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Ambient noise measurements to support emergency seismic microzonation: the Abruzzo 2009 earthquake experience

M.R. Gallipoli[1], D. Albarello[2], M. Mucciarelli[3] and M. Bianca[3]

[1] *Istituto di Metodologie per l'Analisi Ambientale, C.N.R., Tito Scalo (PZ), Italy*
[2] *Dipartimento Scienze della Terra, Università di Siena, Italy*
[3] *Dipartimento di Strutture, Geotecnica e Geologia Applicata, Università della Basilicata, Italy*

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ABSTRACT After the 2009 Abruzzo earthquake (Italy), a surface geophysical survey was undertaken to support emergency microzonation studies. The technique most used was the Horizontal-to-Vertical Spectral Ratio (HVSR) applied to ambient seismic noise. More that 200 single-station measurements were performed by a group that comprised also of volunteer professionals over a two-week time span. The availability of such a large database, which is homogenous both from the instrumentation and the processing point of view, allowed us to compare the results with other expeditious techniques for microzonation. The main findings of our study reveal that: 1) the HVSR results obtained from seismic noise measurements are well correlated with the ones obtained by strong motion recordings; 2) available geological maps, even in a digital form, are unable to correlate with the observed presence/absence of amplification revealed by seismic measurements; 3) the simple lithological classification of outcrops, however detailed, cannot be used as a standalone tool to identify the presence/absence of seismic amplification phenomena. Surface geological data are not sufficient. Borehole and geophysical data are also needed to identify the seismic bedrock and provide estimates of the V_S average value in the sedimentary cover.

Key words: Abruzzo earthquake, HVNSR, site amplification, geological soil classes.

1. Introduction

Immediately after a damaging seismic event, identification of safer sites where temporary structures for shelter and assistance have to be located is of primary importance to optimize available resources and provide safer accommodation. For this purpose, identification of sites where possible amplification of ground motion could occur is a basic tool to reduce the effects of aftershock seismic activity. Furthermore, it is of great importance to distinguish sites where enhanced local damage is the effect of lower quality buildings with respect to situations where the local geo-structural configuration is responsible for ground motion amplifications. Just after this exploratory phase, and within a few months after the main shock, local authorities should be provided with effective seismic microzonation maps, necessary to plan for reconstruction and to create temporary structures.

Thus, both for earlier and later post-seismic activities, effective exploratory tools should be provided for the seismic characterization of the subsoil in the areas shaken by the earthquake. Since an extensive application of these procedures is requested (in general seismic microzonation studies involves areas of the order of hundreds of square km), to warrant their actual feasibility these tools should be characterized by robustness, cheapness and speed. It cannot be expected that such procedures supply detailed information about the seismic stratigraphy (V_S profile, damping factors, and so on) necessary to define the local seismic response (e.g., Kramer, 1996). For this purpose, very intensive surveys are necessary including both *in situ* measurements (down-hole and cross-hole measurements) and laboratory analyses. These procedures are able to provide detailed information but require strong economic efforts and relatively long field procedures.

To distinguish intensive and extensive procedures, “Guidelines for Seismic Microzonation” recently published in Italy (Gruppo di lavoro MS, 2008), indicates three levels of seismic microzoning maps. The first one is devoted to the development of a reference geological model and should be provided on the basis of extensive geological surveys and exploitation of data available in advance. It represents the cheapest phase of microzonation activities since no quantification of the local seismic response is expected: it only concerns the identification of areas where such effects are expected on the basis of exploratory surveys. The second level introduces prospecting activities (including both surface measurements and drilling) and aims at the first order quantification of the local seismic response from the application of tabulated parameters. These tables (abacus) are entered by considering two parameters: the depth of the seismic bedrock (i.e., the depth of soils or rocks with V_S values higher than 800 m/s) and the average V_S above the bedrock. The third level includes detailed measurements and concerns more critical situations, i.e., sites where complex effects (2-D, 3-D effects, liquefaction, etc.) are expected.

The recent Abruzzo earthquake (April 6, 2009), which struck the Abruzzo region with macroseismic intensities reaching IX MCS (Galli *et al.*, 2009), represented an important benchmark for these guidelines that were applied in order to plan monitoring activities immediately after the event.

