvial basin (Italy).* Ann. Geophys., **44,** 137-154.

Lermo J. and Chávez-García F. J.;1994: *Are microtremors useful in site response evaluation?* Bull. Seismol. Soc. Am., **84**, 1350-1364.

Margheriti L., Azzara M., Cocco M., Delladio A. and Nardi A.; 2000: *Analysis of borehole broadband recordings: Test Site in the Po Basin, Northern Italy*. Bull. Seismol. Soc. Am., **9**, 1454-1463.

Martelli L., Severi P., Biavati G., Rosselli S., Camassi R., Ercolani E., Marcellini A., Tento A., Gerosa D., Albarello D., Guerrini F., Lunedei E., Pileggi D., Pergalani F., Compagnoni M., Fioravante V. and Giretti D.; 2011: *Analysis of the local seismic hazard for the stability tests of the main bank of the Po River*. Gruppo Nazionale di Geofisica della Terra Solida (GNGTS), 30° Convegno Nazionale, Trieste, 14-17 November 2011.

Michelini A., Faenza L., Lauciani V. and Malagnini L.; 2008; *ShakeMap implementation in Italy*. Seism. Res. Lett., **79**, 688–697.

Ministero delle Infrastrutture e dei Trasporti; 2008: *Norme tecniche per le costruzioni*. D.M. 14 Gennaio 2008, Supplemento ordinario alla Gazzetta Ufficiale No. 29, 4 Febbraio 2008.

Nakamura Y.; 1989: *A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface*. Quarterly Report of Railway Technical Research Institute (RTRI), **30**.

Pesaresi D., Dall'Olio L., Rovelli A., Romanelli M., Barnaba C. and Abu Zeid N.; 2012: *Installation of a very broad band borehole seismic station in Ferrara (Emilia).* Gruppo Nazionale di Geofisica della Terra Solida (GNGTS), 31° Convegno Nazionale, Potenza, 20-22 November 2012

Priolo E., Romanelli M., Barnaba C., Mucciarelli M., Laurenzano G., Dall'Olio L., Abu-Zeid N., Caputo R., Santarato G., Vignola L., Lizza C. and Di Bartolomeo P.; 2012: *The Ferrara thrust earthquakes of May-June 2012: preliminary site response analysis at the sites of the OGS temporary network.* Ann. Geophys., **55**, doi: 104401/ag-6172.

Steidl J.H., Tumarkin A.G. and Archuleta R.J.; 1996: *What is a reference site?* Bull. Seism. Soc. Am., **86**, 1733-1748.

Tertulliani A., Arcoraci L., Berardi M., Bernardini F., Brizuela B., Castellano C., Del Mese S., Ercolani E., Graziani L., Maramai A., Rossi A., Sbarra M. and Vecchi M.; 2012: *The Emilia 2012 sequence: a macroseismic survey*. Ann Geophys, **55**, doi: 104401/ag-6140.

