Site response estimation in the Vittorio Veneto area (NE Italy) Part 1: geophysical measurements and in situ soil characterization

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ABSTRACT In 1936, the Vittorio Veneto (Treviso, NE Italy) area was heavily hit by a M=5.8 earthquake that occurred about 20 km from the city. The damage distribution was heterogeneous, suggesting the influence of site effects. In order to assess the seismic response of this area, surveys were conducted consisting of seismic noise measurements (Nakamura's approach), reference site spectral ratios (RSSR) of weak earthquakes and shallow seismic refraction profiling. The horizontal-to-vertical spectral ratios (HVSR) from the ambient noise measurements reveal clear resonant peaks with variable HVSR amplitudes. The large amplitude of most peaks suggests an impedance contrast at shallow depths. The RSSR of about 40 weak events provide quantitative estimates of the seismic amplification in the northern part of Vittorio Veneto. Two sites, located on the left bank of the river, show high values of amplification, about 5 times larger than the signal amplitude at the reference sites, with a narrow-band peak at a frequency of about 5 Hz. The results generally agree with the HVSR resonant frequencies. In addition, a shear wave velocity profiling based on the inversion of Rayleigh waves has been performed at some sites. The technique consists of a surface wave analysis on both single and multichannel seismic records to retrieve the phase and group velocity of the Rayleigh wave fundamental mode and an inversion of the dispersion curves to obtain S-wave velocity models. The resulting equivalent S-wave velocity profiles are then constrained to match the observed HVSR fundamental resonant frequencies.

1. Introduction

The area of Vittorio Veneto (see Fig. 1) is prone to earthquakes. On October 18, 1936, it was hit by a M=5.8 event localized at about 20 km from the city, that caused a very heterogeneous damage distribution, with maximum MCS intensity of IX, suggesting the occurrence of site effects. The maximum damage occurred in the south-western part of the Vittorio Veneto area (Fig. 2; CEN area) and in the Vittorio Veneto town centre (VVC). Severe damage was caused here and some buildings collapsed. Before the 1936 earthquake, the area had been struck by several other, important historical earthquakes, such as the 1776 Tramonti event (MCS intensity VIII-IX), the 1873 Belluno event (MCS intensity X), and the 1695 Asolo event (MCS intensity IX). Blind active faults exist within the area (Poli *et al.*, 2008), while other potential, seismogenic structures

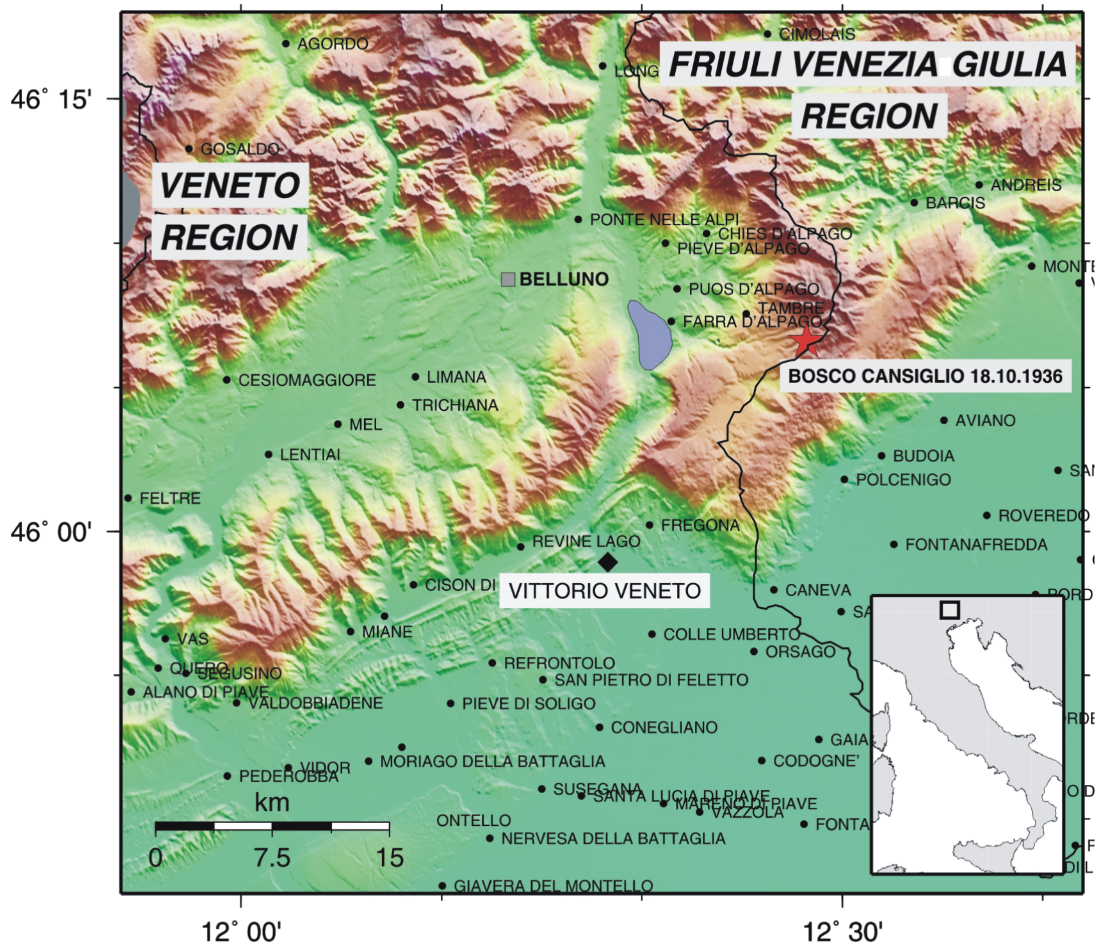

Fig. 1 - Base map of the study area, showing the location of Vittorio Veneto (black diamond) and the epicentre of the M=5.8, October 18, 1936 Cansiglio earthquake.

are argued.

In order to assess the seismic response in Vittorio Veneto and map the local effects due to different shallow soils (see Priolo *et al.*, 2008), field surveys based on the integration of different seismological methods, were carried out.

First, we conducted a study based on the analysis of environmental noise recordings, following Nakamura's approach (1989). This well known technique is based on the observation that "the vertical component is not subject to the very important site effects suffered by the horizontal components and may thus be used to measure ground motion incident to the very local site conditions" (Lermo and Chavez-Garcia, 1993). Recent studies (Bard, 1999; Faeh *et al*., 2001) have confirmed the close connection between horizontal-to-vertical spectral ratios (HVSR) and the ellipticity of surface waves (Nogoshi and Igarashi, 1970). Thus, the ratio between the horizontal and vertical spectral components of motion can reveal the presence of amplification peaks due to the presence of an impedance contrast at some depth, and provide a first order estimate of the spatial distribution of the amplification. The use of microtremors for site amplification studies has become quite popular in recent years for many reasons. For instance, it allows for significant reductions in field data acquisition time and costs; it does not require an ongoing earthquake sequence; and it does not require the long and simultaneous deployment of several instruments to collect a useful data set.