The cheaper techniques rely on the basic idea that the response of underground structures to ambient vibrations (i.e., uncontrolled sail vibrations induced by natural and anthropic sources) may supply useful indications about their mechanical behaviour under the seismic load, at least as it concerns low strain levels. Two main approaches have been developed respectively based on single-station and multi-station (seismic array) configurations. The importance of these procedures is widely recognized (see, e.g., Bonnefoy-Claudet *et al.*, 2006) and has been the subject of at least two important international projects (e.g., EVG1-CT-2000-00026 SESAME, NATO-SfP980857). Such a growing interest has been driven by the possibility of using such a small amplitude ground motion for cost effective seismic characterization of subsoil and the parameterization of building dynamical response (e.g., Wenzel and Pichler, 2008; Mucciarelli *et al.*, 2009). In particular, Horizontal-to-Vertical Noise Spectral Ratios deduced by single station measurements of ambient seismic noise (HVNSR) have been considered in many cases as an important tool for a cheap and fast seismic characterization of the shallow subsoil in the frame of microzonation studies (see, e.g., Mucciarelli *et al.*, 2003; D’Amico *et al.*, 2008). This technique provides two basic pieces of information: identification of seismic resonance phenomena induced by the presence of sharp seismic impedance contrasts in the subsoil and the relevant resonance frequency (e.g., Bard, 1999).

Since HVNSR measurements can be performed by single operators, with very portable

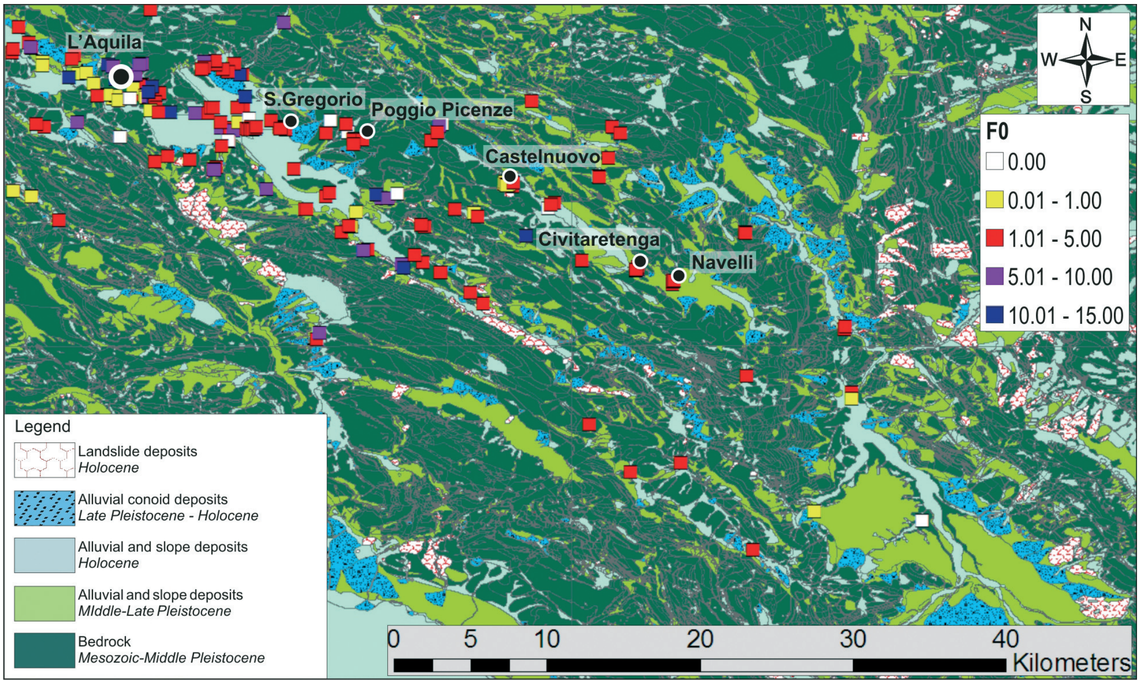

Fig. 1 - Frequency values of HVNSR main peak (F_0) on the 5 classes of outcropping soils on the CARG geological map.

instruments, this technique was widely applied in the area shaken by the April 6, 2009 Abruzzo earthquake, to provide a first exploratory analysis of site effects. In the first two weeks after the main shock, more than 200 ambient vibration recordings (Fig. 1) were performed using the HVNSR approach. The survey was performed using the same kind of equipment, acquisition processing, data analysis and reliability test. Measurements were carried out in the whole area involved in the seismic event, even in the most heavily damaged areas where accessibility for other instruments was problematic, both due to lack of permits and for logistical difficulties. The principal aim was to characterize the main lithologies listed in the available geological maps and identify both sites with 1D resonance effects and those with more unusual effects.