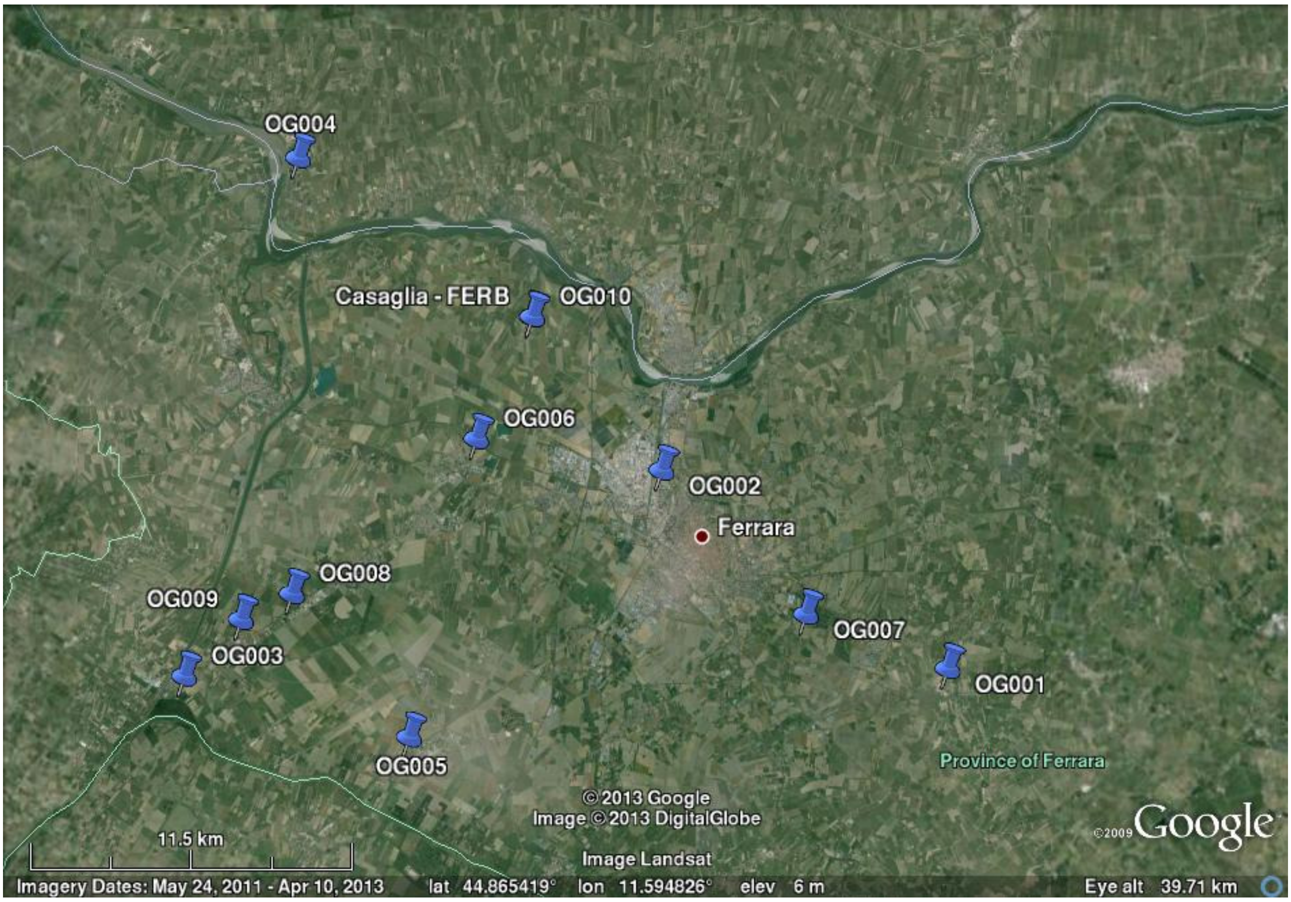

Fig. 1: OGS Temporary Network deployed in Ferrara area. Site OG010 is set at the top of the borehole hosting the FERB station. Site OG012 is very close OG002.