The site response has also been estimated at eight sites located in the northern part of Vittorio Veneto (see Fig. 2; SRV and VVC) by computing the spectral ratios of two reference sites (RSSR) for a data-set of weak earthquakes recorded during a period of about six months. The method used to estimate the RSSR is the generalized inverse technique (GIT). And was originally proposed by Andrews (1986), and allows is to determine spectral ratios for each component of the seismic signal with respect to one or more pre-defined reference sites (Field and Jacob, 1995; Hartzell *et al*., 1996; Bonilla *et al*., 1997; Parolai *et al*., 2000; Michelini and Govoni, 2001).

The RSSR computed at these points by comparison with HVSR measurements at the same sites helped in the amplitude calibration of the whole HVSR data set to allow the mapping of both the resonant frequency and the corresponding amplification level [details on the procedure are better explained in Priolo *et al*. (2008)].

In order to gain a better understanding of the shear wave distribution with depth, some shallow seismic refraction survevs have been carried out. A surface wave analysis has been performed on multi-channel records as well as on single-station records acquired simultaneously. Rayleigh waves contain important pieces of information, which are strictly related to the S-wave velocity profile. Recent field tests demonstrated the accuracy and consistency of calculating near-surface S-wave velocities using multi-channel analysis of surface waves [MASW, e.g., Xia *et al*. (2002)]. In seismic prospecting, the application of these techniques is increasing since they are not invasive and present significant economical advantages in comparison with down-hole and cross-hole methods. In this study, we took advantage of the HVSR information (i.e. the frequency of the HVSR peak) to constrain the inversion of the 1-D S-wave velocity profile of soils.

2. Geological description of the area

The study area belongs to the Southalpine domain and the main tectonic structures are south and south-east verging thrust faults. The city of Vittorio Veneto is located on the southern slopes of the Belluno Pre-Alps. The city extends length wise from NNW to SSE, where the outlet of the Meschio River goes into the Venetian plain. The city is located on Quaternary deposits, while the pre-Quaternary substratum only outcrops in the surrounding zones. Different soil types outcrop in this area (see Fig. 2 for reference). Lacustrine or peat deposits are found in old Serravalle (SRV) along a 200 m wide gorge, north of Serravalle castle and in Ceneda (CEN). Pelites and sands, of alluvial or colluvial origin, characterize the town centre of Vittorio Veneto (VVC), while southwards, where the modern city settlement is growing, surface sediments become coarser (gravels and cobbles; VVN). Several alluvial fans surround the city. They originate from the lateral streams and tributary rivers that flow from the mountain flanks. In general, they are composed of relatively fine sediments (commonly silt, clay or sand). Debris and glacial deposits outcrop both west and east of the investigated area. A more detailed description of the local geology with maps of the Quaternary deposits is given in this volume (Avigliano *et al*., 2008).

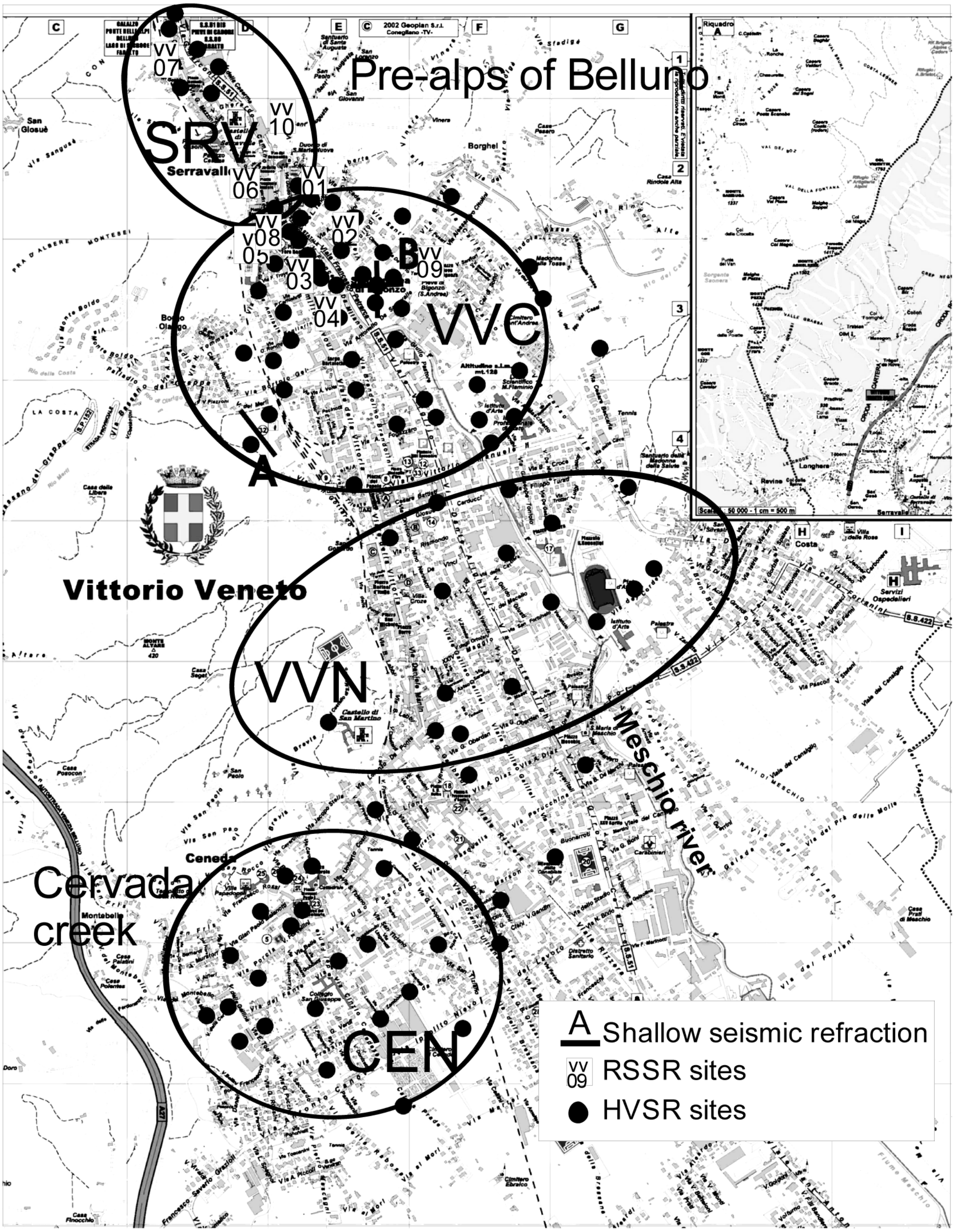

Fig. 2 - Base map of the Vittorio Veneto municipal area showing the location of the seismic noise acquisition sites (black circles), temporary seismic stations for reference site spectral ratios of weak earthquakes (white squares) and refraction lines (black solid lines) used for the surface waves analysis.

