



SITE RESPONSE ESTIMATION IN VITTORIO VENETO (ITALY)

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SUMMARY

The area of Vittorio Veneto (Treviso, Italy) was heavily injured by a M=5.8 event in 1936, localized at about 20 km of distance. The damage distribution was extremely heterogeneous, suggesting the influence of site effects. In order to assess the seismic response of this area, some geophysical surveys consisting of environmental seismic noise measurement (Nakamura's approach), shallow seismic refraction have been carried out. The horizontal-to-vertical spectral ratios (HVSr) resulting from the ambient noise measurements reveal that most sites display clear resonant peaks, with variable HVSr amplitudes. The large amplitude of most peaks suggests the presence of a large impedance contrast between the sediment coverage and the underlying formation. In addition, we perform a shear wave velocity profiling based on the inversion of surface waves. The technique consists of a surface wave analysis performed on both single- and multi-channel records, by inverting the phase and group velocity of the Rayleigh wave fundamental mode. By using a non-linear inversion technique, we constrain the resulting equivalent S-wave velocity profiles to feature S-wave velocity contrasts higher than two in a depth range of 8-20 m. In this way, we obtain some S-wave velocity models, whose fundamental frequencies match exactly those estimated independently by the HVSr. Additional information coming from other studies such as a geological studies, refraction seismic lines, geophysical drillings and down-hole measurements support our results.

INTRODUCTION

In 2000, the National Group for the Defence against Earthquakes (GNDT), funded by the Italian Civil Protection Agency, started a research program aimed toward the determination of seismic risk scenarios for the Friuli-Veneto region. Among this project, the group devoted to 'site characterization and site effects' decided to focus the study on the city of Vittorio Veneto, in virtue of its importance by the historical point of view. The area of Vittorio Veneto (Figure 1) is prone to earthquakes. It was injured by a M=5.8 event on October 10, 1936, localized at about 20 km of distance, that caused a very heterogeneous damage distribution with maximum MCS intensity of IX, suggesting the occurrence of site effects. The maximum damage of the Vittorio Veneto area was localized in locality, named Ceneda, located near the South-Western part of the city. Here, severe damages and some collapses occurred. The area has been

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struck by several, relevant historical earthquakes, such as the 1776 event of Tramonti (MCS intensity VIII-IX), the 1873 event of Belluno (MCS intensity X), and that of 1695 of Asolo (MCS intensity IX). Blind active faults exist within the area, while other potentially dangerous structures are hypothesized (e.g. the Montello thrust fault). The present seismicity level of the area is rather low.

In order to assess the seismic response in Vittorio Veneto, a geophysical survey consisting of environmental seismic noise measurements (Nakamura's approach) has been carried out. The technique is based on the observation that "the vertical component is not subjected 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 [6]). It follows that the ratio between the horizontal and vertical spectral components of motion can provide a first order estimate of the site transfer function.

Recent studies (Bard [2]; Faeh [3]) have confirmed the close connection between HVSR and the ellipticity of surface waves (Nogoshi [8]). In particular, these authors have shown that i) the lowest frequency peak of the H/V curve coincides with the fundamental resonance frequency of the site (if any), ii) the peak occurs whenever the soil-bedrock impedance contrast exceeds a value of about 2.5, and iii) the H/V ratio does not provide an estimate of the entire bandwidth over which the motion is amplified.

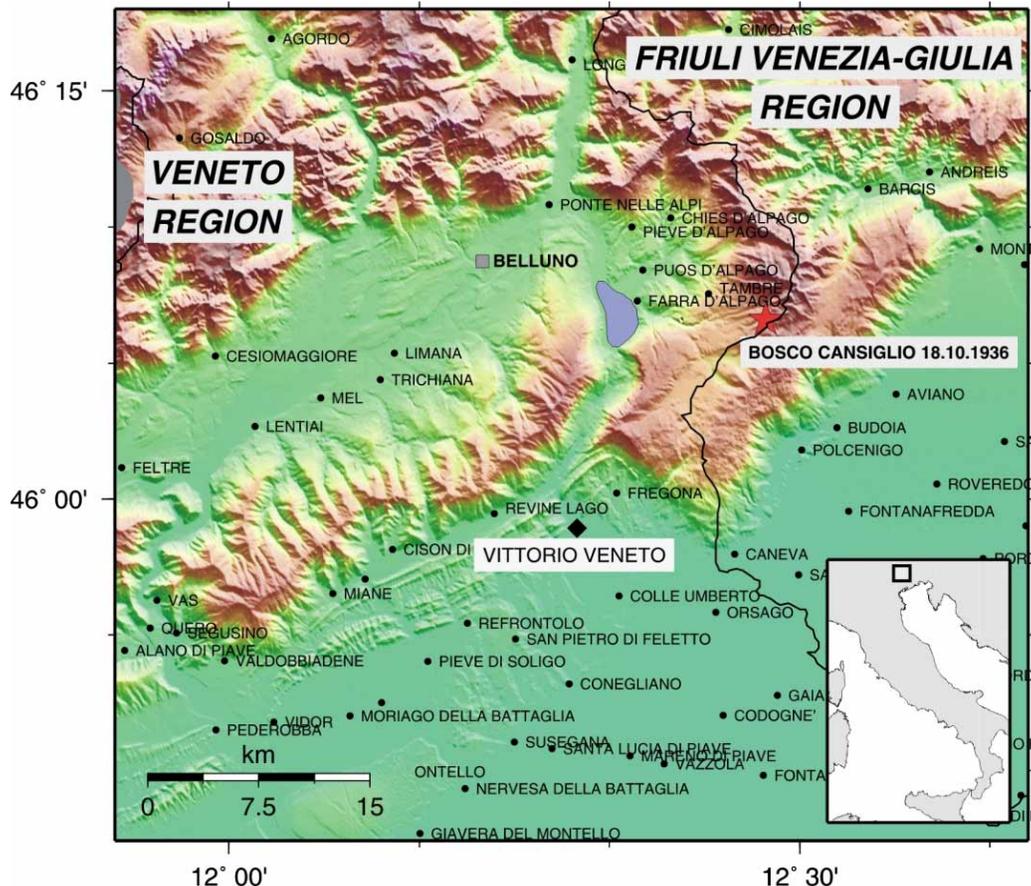


Figure 1. Base map of the study area, showing the location of Vittorio Veneto town (black diamond) and the epicenter of the M=5.8, October, 16, 1936 Cansiglio earthquake.