A few weeks after this first preliminary survey, a systematic survey was performed, aimed at the seismic microzonation of more damaged municipalities, to plan restoring activities and retrofitting. In this second phase, passive seismic techniques (ambient noise array) also played a major role in supporting geological surveys, subsoil seismic, drilling activities and active geophysical prospecting. In this phase, several prospecting techniques (active seismic prospecting with body and surface waves, electric and gravimetric surveys, down-hole seismic measurements, direct seismic response evaluation by earthquake observation) were applied to better constrain local seismic response in the considered areas. Availability of such a huge amount of data also represented an opportunity to evaluate performances of HVNSR measurements in relationship with other first level indications of the subsoil dynamical properties. Furthermore, it provided a benchmark for guidelines recently emanated by the Civil Protection Department.

This experience, shared by several research groups operating in the area with the important support of local professional geologists and engineers, provided a number of indications about the optimal applications of these "light" prospecting techniques. In particular, they stressed the importance of clearly stated and well established experimental protocols to provide comparable measurements along with the definition of quality standards to select meaningful measurements. These were provided in advance in the form of specific guidelines followed by the research groups involved [see for details Albarello *et al*. (2010)]. Furthermore, since most of the measurements were carried out by using the same instrumental and processing tool, they turned out to be highly comparable.

This paper discusses some results obtained during this survey, focusing on the ex-post assessment of reliability of HVNSR measurements and on the feasibility of the results provided in the frame of seismic microzonation studies.

2. A posteriori reliability of HVNSR compared with earthquakes and geology

In the first two weeks after the main shock, more than 200 ambient vibration recordings were performed. All measurements were performed with the same equipment (Micromed Tromino), a digital tri-directional tromometer, which is a high-resolution seismometer whose 24-bit dynamic is aimed at the very low amplitude range. Seismic noise was sampled for at least 12 minutes at each site and the HVNSR were calculated by averaging the H/V obtained by dividing the signal into non-overlapping windows of 20 s. Each window was de-trended, tapered, padded, FF-Transformed and smoothed with triangular windows with a width equal to 5% of the central frequency. The Euclidean average was used to combine E-W and N-S components in the single horizontal (H) spectrum. Average vertical component spectra were obtained from the same procedure. For each HVNSR curve the relative ±2 confidence interval is given. Some authors (Chatelain *et al*., 2008) suggest that transient can affect estimates of fundamental frequency of soils, but in our previous experience a simple variation of amplitude never caused this problem, according to Parolai and Galiana-Merino (2006), Mucciarelli (2007) and Parolai *et al*. (2008). We checked, however, for anomalous variation in the time-frequency domain, removing sections whose spectra significantly differed from the average. To assess the goodness of the measurements, we checked not only the reliability with respect to the SESAME (2004) criteria but also compared other aspects:

1) total duration of the recordings;
2) temporal stationarity of spectral ratios;
3) isotropy of the signal in terms of spectral ratios;
4) absence of electromagnetic noise;
5) overall trend of the HVNSR curve to more rigid ones.

Each HVNSR curve deduced from ambient noise measurements was evaluated in terms of F_0, A_0, F_{max} and A_{max}. F_0 and A_0 are the frequency and amplitude of the fundamental resonance frequency, that is the lowermost one with a peak that passes all the statistical significance tests. F_{max} and A_{max} are the frequency and amplitude of the highest peak, when the fundamental frequency does not coincide with the highest peak, as it may occur in a multi-layered environment. The presence of at least one significant maximum in the HVNSR curve is assumed