3. Horizontal to vertical spectral ratios

3.1. Data acquisition and processing

Seismic noise was recorded at about 100 different sites (Fig. 2). Data was acquired using two different types of portable seismic stations, namely Orion Nanometrics and MarsLite Lennartz, all equipped with three component 1 Hz Lennartz Le-3C sensors. These sensors have a flat frequency response between 1 and 80 Hz. Below 1 Hz, the instrument response decays at approximately 10 db/octave so that the signal-to-noise ratio is high enough to compute the spectral ratios down to the frequency of about 0.2-0.5 Hz. At each site, microtremors were recorded for a minimum time of twenty minutes. The sampling interval was set at 100 Hz, to guarantee reliable spectral estimates up to 30 Hz.

The mean H/V ratio is estimated from HVSR measurements computed on a set of running time windows. Outliers are manually removed at the pre-processing stage, producing a set of separate data time windows. We used a window length of 180 seconds with a 10% overlap. A minimum of six running time windows, for a total length of 20-30 minutes, were used to determine the mean HVSR. For the generic i-th time window, the signal was processed as follows:

1) DC removal and linear detrending;
2) 5% cosine tapering;
3) computing the horizontal component of motion as vectorial sum of the two horizontal components;
4) computing the square root of the power spectral density (PSD) of the horizontal and vertical components (Hi and Vi, respectively);
5) computing the {H/V}i = Hi/Vi ratio; and 6) estimating the average H/V and the associated error by the median and standard deviation of the {H/V}i population, respectively.

In such processing, the PSD (step 4) is computed using methodologies for the analysis of noisy signals, i.e. the Welch's (Welch, 1967) or Burg's (Kay and Marple, 1981) methods, and no smoothing is applied in the spectral ratio computation (step 5). In our tests, the two methods provide very similar estimates.

3.2. Results

The final dataset consists of HVSR estimates from seismic background noise at about 100 sites. The frequency band of analysis is 0.5-22 Hz, which is the most important for seismic engineering purposes. The amplitude of the seismic noise recorded at all sites in the Vittorio Veneto municipal area is generally large, as a result of many anthropic activities (e.g., machinery, cars, etc). The HVSR standard deviation is generally low, confirming an overall stability of the estimations. Most sites display clear resonant peaks, with variable HVSR amplitudes, while only few of them feature a flat response. Fig. 3 shows the peak resonance frequencies and the corresponding HVSR amplitude at each site. The colour and size of the circles indicate H/V peak frequency and amplitude respectively. White circles (i.e. in SRV) indicate sites with very low H/V amplitude or flat response. The measured peak frequencies have then been interpolated in order to visually enhance the spatial distribution. The resulting map suggests the presence of four distinct zones characterized by different resonance frequencies. North of the Serravalle gorge, SRV features resonant frequencies in the 3-5 Hz range. South of it, VVC shows resonance

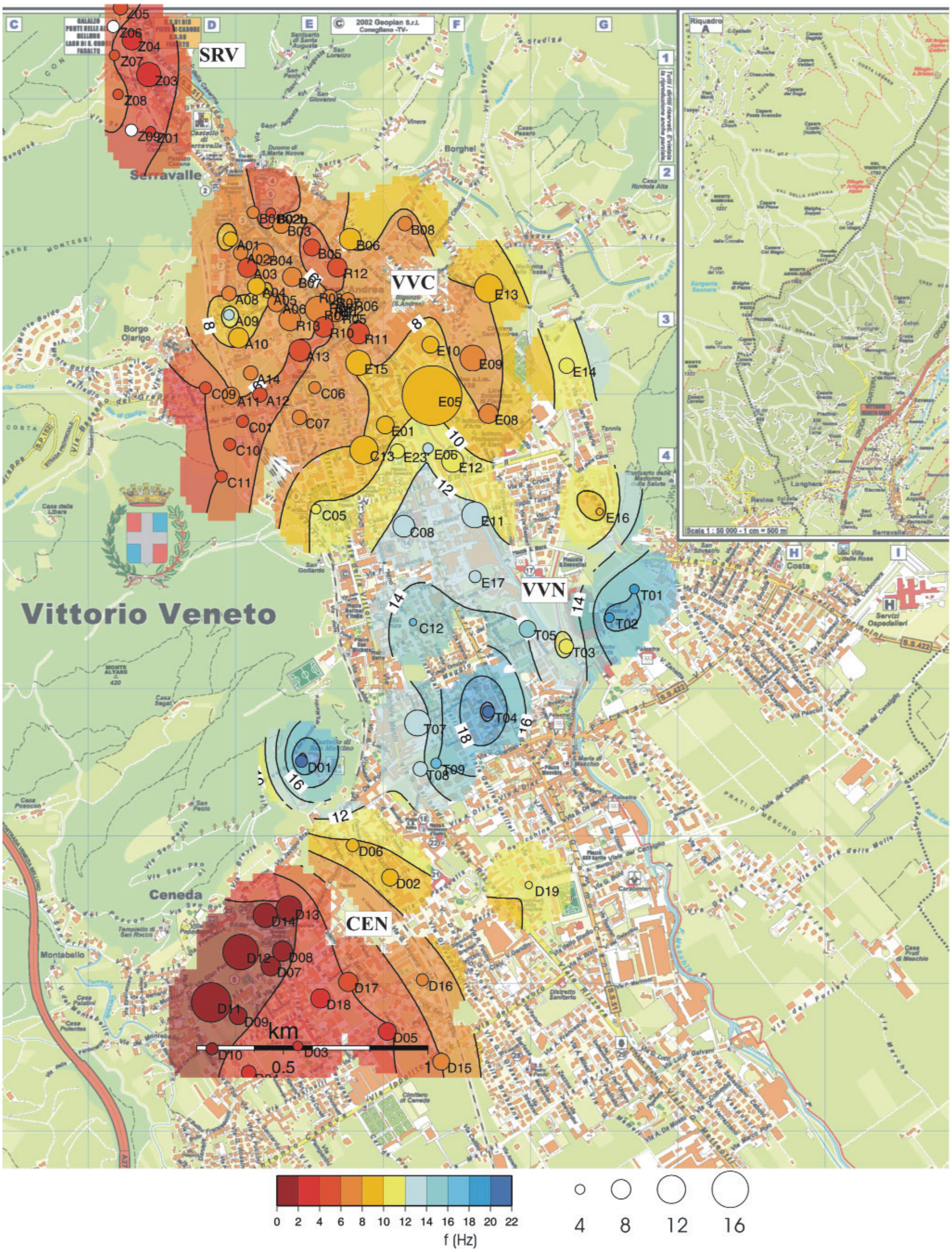

Fig. 3 - HVSR amplitude in the frequency range 0.5-22 Hz. The colour and size of the circles indicate peak frequency and amplitude of the HVSR, respectively. White circles indicate sites with very low H/V amplitude or flat response. The value of resonance frequency is also indicated along the iso-frequency lines computed by interpolating the peak frequencies.