The use of microtremors for site amplification studies has become quite popular in recent years since for many reasons: 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 produce a proper data set. However, the method has some well known limitations, i.e., the HVSR of microtremors can detect only the fundamental resonant frequency of the site, and the interpretation of the H/V amplitude level should be made with caution.

In this study, we perform a shear wave velocity profiling based on the inversion of surface waves. To this purpose, a number of shallow seismic refraction lines have been carried out. The technique consists of a surface wave analysis performed on both single- and multi-channel records, by inverting the phase and group velocity of the Rayleigh wave fundamental mode. Rayleigh waves contain important information strictly related to the S-wave velocity distribution at depth. 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 [11]). In seismic prospecting the application of these techniques is increasing since they are not invasive and in comparison with down-hole and cross-hole present significant economical advantages. In addition, we use the information of HVSR to constrain the inversion of the 1-D S-wave velocity profile of soil. By using a non-linear inversion technique, we constrain the resulting equivalent S-wave velocity profiles to feature S-wave velocity contrasts higher than two in a depth range of 8-20 m. In this way, we select among the set of equivalent S-wave velocity models those whose fundamental frequency match exactly that estimated independently by the HVSR.

In the following, we first provide a short description of the various geological formations that outcrop in the studied area. Then, we describe in detail the results obtained by the microtremor field acquisition in order to assess the seismic response in terms of resonance frequency. Finally HVSR results are used to constrain the inversion of surface wave dispersion properties for site characterization of soils

GEOLOGICAL DESCRIPTION OF THE AREA

The study area belongs to the sudalpine Alps domain, and the main tectonic structures are characterized by South and South-East verging thrust faults. The city of Vittorio Veneto is located on the south slopes of the Pre-Alps of Belluno. The city extends lengthways, from NNW to SSE, at the outlet of the Veneto plain, and is crossed by the Meschio river.

The sketch of geological formations and different soils which characterise the Vittorio Veneto basin is shown in Figure 2. The city is located on Quaternary deposits, while the pre-Quaternary substratum outcrops only in the surroundings zones.

Different soils outcrop along this area. Lacustrine or peaty deposits are found beneath Serravalle Vecchia (SRV) located along a gorge, about 200 m wide, North of the Serravalle castle and beneath Ceneda locality (CEN). Pelites and sands, which have an alluvial or colluvial origin, characterize the centre town of Vittorio Veneto (VVC) while towards South, where the city settlement is growing, surface sediments become coarser (gravels and cobbles, VVN).

Several alluvial fans surround the city. They are originated and put down by the lateral streams and rivers that flow from the mountain flanks. In general, they are composed of relatively fine sediments (commonly silt, clay or sand). Detritus and glacial deposits outcrop at both the West and East sides of the investigated area.