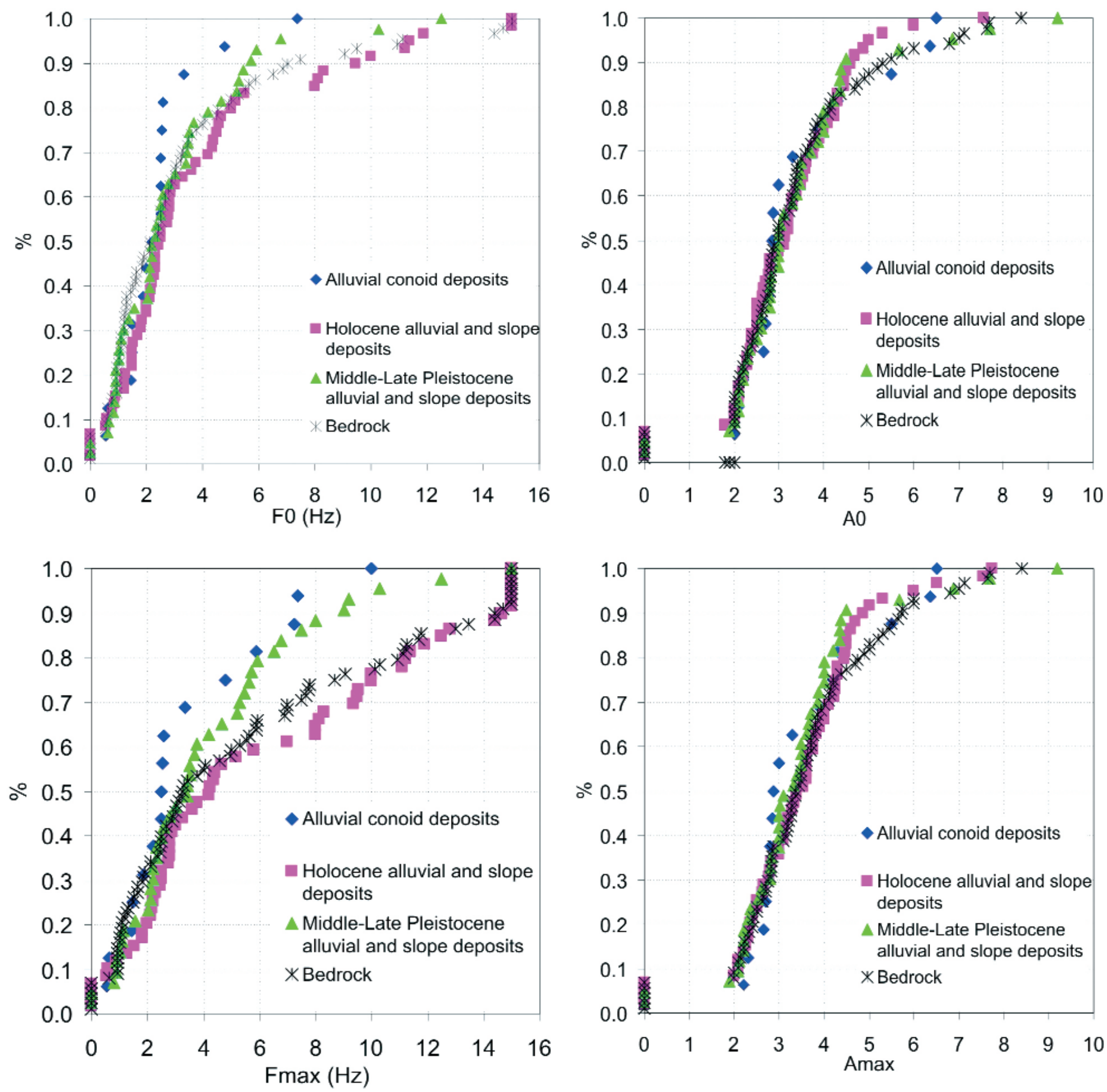

Fig. 2 - Percentage trends of the parameters F_0, A_0, F_{max} and A_{max} for the 4 classes of outcropping soils on the CARG geological map.

as an indication of possible seismic resonance phenomena at the relevant site and, as a consequence, of possible amplification of the local ground motion ("amplifying sites").

Within each village, we carried out several measurements in the most damaged areas. The principal aim was to characterize the main lithology listed in the available geological maps and identify both sites with 1D resonance effects and those with more unusual effects.

The most up-to-date geological map available for the earthquake-struck area, immediately after the main shock, was the geological map 359 - L'Aquila of the new Geological Map of Italy at the scale 1:50,000, which has been recently drawn up in the framework of the CARG project (CARG is the Italian acronym for Geologic Cartography). In this geological map, the outcropping