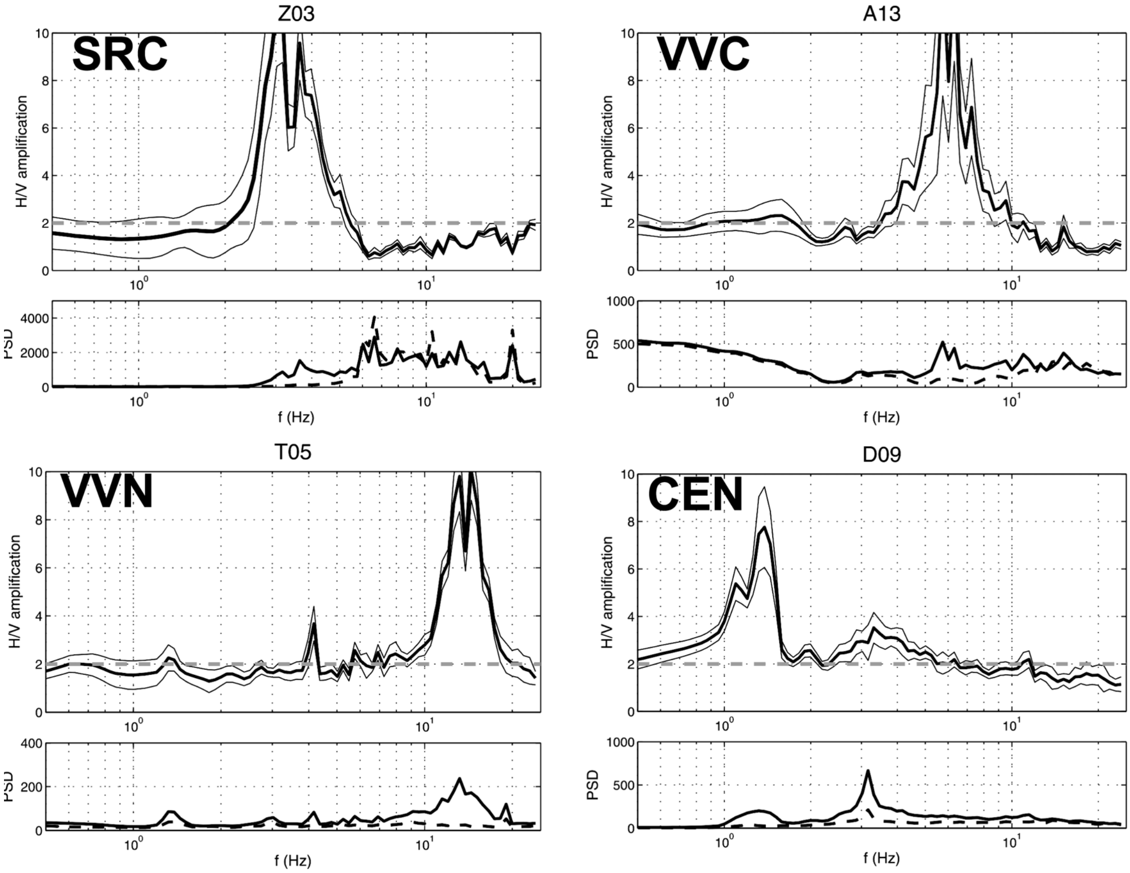

Fig. 4 - HVSR estimated at four different sites in the Vittorio Veneto area. The name of the site is indicated at the top of each panel for each site, the top panel represents the HVSR (thick line) plus/minus the first standard deviation (thin lines), while the bottom panel represents the PSD computed for the horizontal (solid line) and vertical (dashed line) components.

frequencies, from 3 to 10 Hz, which increase further south. For instance, VVN, the area of recent expansion of the town, features very high resonant frequencies (10-20 Hz). Finally, at CEN the fundamental frequency ranges from about 8-9 Hz toward the valley centre to a very low value of about 1.3 Hz, in the heart of the quarter. The lowest frequencies are retrieved in the western, oldest part of CEN. This area suffered the strongest damage during the 1936 Cansiglio earthquake. In Fig. 4, we show examples of HVSR estimates in the four areas: site Z03 for SRV, site A13 for VVC, sites T05 and D09 for VVN and CEN, respectively.

4. Reference site spectral ratios of weak earthquakes

4.1. Data acquisition and processing

Ten seismic stations (the same type as those described in the previous section) were deployed in SRV and VVC areas (see Fig. 2) from December 2001 to July 2002. Three stations (VV06,

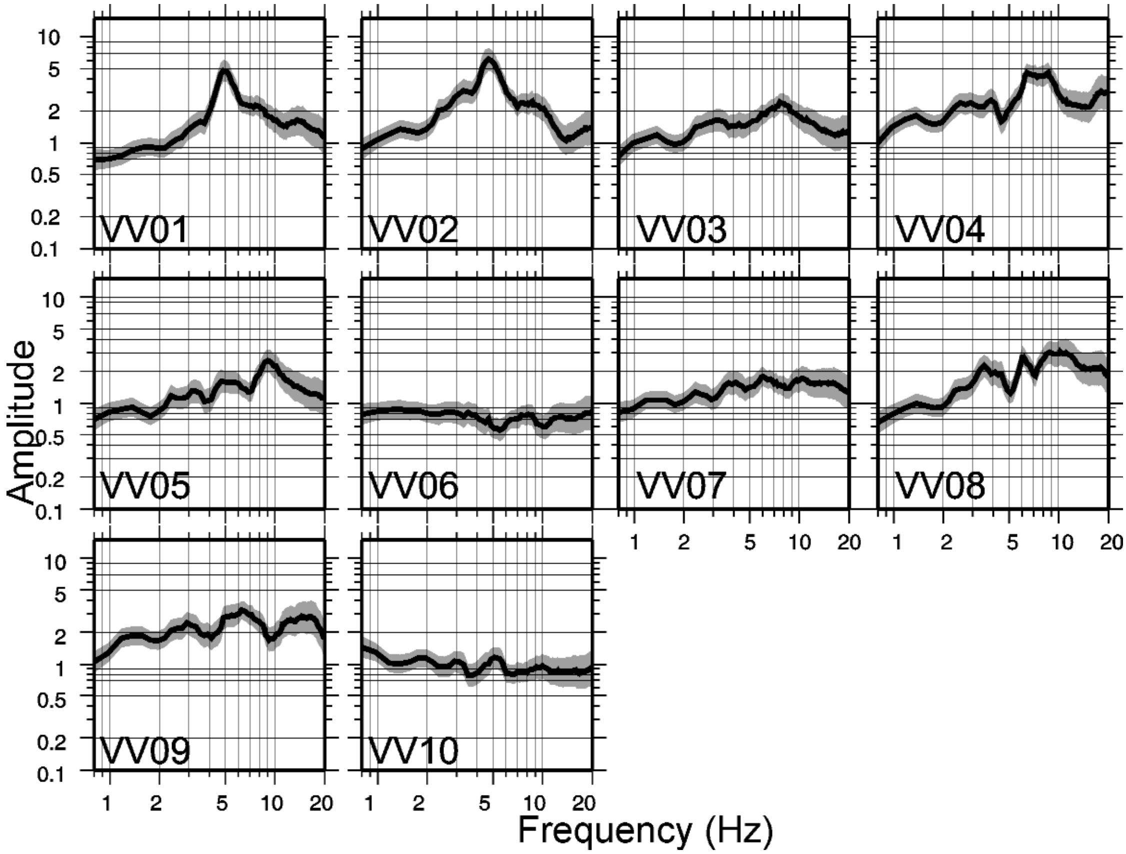

Fig. 5 - Horizontal component spectral ratios (RSSR) computed for each station with respect to the average value of the 3 reference sites (VV06, VV07, VV10) lying on the bedrock for all 40 recorded events of Table 1. Shaded area corresponds to $\pm 1\sigma$ of the single measurements around the calculated mean value at each frequency.