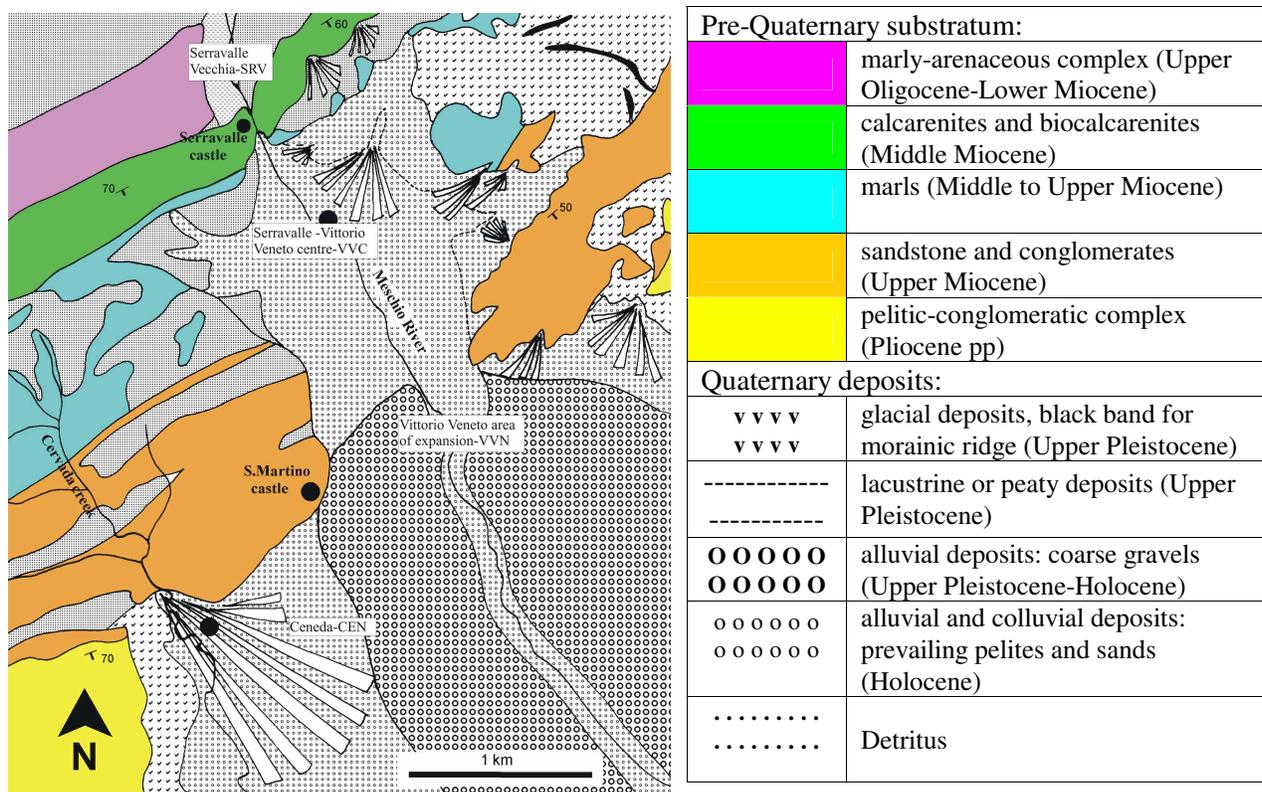


Figure 2. Geological sketch of the Vittorio Veneto area (M. E. Poli, personal communication).

HORIZONTAL-TO-VERTICAL SPECTRAL RATIOS (HVSR)

Data acquisition and processing

The seismic noise was recorded at about 100 different sites (Figure 3). Data acquisition was performed using two different types of portable seismic stations, namely Orion Nanometrics and Mars Lite 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 response of the instrument decays by approximately 10 db/octave so that a conservative threshold for marking the frequency below which the data contain mainly instrumental noise (i.e., combined seismograph and sensor self-noise) is 0.5 Hz. At each site, microtremor acquisition lasted for a minimum of twenty minutes of continuous recording time. The sampling interval was set to 100 Hz, guaranteeing reliable spectral estimates up to 30 Hz. The recorded noise level was high enough at all sites in a wide frequency range. Much attention was paid to avoid, as much as possible, the introduction of near instrument transient and coherent signals (e.g., operator induced) and, whenever possible, the geophone-soil coupling was improved by burying the sensor into the ground.

The mean H/V ratio was estimated by averaging the HVSR computed on a set of running time windows. At the pre-processing stage, outliers were manually removed, producing a set of disjointed data time windows. In this study, we have used a window length of 180 seconds with 10% of overlap. A minimum of six running time windows, for a total length of 20-30 minutes, was used to determine the mean HVSR. For the generic i -th time window, the signal is processed as follows: 1) DC removal and linear detrending; 2) 5% cosine tapering; 3) computing the horizontal component of the motion, as a vector sum of the two horizontal components; 4) computing the square root of the power spectral density (PSD) of the horizontal and vertical components (H_i and V_i , respectively); 5) computing the $\{H/V\}_i = H_i/V_i$ ratio; and 6) the average H/V and associated error are estimated by the median and standard deviation of the $\{H/V\}_i$ family, respectively. In the processing above, the PSD (step 4) is computed using methodologies designed

for the analysis of noisy signals, i.e., the Welch's (Welch [10]) or Burg's (Kay [5]) methods, and no smoothing is applied in the spectral ratio computation (step 5). In our tests, the two methods result in very similar estimates.