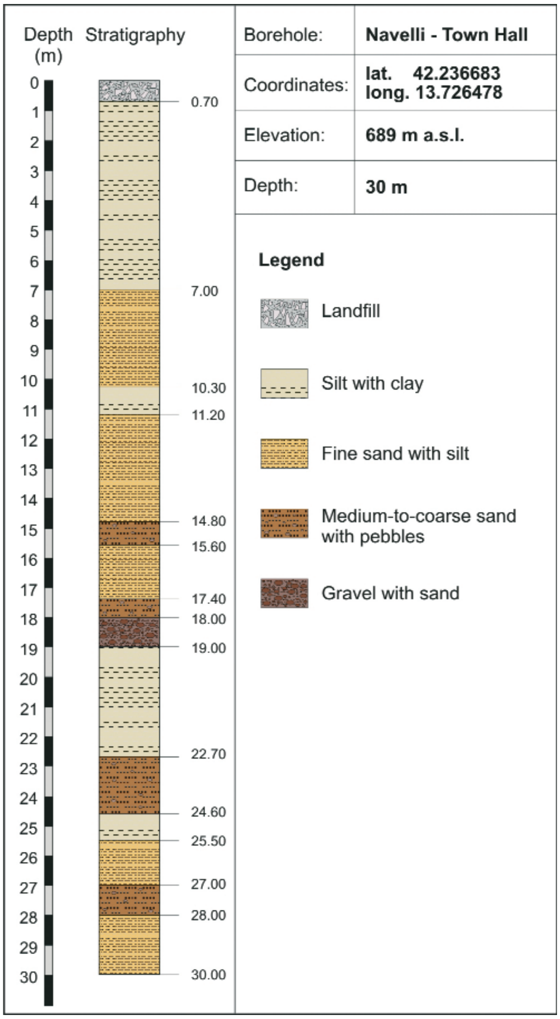

Fig. 3 - Stratigraphic log of the geological borehole which has been drilled in the foundation soil of the town hall building of Navelli.

soils are grouped into formational units, each of which is, therefore, made up of heterogeneous lithologies. In order to draw a sort of "lithological" map from the CARG geological map, and due to the impossibility of splitting each formational unit into more detailed lithological units, we grouped the formational units into 5 distinct classes of soil. Great accuracy was devoted to grouping the post-Middle Pleistocene deposits into 4 different classes, whereas the pre-Middle Pleistocene formations were all grouped into an unique "bedrock" class. The final 5 classes of soils were assessed as follows:

1. landslide deposits (Holocene);
2. holocene alluvial and slope deposits (Holocene);
3. alluvial, fan shaped deposits (Late Pleistocene-Holocene);
4. middle-Late Pleistocene alluvial and slope deposits (Middle-Late Pleistocene);
5. pre-Middle Pleistocene bedrock.

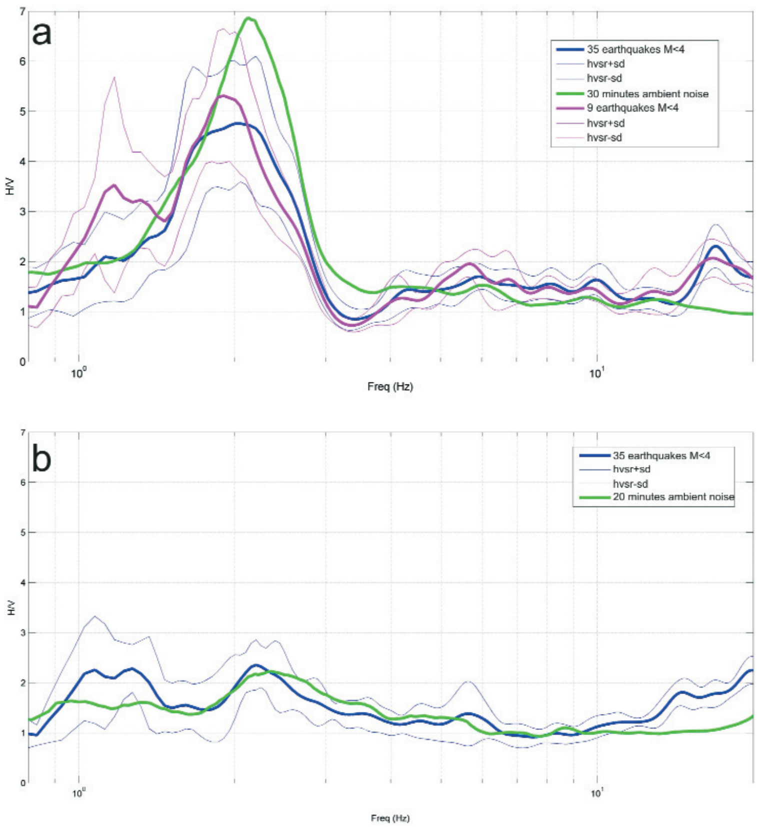

Fig. 4 - HVSR curves of Navelli town hall (a) and historical centre (b) estimated with earthquakes and ambient noise.