VV07 and VV10; see Fig. 2) were installed on outcropping limestone bedrock and chosen as reference sites. The remaining stations were deployed on the Quaternary cover (alluvial, fluvio-glacial and lacustrine deposits). A total of 40 events were recorded (Table 1). Their epicentral distances for Serravalle vary between 15 and 200 km, approximately. The distribution of the back-azimuths spans a broad circular sector comprised, anticlockwise, between N120°E and N160°W. In order to calculate the spectra of the recorded seismograms, the whole dataset was first re-sampled at 100 sps, in order to have all data sampled similarly. The Fast Fourier Transform (FFT) was calculated on a constant, 5.12 s analysis window comprising the S-wave arrival. The mean and the trend were removed from the extracted time series and a 5% cosine taper was applied before the FFT. The window starting points were automatically defined on each seismogram on the basis of a time-distance relation and an S-wave estimated velocity, in such a way as to always contain the onset of S-waves. Finally, the window length, selected as input, assured us that all the main shear phases and part of their codas would contribute to the spectrum. The horizontal components were summed as a complex time series, using the technique of Steidl

Table 1 - Events recorded by the array during the acquisition campaign and used in the study. The best 11 recorded earthquakes, selected for their large signal-to-noise ratio, are highlighted.

Event N°	Date	Time	Lat°N	Lon°E	Depth	MD	Epicentre
10923	18/12/2001	17:43:57.71	45,967	11,179	10,1	3,2	CALLIANO (TRENTINO)
10924	19/12/2001	04:36:13.67	46,375	12,721	13,8	2,8	AMPEZZO (FRIULI)
10934	27/12/2001	16:40:41.55	45,819	10,931	5,4	2,7	M.ALTISSIMO DI NAGO (TRENTINO)
10938	29/12/2001	22:34:49.42	45,313	14,575	8,2	2,9	BAKAR (CROAZIA)
20027	15/01/2002	07:56:46.39	46,361	12,891	11,5	2,4	VILLA SANTINA (FRIULI)
20039	20/01/2002	11:17:06.25	46,084	10,679	1,8	2,9	CARE' ALTO (TRENTINO)
20040	20/01/2002	17:24:14.82	46,123	10,632	0,2	2,8	CARE' ALTO (TRENTINO)
20052	23/01/2002	16:17:02.06	46,368	12,857	13,8	2,5	VILLA SANTINA (FRIULI)
20053	23/01/2002	19:19:33.96	46,292	12,864	10,5	2,4	PIELUNGO (FRIULI)
20058	25/01/2002	21:15:22.98	46,236	12,656	10,3	2	ANDREIS (FRIULI)
20074	03/02/2002	02:02:11.88	46,323	12,729	11,6	1,8	TRAMONTI DI SOTTO (FRIULI)
20083	14/02/2002	03:13:38.81	46,429	13,1	14,2	2,5	M.SERNIO (FRIULI)
20084	14/02/2002	03:18:02.91	46,426	13,1	11,2	4,9	M.SERNIO (FRIULI)
20086	14/02/2002	03:25:57.49	46,442	13,115	13,9	2	M.SERNIO (FRIULI)
20087	14/02/2002	03:26:50.07	46,423	13,097	13,9	2,3	M.SERNIO (FRIULI)
20092	14/02/2002	03:36:35.87	46,42	13,107	13,3	2,3	M.SERNIO (FRIULI)
20107	14/02/2002	04:45:37.48	46,422	13,103	14,7	2,8	M.SERNIO (FRIULI)
20112	14/02/2002	06:27:16.38	46,378	13,11	12,5	2,3	MOGGIO UDINESE (FRIULI)
20138	17/02/2002	14:37:17.85	46,425	13,069	14,6	2,2	ARTA (FRIULI)
20158	22/02/2002	09:04:59.04	46,34	13,061	5,1	3	TOLMEZZO (FRIULI)
20173	25/02/2002	10:55:22.71	46,425	13,098	14,1	3,2	M.SERNIO (FRIULI)
20188	03/03/2002	20:16:01.79	46,292	13,042	9,6	2,8	TRASAGHIS (FRIULI)
20191	05/03/2002	11:18:12.82	46,199	12,122	13,1	2,1	M.PELF (VENETO)
20239	28/03/2002	07:07:32.37	46,344	12,891	7,5	2,2	VILLA SANTINA (FRIULI)
20252	01/04/2002	21:21:25.00	46,256	12,326	9,2	2,6	LONGARONE (VENETO)
20299	20/04/2002	23:54:08.77	46,418	13,115	16,9	2,8	M.SERNIO (FRIULI)
20338	06/05/2002	03:24:17.07	46,36	12,638	12,2	3,8	FORNI DI SOTTO (FRIULI)
20348	08/05/2002	13:59:45.73	46,367	12,638	12,6	2,9	FORNI DI SOTTO (FRIULI)
20352	12/05/2002	06:50:58.86	46,307	11,019	3,9	2,7	TUENNO (TRENTINO)
20368	17/05/2002	20:31:38.85	46,385	12,892	13,3	2,1	VILLA SANTINA (FRIULI)
20382	26/05/2002	17:55:38.74	45,788	11,674	7,3	2,7	CONCO (VENETO)
20383	26/05/2002	19:37:57.31	45,809	11,596	9,6	3,2	CONCO (VENETO)
20384	27/05/2002	02:53:05.19	45,438	11,352	7,9	2,8	MONTEBELLO VICENTINO (VENETO)
20393	30/05/2002	13:01:49.79	46,359	12,616	10,1	1,5	FORNI DI SOTTO (FRIULI)
20399	02/06/2002	13:19:17.44	45,632	14,238	9,6	3	KNEZAK (SLOVENIA)
20400	02/06/2002	13:37:18.77	45,634	14,221	9,6	3,9	KNEZAK (SLOVENIA)
20401	02/06/2002	13:42:08.02	45,661	14,266	12	3,3	KNEZAK (SLOVENIA)
20420	09/06/2002	10:40:59.68	46,188	12,647	7	2,3	ANDREIS (FRIULI)
20438	11/06/2002	03:12:14.07	45,165	11,804	9,5	2,6	STANGHELLA (VENETO)
20473	20/06/2002	00:09:58.41	46,148	12,222	5,5	2,7	BELLUNO (VENETO)
20505	06/07/2002	08:30:10.61	46,297	13,189	13,1	3,5	GEMONA (FRIULI)

et al. (1996). The amplitude spectrum of complex time series provides the total amplitude of horizontal motion at a given frequency, preserving the phase between components. Overall, 388 spectra were used, considering both horizontal and vertical component records spectra, each one determined on the basis of 204 points with frequency increments of 0,098 Hz from 0 to 20 Hz. Finally, spectral values typical of each station were retrieved by averaging the relevant traces' spectra over the entire frequency range.