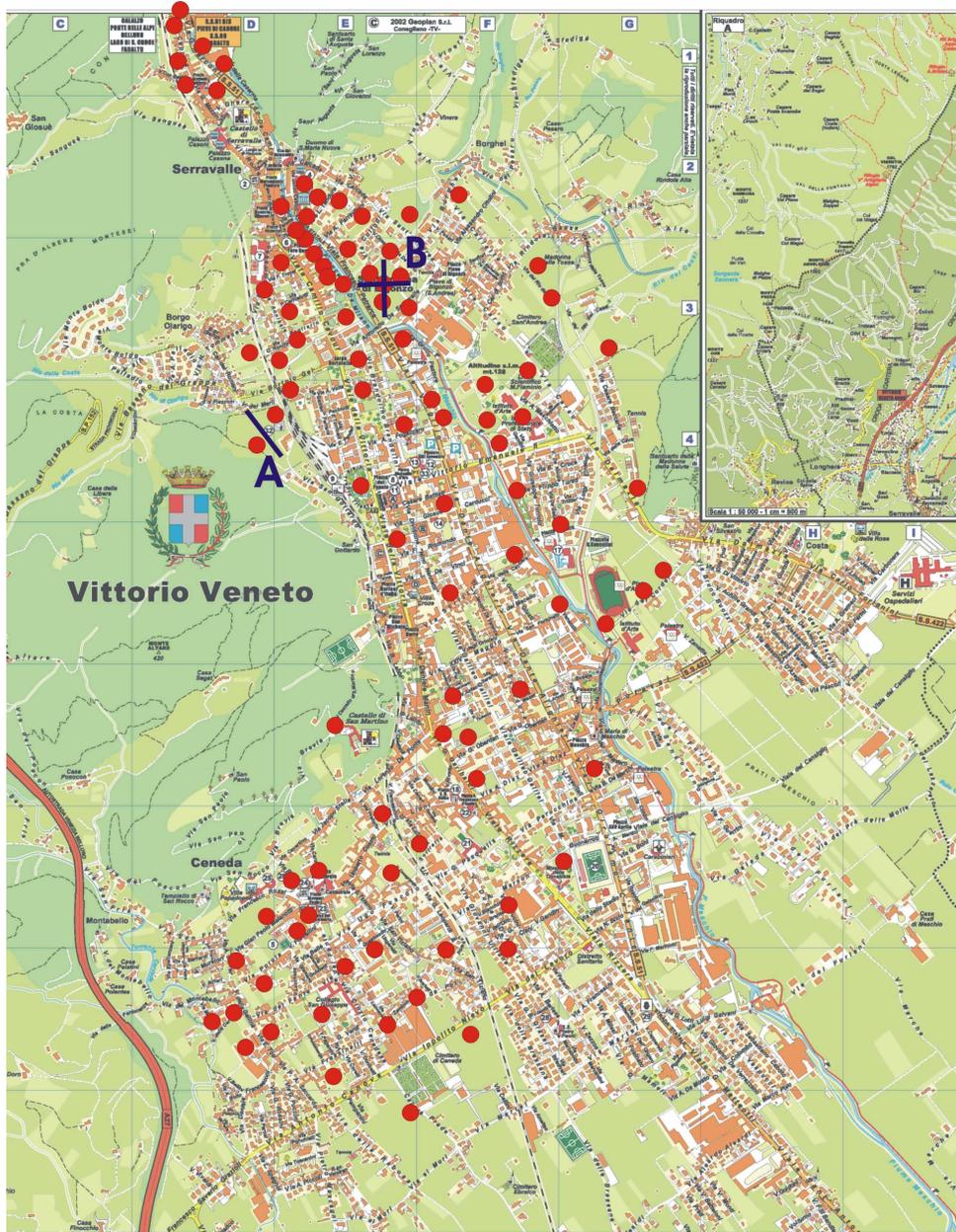


Figure 3. Base map of the Vittorio Veneto municipal area showing the location of the seismic noise acquisition sites (red circles) and refraction lines (blue lines) used for the surface waves analysis.

Results

The final data-set consists of the HVSR estimated 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 was generally large, as a result of anthropic activities (e.g., working equipment, cars, etc). The standard deviation value was generally low, confirming a general stability in the HVSR measurements. Most sites

display clear resonant peaks, with variable HVSR amplitudes, while only few of them feature a flat response. The large amplitude of the HVSR peaks usually found throughout the area suggests the presence of a large impedance contrast between the sediment coverage, with varying thickness, and the underlying formations (Bard [2]).

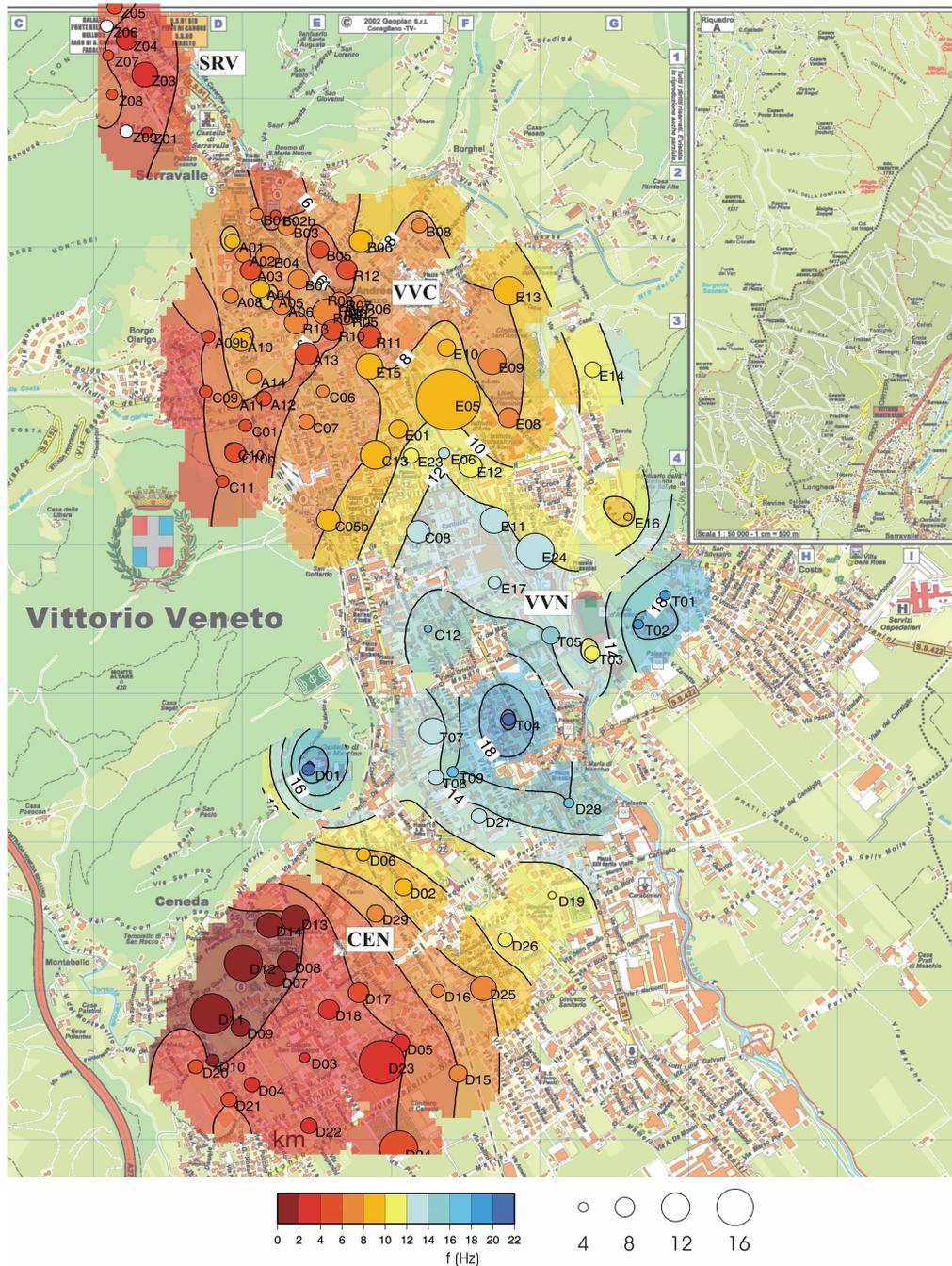


Figure 4. HVSR amplitude in the frequency range 0.5-22 Hz. The color and size of the circles indicate peak frequency and amplitude of the HVSR, respectively. White circles indicate sites with very low H/V amplitude or flat response. The value of resonance frequency is also indicated along the iso-frequency lines computed by interpolating the peak frequencies.