Since all measurements were estimated with the same criteria of analysis and reliability, we were able to correlate the parameters F_0, A_0, F_{max} and A_{max} with the 5 classes of outcropping soils.

Fig. 1 reports the F_0 values on the geological map: most sites are characterized by resonance frequencies between 1-5 Hz and the "amplifying sites" fall, not only on the alluvium deposits, but also on the "bedrock". Indeed, Fig. 2 shows that there is not a difference in the percentage trends of the parameters F_0, A_0, F_{max} and A_{max} for each class of selected soil. Although there is a slight difference between the F_{max} of Middle-Late Pleistocene alluvial and slope deposits, alluvial fan shape deposits, Holocene alluvial and slope deposits and bedrock (Fig. 2), we can say that there is no clear differentiation between the frequency-amplification characteristic of sites mapped as belonging to different soil or rock lithologies.

The absence of differentiation between the HVNSR curves and the different outcropping lithology can be explained in 3 ways:

1. the HVNSR curves are wrong or not representative of the actual presence of resonant layers;
2. the geological classification used does not have the appropriate scale for a right attribution of lithology;
3. the outcropping soil is not a sufficient criterion to explain the presence/absence of seismic amplification, but a more comprehensive geological model is needed.

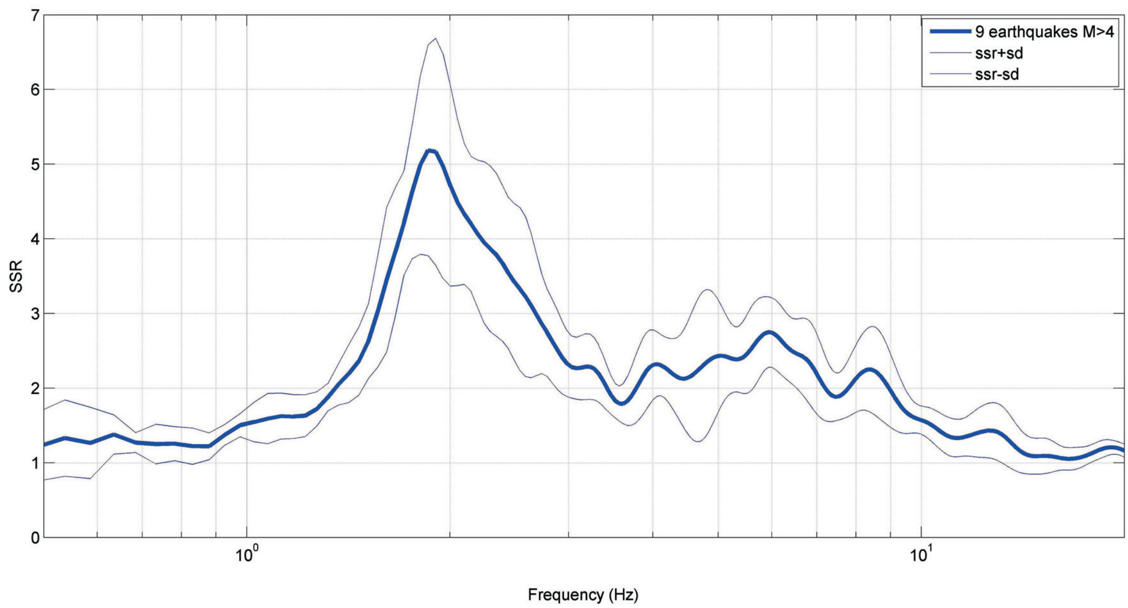

Fig. 5 - SSR between the reference site and the Navelli town hall site.

Having collected a statistically significant sample of ambient noise HVNSRs, having installed accelerometric stations in some geologically interesting sites, and having made a detailed geological survey in all the towns of the epicenter area, we have been able to evaluate the truthfulness of these hypotheses.

2.1. Are the HVNSR curves wrong or not representative of the actual presence of resonant layers?

The first example of a good agreement between earthquakes and HVSR ambient noise curves in the city of L'Aquila was pointed out by De Luca *et al.* (2005). They have also revealed that these techniques can indicate the presence of significant seismic ground-motion amplification effect at low frequencies (0.6 Hz). In order to interpret observations in terms of the local geology, they performed a 2D numerical modeling of the sedimentary basin underlying the city of L'Aquila, based on a geological section derived from gravity measurements. This analysis indicates that the ground-motion amplification in the city of L'Aquila is related to the presence of a sedimentary basin, filled by lacustrine sediments, with a maximum depth of about 250 m. After the shock of April 6 and during the measurement survey, we independently performed some ambient noise recordings in the historical centre of L'Aquila and we again found a clear peak at 0.6 Hz, confirming the agreement with the results obtained by the earthquake HVSR.