4.2. Results

Spectral ratios for each station, calculated on the average of the 3 reference sites, were produced for all 40 events recorded by the array (see Fig. 5). In detail, the results show that the amplification levels measured at all three reference sites (VV06, VV07 and VV10) are always lower than 2 (see Fig. 5). The VV06 spectral ratio curve, in particular, is constant around unity over the whole frequency range (i.e. null amplification). Also, results for station VV10, located on the steep flank of the Sant'Augusta Hill, show no substantial amplifications either, suggesting the absence of topographically induced amplifications which could theoretically have been expected.

Results for VV01 and VV02, both located on alluvial and lacustrine deposits, reveal maximum amplifications of about 5 and 8 times, respectively. Both amplifications occur within a sharply defined peak at 5 Hz. The spectral ratios for the horizontal components show fairly symmetrical peak sides, a typical signature of sharp 1-D impedance contrast between overlying flat layers.

Station VV04, also deployed over a sequence of composite incoherent deposits, recorded the largest overall amplifications after sites VV01 and VV02. VV04 features maximum levels of amplification about 4-5 times larger than the reference sites at frequencies between 6 and 9 Hz. At the same time, a pretty sharp relative minimum of the spectral ratio for the horizontal component is peculiar to this site at about 4.5 Hz.

Finally, sites VV03, VV05, VV08 and VV09 have very similar behaviour compared to each other for what concerns their horizontal components. Maximum relative amplitudes reach in general a value of 3, for frequencies above 5 Hz, after a slight, constant increase of the spectral ratio curve at lower frequencies. A relative minimum is also well developed at 5 Hz, especially for site VV08.

It is important to stress that the results obtained here are robust, regardless of the direction of the incoming wave field. This is well demonstrated by the small error bars in the spectral ratios of Fig. 5. In addition, we can rule out, with some confidence, that the results are affected by the influence of buildings on free field ground motion, as sensors were installed inside of them. In this regard, HVSR returned the same amplification peak frequencies in whole of the monitored area (see Fig. 6). The main peak amplitudes often disagree though, HVSR amplitudes being usually higher than those derived from the classical RSSR.

Some discrepancies exist also between the horizontal and vertical RSSR (see Fig. 6): the curves generally have different shapes at frequencies beyond 6 Hz. The vertical component RSSR results for sites VV01 and VV04 look different from the horizontal component ones, showing resonant peaks at high frequencies which bear, however, little importance for engineering purposes.

As for possible non linearities in the soil response, in the case of strong ground shaking, this

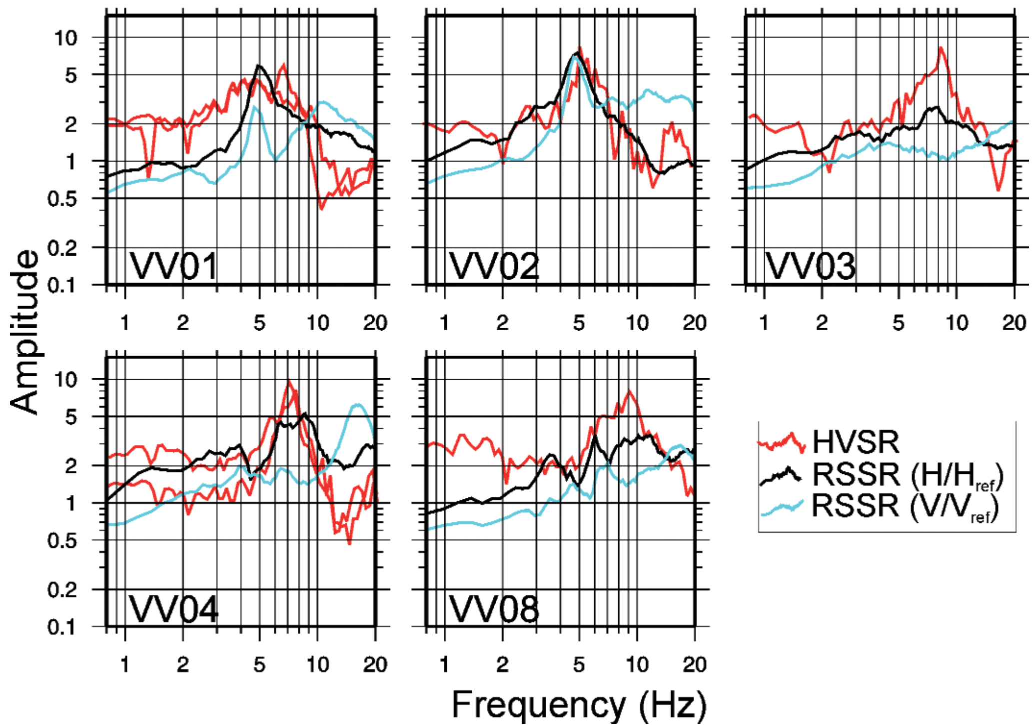

Fig. 6 - HVSR and RSSR comparison at some sites.

aspect cannot be addressed with the dataset used in this study as it consists primarily of fairly small earthquakes.

5. In situ measurement of shear wave velocities of shallow soils from surface waves analysis and inversion

5.1. Data acquisition and processing

A surface wave analysis has been performed on three shallow seismic refraction profiles that were collected at two sites in Vittorio Veneto, namely site A and site B in the map of Fig. 2. Here, we estimate the near surface vertical structure of the sites, i.e. the S-wave velocity and average thickness of the weathered layer. The seismic profiles consist of an off-end, 105 m long spread-line at site A, and two crossed lines (N-S and E-W oriented) at site B. In all cases, data were acquired using a 12-channel seismograph, with inter-receiver spacing of 5 m and 1 ms sampling interval. For these shallow seismic refraction surveys (e.g. see Fig. 7), a surface wave analysis was performed to retrieve the Rayleigh wave dispersion curves. Phase and group velocity for the fundamental mode and first higher mode of Rayleigh waves was estimated by 2-D transforms (Frequency-Time Analysis and F-K transforms) of the seismic records in the frequency range 8-30 Hz (Fig. 8). In addition, the McMechan and Yedlin (1981) technique was applied to obtain phase velocity dispersion from an array of seismic traces.