Figure 4 shows the peak of the resonance frequency and the corresponding HVSR amplitude value of each site. The color and the size of the circles indicate peak frequency and amplitude of the HVSR, respectively. White circles (i.e. in the area of Serravalle) indicate sites with very low H/V amplitude or flat response. The peak frequency values have been interpolated in order to visually enhance the geographical distribution.

The resulting map suggests the presence of four distinct zones characterized by different resonance frequencies. From North to South, SRV features resonant frequencies in the range 3-5 Hz, while VVC features higher resonance frequencies from 3 to 10 Hz. The fundamental frequency increases further towards South. The area located at the centre of the map (VVN) corresponds to the area of expansion of the town. It shows up much higher resonant frequencies (10-20 Hz). Finally, in the area of Ceneda (CEN) the fundamental frequency decreases from about 8-9 Hz to a very low value of about 1.3 Hz. The lowest frequencies are localized in the oldest part of CEN, at West. This area suffered the strongest damages during the 1936 Cansiglio earthquake.

In Figure 5, we show some examples of HVSR estimated at the four zones: site Z03 for SRV, site A13 for VVC, sites T05 and D09 for VVN and CEN, respectively. These sample sites — and in general most studied sites — feature a clear HVSR peak which corresponds to the fundamental mode of vibration and suggest the presence of a relevant acoustic impedance contrast at depth.

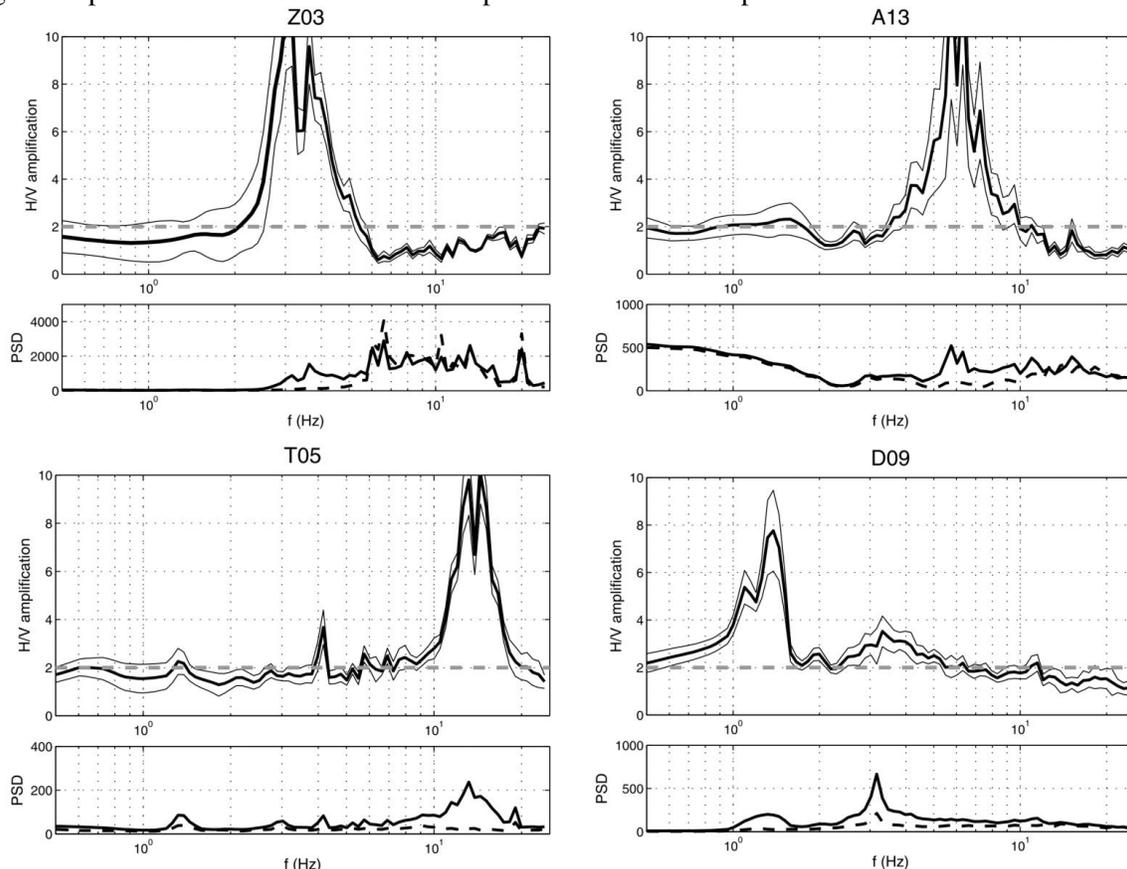


Figure 5. HVSR estimated at different sites in the Vittorio Veneto area. The name of the site is indicated at the top of each panel For each site, the top panel represents the HVSR (thick line) plus/minus the first standard deviation(thin lines), while the bottom panel represents the power spectral density (PSD) computed for the horizontal (solid line) and vertical (dashed line) components.

In another study (Restivo [1]), the HVSR computed from seismic noise at Serravalle have been compared with those estimated at some sites nearby using a reference site and weak earthquake records. The comparison shows that while the two techniques provide coherent estimates of the fundamental frequency, the main peak amplitudes often disagree, the seismic noise spectral ratio peak being usually higher than that derived from the classical spectral ratios.

IN SITU MEASUREMENT OF SHEAR WAVE VELOCITIES OF SHALLOW SOILS FROM SURFACE WAVES ANALYSIS AND INVERSION

Data acquisition and processing

The surface waves analysis is performed for shallow seismic refraction surveys that were acquired at two sites of Vittorio Veneto area, namely site A and site B in the map of Figure 3. This work aims at estimating near surface elastic parameters and determining the average thickness of the weathering layer. Moreover, the resonance frequency estimated by the HVSR locally is used to constrain the shallow velocity model.