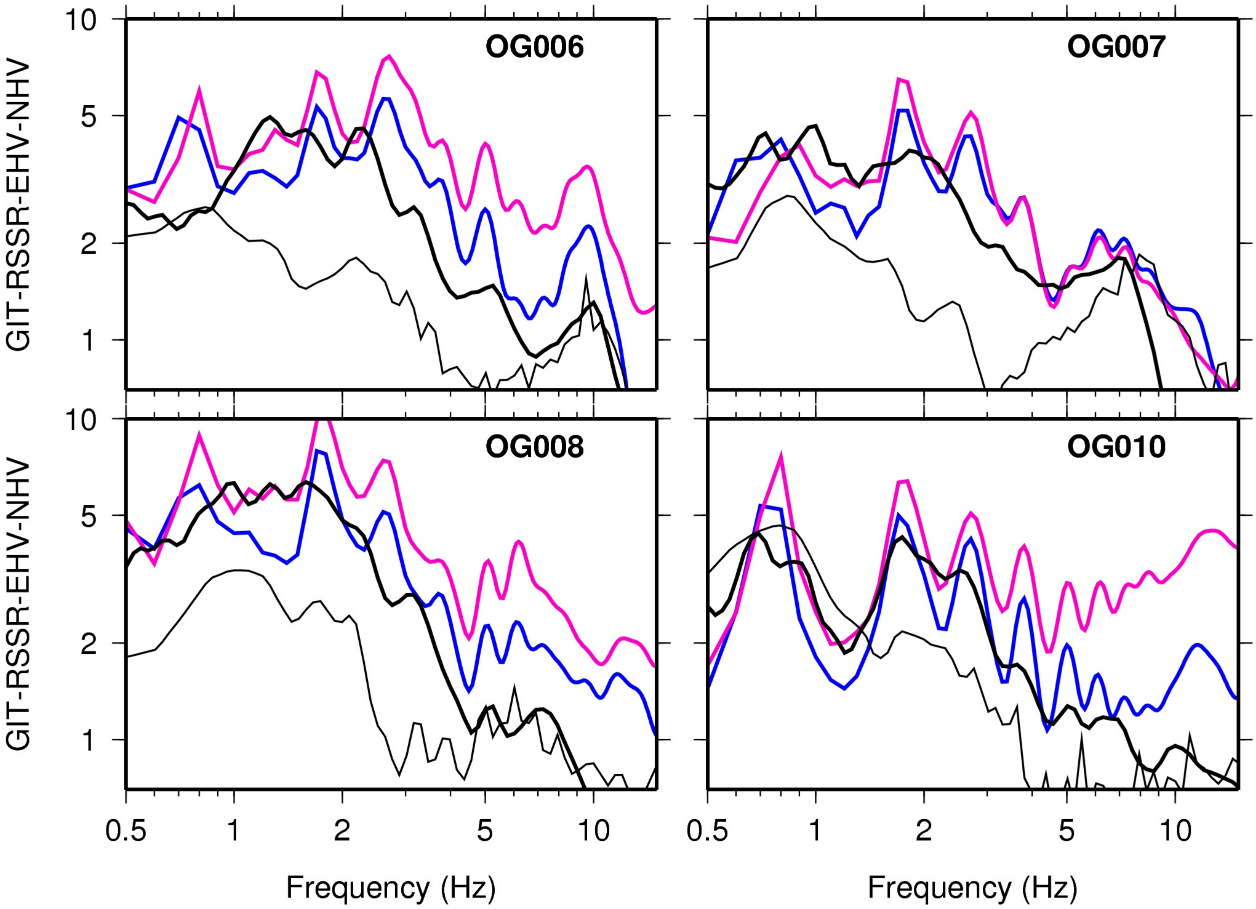

Fig. 2: Comparison between the GIT (blue), RSSR (pink), EHV (bold black) and NHV (thin black) methods, for sites OG006, OG007, OG008 and OG010. Reference site is Casaglia borehole station (FERB).

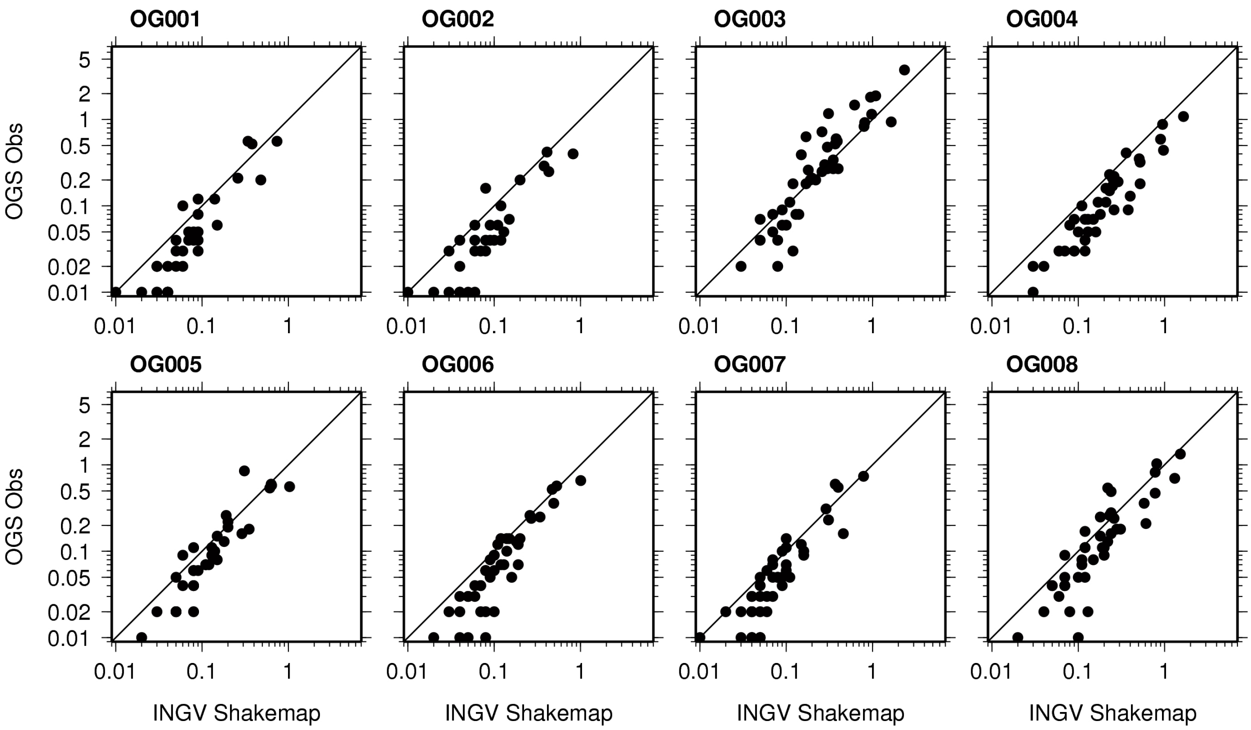

Fig. 3: Comparison between the theoretical PGA derived by the shake maps and the observed PGA at the OGS stations for the main events of 2012 Emilia sequence.