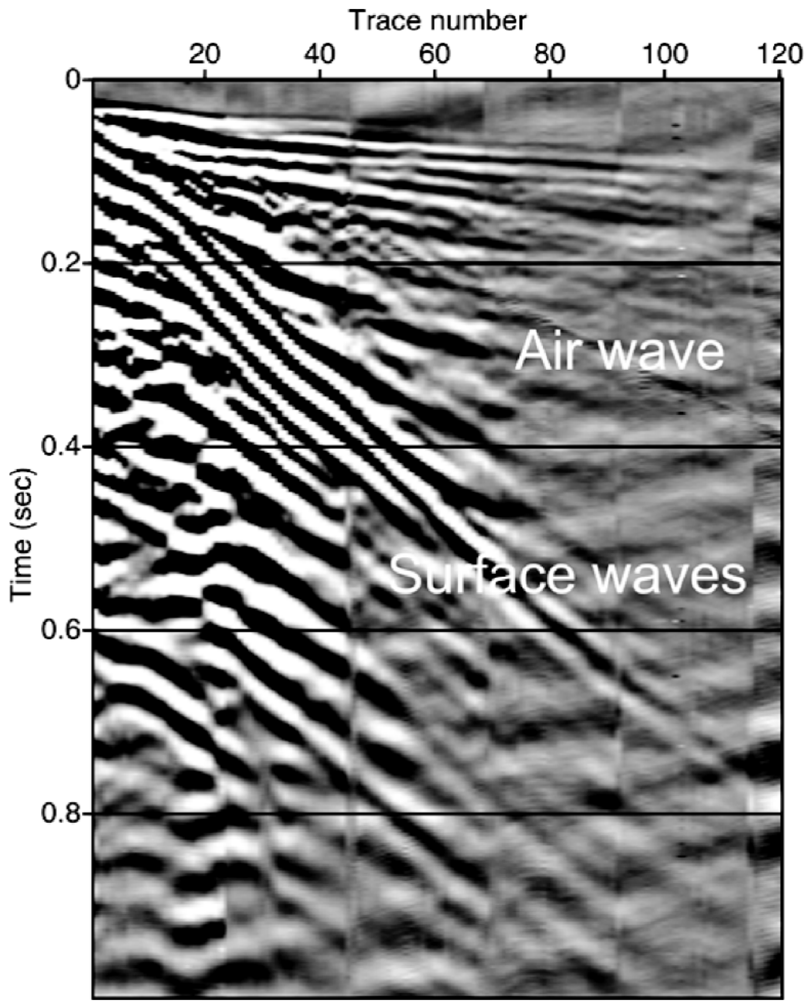

Fig. 7 - Seismic survey at site B. Surface waves, as well as the air wave are well identified.

The observed phase and group velocities can be used to determine the S-wave velocity and soil thicknesses. Phase and group velocities depend primarily on the shear wave velocity and are insensitive to usual variations of density and compressional wave velocity with depth. Since the inversion of the surface wave dispersion properties generally leads to smoothed equivalent S-wave velocity profiles with no evidence of sharp impedance contrasts, we use the information contained in the seismic noise spectral ratios (HVSR) to constrain the solutions of the inversion. The S-wave distribution versus depth is left free to vary at the top, while a homogeneous layer is imposed at the bottom. An iterative, weighted inversion method is used (Herrmann and Ammon, 2002), which allows velocity discontinuities in the resulting model to be force. One can fix the layer thicknesses and invert for velocity, or fix the velocities and invert for layer thickness. In order to evaluate the stability of the results, several inversion runs of 10-20 iterations each are performed using different starting models, smoothing, and damping. The constrained linear

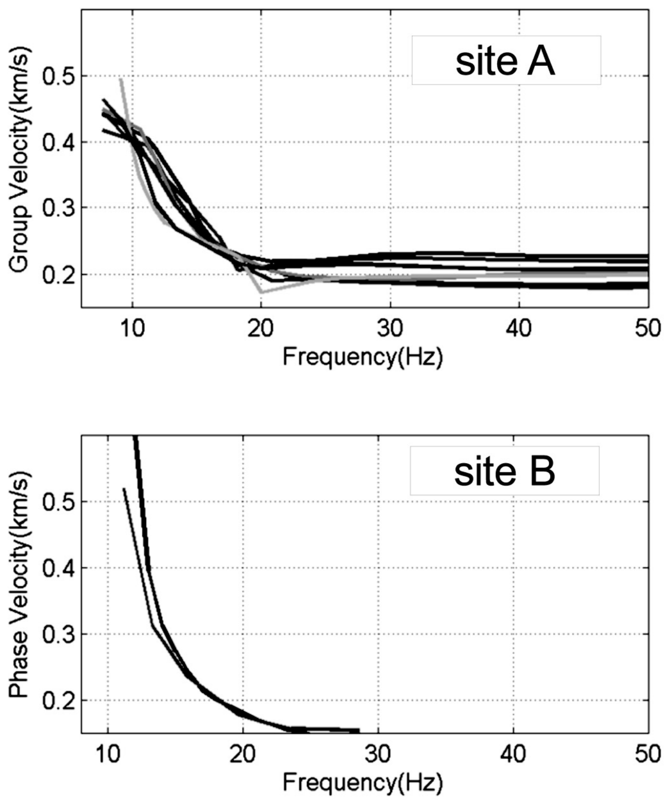

Fig. 8 - Rayleigh wave group (top panel) and phase (bottom panel) dispersion curves for A and B (see Fig. 2 for location) investigated sites.

inversion provides a number of possible models, which display sharp velocity contrasts or velocity gradients and feature a fundamental frequency coherent with the observed HVSR. The variability of the shear wave velocity models obtained here is strictly dependent on the uncertainties in the dispersion curve measurement and in the estimation of the resonant frequencies.

5.2. Results

At site A, the constrained inversion provides a family of equivalent models which display a sharp velocity contrast between 17 and 20 m (Fig. 9). All these models feature a resonant frequency at 6 Hz as independently estimated by the noise HVSR analysis.

At site B, the interpretation provides a family of S-wave velocity models which feature, a shear wave velocity gradient in the shallowest part and a velocity contrast at about 12-13 m. These models are also confirmed by the results of a down-hole sounding to 80 m depth, which reveals the presence of a thick clay level (~10 m), while a monotonous sequence of coarse gravel characterizes the stratigraphic column at depth.