At the first site, an off-end spread-line having 105 m of length has been acquired, using a 12 channel seismograph, with inter-receiver geophone spacing of 5m, and sampling interval of 1 ms. At site B, two crossed lines (NS and EW oriented), have been acquired.

For these shallow seismic refraction surveys (Figure 6), the surface wave analysis has been performed by inverting the Rayleigh wave fundamental mode, in order to provide a group of equivalent V_S profiles up to a depth of 20 m. Phase and group velocity for the fundamental mode and first higher mode of Rayleigh waves are measured by 2-D transforms (Frequency-Time Analysis and F-K transforms) of the seismic surveys in the frequency range from 8 to 30 Hz (Figures 7 and 8).

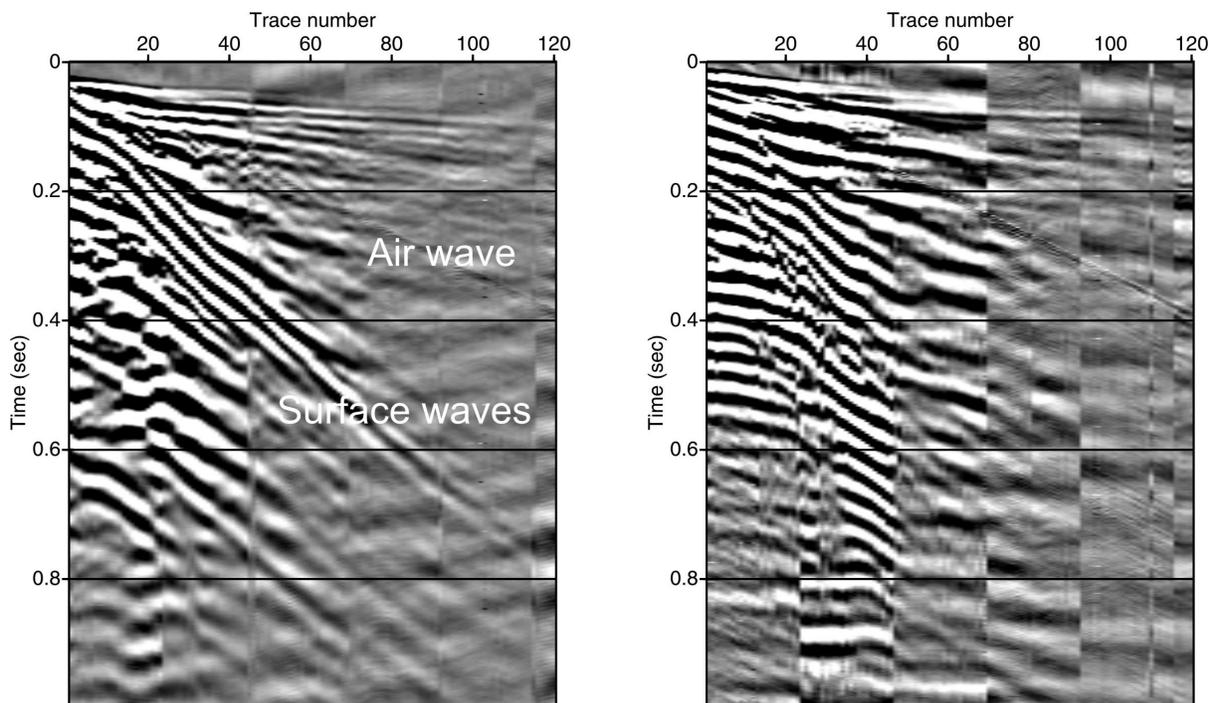


Figure 6. Seismic surveys at site B. Right panel = North-South Section, Left panel = West-East Section. Surface waves are well identified on the left panel.

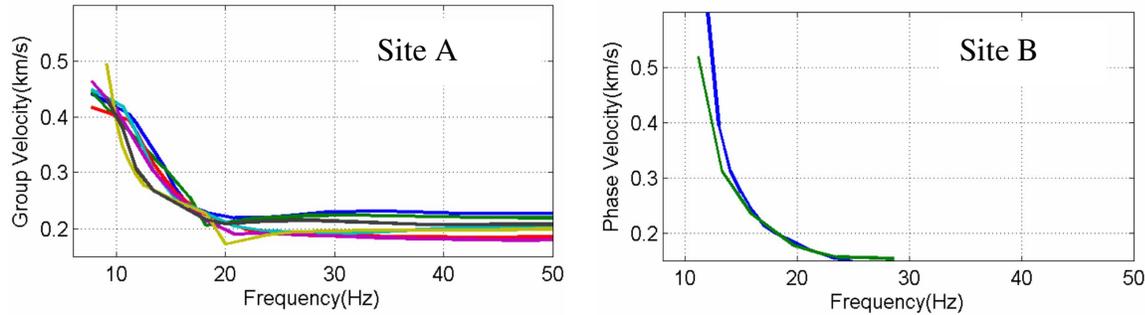


Figure 7. Group (left panel) and phase (right panel) measurements at the investigated sites.

In addition, the McMechan and Yedlin [7] technique is applied to obtain phase velocity dispersion from an array of seismic traces (Figure 8). This technique performs a p - τ stack followed by a transformation into the p - ω domain. A separate stacking procedure is not required to accomplish these operations if they are performed in the frequency domain.

The observed phase and group velocities can be used to determine the structure of the sediments by comparison with the phase velocities computed by a synthetic model. Phase and group velocities depend primarily on the shear wave velocity and are insensitive to realistic variations of density and compressional wave velocity with depth. This can be seen by comparing the partial derivatives of the phase and group velocity with respect to S-wave velocity, P-wave velocity and density. For the two latter parameters we used realistic profiles taking into account a depth of about 0-3 m for the water table.