During the microzonation study, we had the opportunity to compare the HVSR and Standard Spectral Ratio (SSR) curves obtained by ambient vibration and earthquake recordings in the towns of Navelli, Castelnuovo and San Gregorio (Fig. 1). Each of these sites is representative of peculiar litho-stratigraphic conditions.

The seismic recordings were acquired by Etna-Kinemetrics accelerometers, while the 20-30

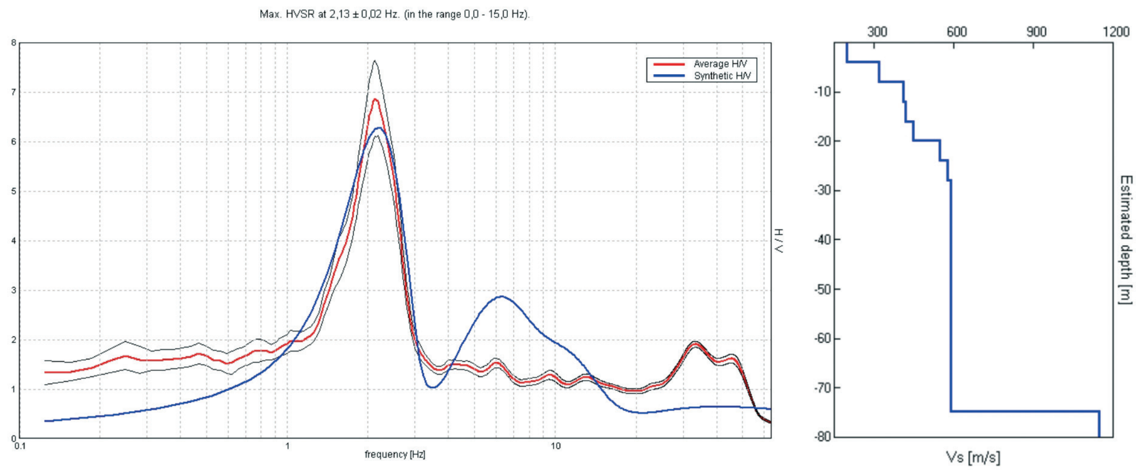

Fig. 6 - Comparison between ambient noise and synthetic HVSR curves (left) obtained at the town hall site in Navelli; V_s profile of the same site (right).

minutes of ambient noise were recorded by a digital tri-directional tromometer. The HVSR technique on earthquake recordings is widely used for seismic amplification studies (Lermo and Chavez-Garcia, 1993; Field and Jacob, 1995; Lachet *et al*., 1996; Mucciarelli, 1998). The data analysis was performed with the same procedure described above for the HVSR ambient noise technique except, of course, the average of multiple S wave windows, given the short duration of strong motion recordings.

In Navelli, a town about 35 km from the epicenter, heavy damage occurred on the town hall building made up of reinforced concrete (RC), that represents an anomalous case of damage compared with those that occurred in the neighboring area. This site is characterised by the erosional top of a stratigraphical succession of Upper Pleistocene lacustrine, sand-silt-clay deposits ascribed to the Majelama Valley Synthem in the geological sheet 360. This lacustrine sequence unconformably overlies the Jurassic crystalline limestones (ascribed to the Crystalline Limestones with Echinoderma and Corals formation on sheet 360) which outcrop along the southern slope of Mt. San Nico. The surface boundary between the Pleistocene lacustrine deposits and the Mesozoic limestones is morphologically marked by the net change of slope angle between the plain and the southern slope of Mt. San Nico, but it is covered by a few-meter thick wedge of calcareous, gravel-sandy debris created by the erosional processes which have affected the limestone slope during the Holocene.

A geotechnical borehole has been drilled, close to the town hall building, down to a depth of 30 m below ground level, and its stratigraphic log is shown in Fig. 3, which points out that the borehole crosses only the sand-silt-clay lacustrine deposits and therefore, it does not reach the top of the seismic bedrock represented by the Mesozoic limestone. From the litho-stratigraphic assessment, we can assume a 1D setting.