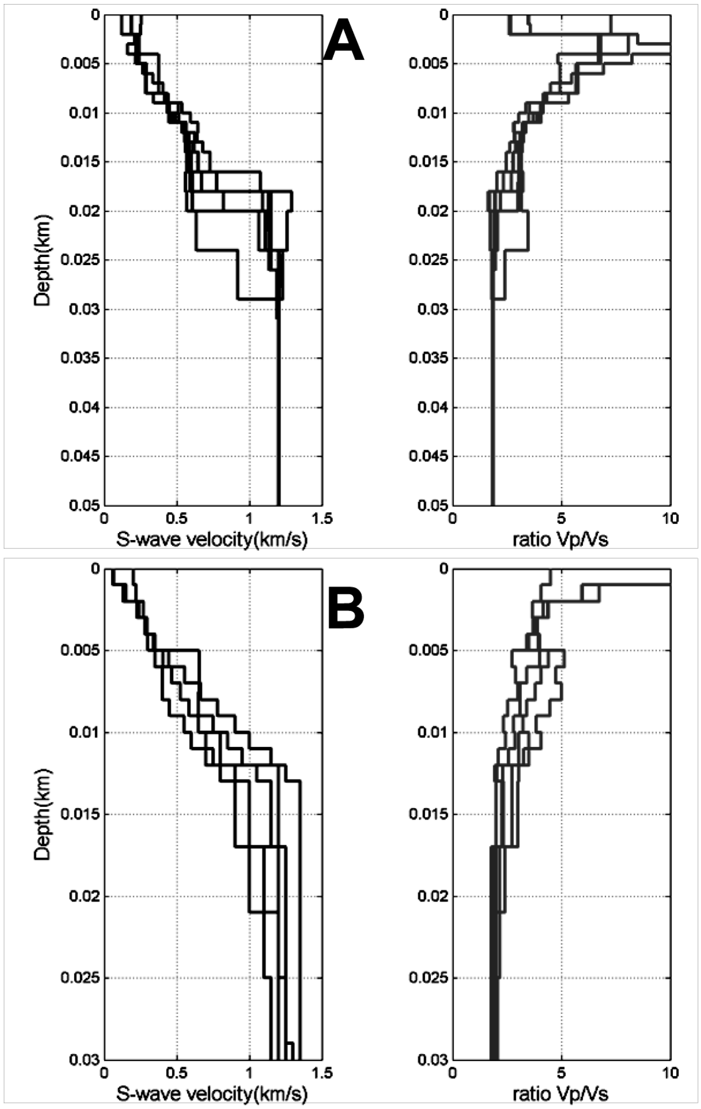

Fig. 9 - S-wave velocities (left panels) and P/S-wave velocity ratio (right panels) for the two sites A and B (top and bottom panel, respectively). Site B features a velocity gradient variation at 12-13 m depth and high P/S-wave velocity ratios at the surface. A deeper impedance contrast is found at about 17-20 m depth below site A.

6. Discussion

From the information provided by the geological studies, geophysical drillings and down-hole measurements which were available for this area, we have found evidence of a correlation between the HVSR results, the RSSR results and the geology of the study area. At two test sites we have also linked the resonance frequency resulting from the HVSR analysis to the underlying shear wave velocity structure. As the map of the Quaternary soils shows, the surface geology that characterizes the Vittorio Veneto basin is rather simple at a local scale (see Poli *et al*., 2008), and we are confident that the resulting velocity structures can be extrapolated further away from the test sites with a good approximation. The map of the fundamental frequency estimated from the noise HVSR suggests that the area can be divided into four zones.

The first zone is the area of Old Serravalle village (SRV). Here the HVSR analyses feature fundamental frequencies in the range 3-5 Hz. The geological map outlines the presence of thin sediments here (i.e. silt and peat), and the available drillings do not detect the geological bedrock down to a depth of 30 m. However, since SRV is located near a deep gorge, we cannot rule out that the peak frequencies resulting from the HVSR are due to a topographic effect and, in particular, correspond to the fundamental mode of vibration of the gorge itself.

In Serravalle (VVC), the historical heart of Vittorio Veneto, the HVSR feature resonance frequencies between 3 and 10 Hz, with higher frequency towards the south. The only drilling performed within the project, at site B (Fig. 2), reaches a depth of 80 m. Down to this depth no evidence of a geological bedrock has been found. The down-hole measurement points out the presence of a thick clay level in the first 10 m and, below that, a sequence of fluvial and glacial deposits of coarse gravels. The resulting shear wave velocities are 200-400 m/s and 750-1200 m/s for the clay and gravel layers, respectively.

The third zone (VVN) defines the area of major expansion of the city. Here, a much higher HVSR resonant frequency has been found (10-20 Hz). The available information coming from the geology and the stratigraphy (locally, at few points), show a bulk presence of gravel, the absence of thin deposits at shallow depth, as well as the probable rise of the bedrock (i.e. the contact of the fluvial-glacial sediments with the underlying formation) to a depth of about 50 m. Therefore, the high HVSR fundamental frequencies are explained by both an increase of the shear wave velocity and a thinning trend of the uppermost Quaternary levels.

Finally, at Ceneda (CEN) we found peak frequencies decreasing from about 8-9 Hz in the centre of the valley, close to the Meschio River, to 1.3 Hz towards the western edge of the basin. The lowest, overall frequencies (i.e. 1.3-1.4 Hz, in the map of Fig. 3) have been found exactly in the part of town which suffered the most severe damage during the 1936 Cansiglio earthquake. At present, no information on the elastic parameters of the soils exist for this area. The available geological data show the presence of a clay lens expanding from the west side eastward, with a thickness of about 20 m. This lens was originated by the lateral Cervada creek (Fig. 2) and extinguishes a few hundred meters eastwards. It seems a reasonable explanation for the low resonance frequencies found in this zone. The surrounding area features frequencies between 4.5 and 11 Hz and it is characterized by an underlying structure similar to VVN, although with an increased depth of the geological bedrock to about 60-70 m.

7. Conclusions

The results of this study indicate that the amount of local site seismic amplification in the Vittorio Veneto municipal area, as determined from the HVSR on microtremors and the RSSR on weak earthquakes, can be relevant. In most sites, HVSR and RSSR display a clear peak, suggesting the presence of a soil-bedrock impedance contrast. Overall, the pattern of the HVSR indicates the presence of four zones which can be associated with the shallow geology and/or with topographic effects.

The HVSR results computed from seismic noise at Serravalle have been compared with site effects estimated at some nearby sites using the RSSR technique. The comparison shows that although the two techniques provide consistent estimates of the fundamental frequency, the main peak amplitude values often disagree, the HVSR ones derived from seismic noise being usually higher than those derived from the classical spectral ratios. Two sites, located on the left bank of the valley, show high values of amplification, 5 times larger than a signal amplitude at the reference sites, in correspondence to well discernible peak frequencies of 5 Hz. RSSR results for the other stations show smaller amounts of site amplification spreading over a broad range of frequencies and they generally agree with HVSR resonant frequencies.

A surface wave analysis, performed using shallow seismic refraction data at two sites in the area of Serravalle-Vittorio Veneto centre, provides a set of S-wave velocity models, whose fundamental frequencies match those estimated independently by the HVSR technique.

Additional information coming from geological studies, refraction seismic lines, geophysical drillings and down-hole measurements have been used in order to correlate the shallow geological structure with the estimated resonance frequency, and constrain possible solutions in the inversion process.

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