Since the inversion of the surface wave dispersion properties generally leads to smoothed equivalent V_S velocity profiles with no evidence of sharp impedance contrasts, we use the information contained in the seismic noise spectral ratios (HVSR) — i.e., the presence of a HVSR peak implies an impedance V_S contrast higher than 2 at some depth — to constrain the solutions of the inversion. The V_S distribution is let free to vary at the top, while a homogeneous layer is imposed at the bottom. An iterative, weighted inversion method is used, which allows to force velocity discontinuities in the resulting model. One can fix the layer thicknesses and invert for layer 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 have been performed using different starting models, smoothing, and damping. The constrained linear 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.

Results

At the two study sites A and B, we invert the fundamental Rayleigh mode using a linear technique (Nolet, [9]; Herrmann [4]) (Figure 8) and use the indications provided by the seismic noise HVSR recorded at the sites closest to the seismic lines (C11 and R01, respectively) (Figure 10), to constrain the solution to feature an impedance V_S contrast within a given depth interval. Using the value of the resonant frequency estimated by the HVSR (i.e. 5 and 6 Hz for the two sites, respectively), and an average medium shear wave velocity of about 300-400 m/s in the shallowest sediments, this interval has been set at 8-20 m for the two investigated sites.

For site A the constrained non-linear inversion provides three possible models (Figure 9), which display a sharp velocity contrast between 17 and 20 m, respectively. All these models feature a fundamental frequency of vibration of 6 Hz, which matches exactly that estimated independently by the HVSR.

Similarly, the analysis provides for site B some Vs model characterized, in the uppermost levels, by a shear velocity gradient and by a velocity contrast at about 12-13 meters. This model is also validated by the results of a down-hole sounding down to 80 m, which points out the presence of a thick clay level (~10 m), while a monotonous sequence of coarse gravel characterises the rest of the stratigraphical column. At both sites, some models display a large P/S velocity ratio on the upper meters (Figure 9). This variation is due to the presence of the water table, although the surface wave analysis method is not suitable for resolving the different degree of water saturation of soils.

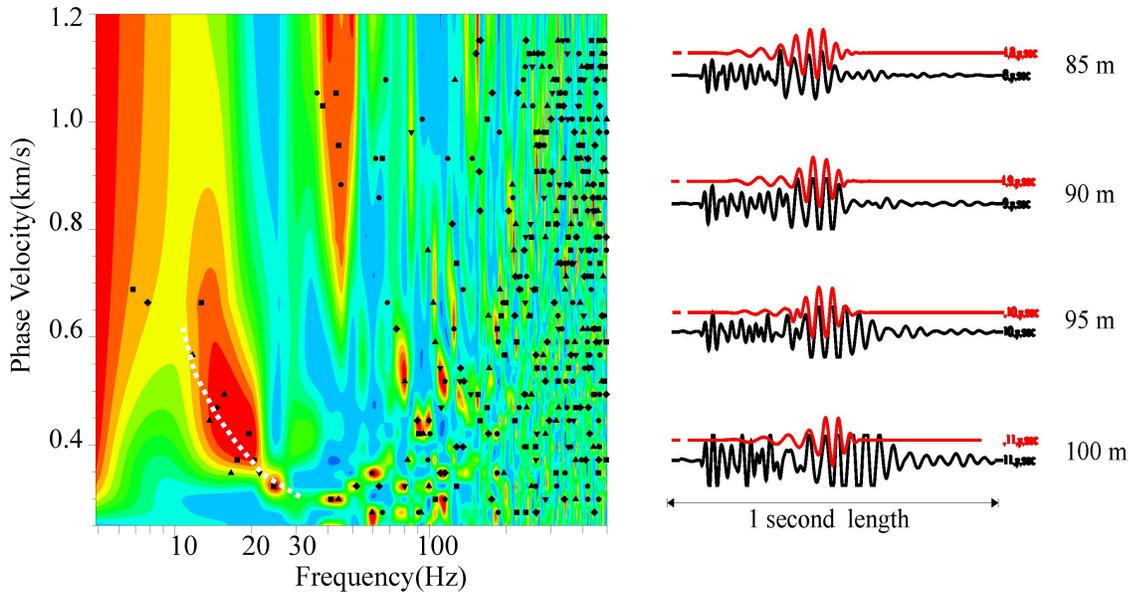


Figure 8. Phase velocity measurements (left) obtained by applying the McMechan and Yedlin (1981) technique. The right panel shows the raw data extracted at offset from 85 m to 100 m (black lines) and the filtered Rayleigh wave fundamental mode (red lines).

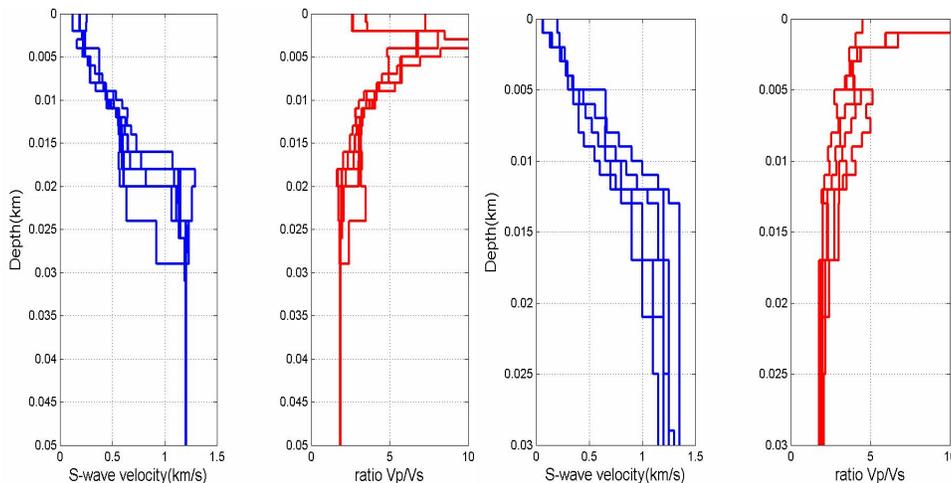


Figure 9. S-wave velocities (blue lines) and P/S-wave velocity ratio (red lines) at the two sites. Site B (right) features a velocity gradient variation at 12-13m of depth and high P/S-wave velocity ratios at the surface. A deeper impedance contrast is found at about 17-20m of depth below site A(left).

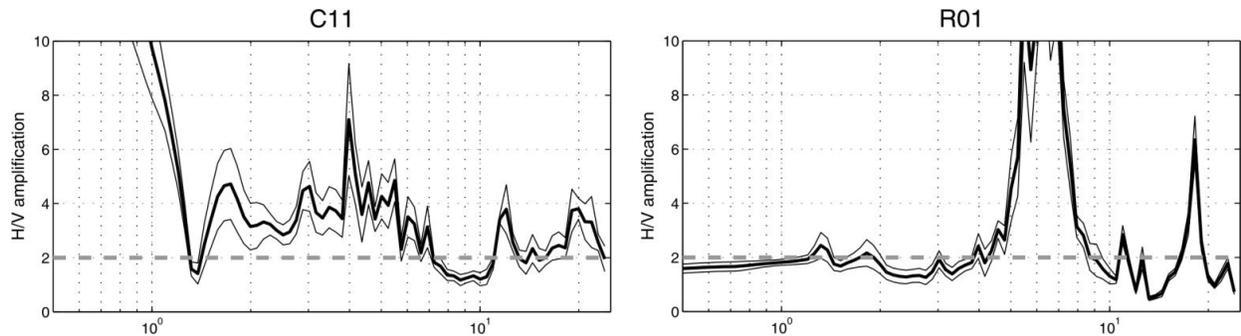


Figure 10. HVSR estimated at sites C11 and R01, located near the shallow seismic refraction lines (sites A and B, respectively). HVSR (thick line) plus/minus the first standard deviation (thin lines).

DISCUSSION

From the information provided by the geological studies, geophysical drillings and down-hole measurements, which were available for this area, we found evidence of a correlation between the HVSR results and the geology of the study area. Only in the two test sites we are able to link the resonance frequency resulted from the HVSR with the underlying velocity structure locally. As the map of the Quaternary soils shows (Figure 2), the surface geology that characterizes the Vittorio Veneto basin is rather simple, therefore we are confident that the resulting velocity structures can be extrapolated in space, with a good approximation, also abroad the test sites. The HVSR map suggests that the area can be divided into four zones.

The first zone is the area of SRV, that lies North. In this area the HVSRs feature fundamental frequencies in the range 3-5 Hz. The geological map evidences the presence of thin sediments (i.e. silt and peat), and the available drillings do not detect the geological bedrock up to 30 m of depth. However, since SRV is located into a deep gorge, we cannot exclude that the peak frequencies extracted by the HVSR are a topographic effect, and in particular, correspond to the fundamental mode of vibration of the gorge.

The area of Serravalle (VVC) features resonance frequencies between 3 and 10 Hz, with higher frequency towards South. Unfortunately, data coming from the stratigraphy of water wells or oil drills are scarce and generally the quality of these data is low, providing poor information about the geotechnical characteristics of the Quaternary sediments. The only drilling performed within the project, at site B (Figure 3), reaches the depth of 80 m. At this depth no geological bedrock was found. The down-hole measurement points out the presence of a thick clay level in the first 10 m and, below it, of a sequence of fluvial and glacial deposits made of coarse gravels. The resulting shear wave velocities are of 200-400 m/s and 750-1200 m/s for the clay and gravel levels, respectively. Three refraction lines performed at sites A, B and C show quite similar velocity structures, which agree with the described models. Therefore, the velocity profiles found by the surface waves analysis performed at sites A and B can be considered representative of the shallow soils that characterized the whole Vittorio-Veneto centre area.

The sites located within the VVN area feature a much higher resonant frequency (10-20 Hz). The available information is that coming from geology (Figure 2) and stratigraphy (locally, at few points), which show the absence of the thin sediments layer at shallow level as well as the probable rise of the bedrock — the contact of the fluvial-glacial sediments with the underlying formation — at about 50 m of depth. Therefore, the high HVSR fundamental frequencies are explained by both an increase of the shear wave velocity and thinning of the uppermost levels.

Finally, at CEN we find frequencies decreasing from about 8-9 Hz to 1.3 Hz towards West. The area of the lowest frequencies (i.e. 1.3-1.4 Hz, in the map of Figure 4) matches exactly the area which suffered the strongest damages during the 1936 Cansiglio earthquake. At present, this area lacks of any information on the elastic parameters of the soils. The available geological data show up the presence of a clay lens expanding from the west side eastward, with a thickness of about 20 meters. This lens was originated by the lateral Cervada creek (Figure 2) and extinguishes in some hundred meters eastward. It seems reasonable to explain this low resonance frequency zone by the presence of this structure. The surrounding zone, i.e. that characterized by frequencies between 4.5 to 11 Hz, is characterized by an underlying structure similar to VVN, although with an increasing depth of the geological bedrock to about 60-70 meters.

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 of microtremors, is generally relevant. In most sites, the HVSR displays a clear peak, suggesting the presence of a large (>2-2.5) 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 topographical effects.

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

The high resonant peaks found at Ceneda show a clear correlation with the strong damage occurred during the 1936, Cansiglio earthquake, and suggest a higher seismic hazard for this zone.

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The base map of Vittorio Veneto (Figure 3) was taken at the web site: <http://www.geoplan.it/>

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