Two days after the main shock two accelerometers were installed in Navelli downtown until

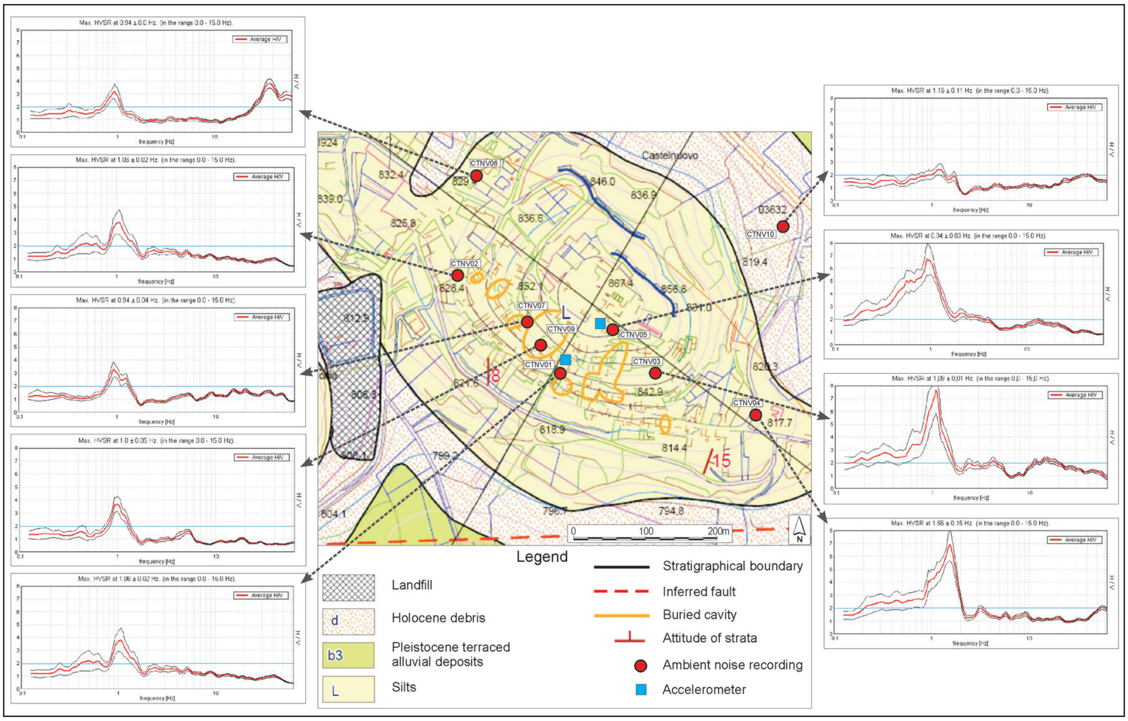

Fig. 7 - Geological map and HVNSR curves of Castelnuovo town. The geological map is taken from the microzonation performed for the Civil Protection Department by the group chaired by L. Martelli (Emilia Romagna Region).

April 29: one in the historical center and the other in the town hall building. The magnitude of the recordings ranges between 3 - 5.1 M_L and the epicentral distance between 20-50 km. Already a visual inspection of the M=5.1 recording on April 9 at 00.52 a.m. reveals that the town hall site had recorded acceleration values and a much larger duration than the reference site for each component. Fig. 4 shows the historical center and town hall HVSR curves obtained by earthquakes and ambient noise: the historical center one has quite a flat shape, so it could be considered as a reference site. Moreover, the HVSR obtained by M>4 earthquakes is in good agreement with the ambient noise one. The town hall HVSR shows a clear peak at about 2 Hz estimated with different data sets (35 earthquakes with M<4, 9 earthquakes with M≥4 and 30 minutes of ambient noise recordings). The agreement between them is good, both in the main peak amplitude and in its shape. The HVSR obtained by M≥4 earthquakes shows a slight decrease in the frequency of the main peak with respect to the HVSR by M<4 earthquakes probably due to a non-linear effect, even if the amplitude seems to increase but within the statistical dispersion. The availability of a near reference site allows us to estimate the SSR curve. The SSR is obtained by performing the ratio between the amplitudes of the Fourier spectrum of horizontal (longitudinal and transversal) components recorded on the town hall site and the same components recorded on the reference one of M≥4 earthquakes. The SSR curve is in good agreement with the HVSR obtained by M≥4 earthquakes (Fig. 5). The availability, at this site, of

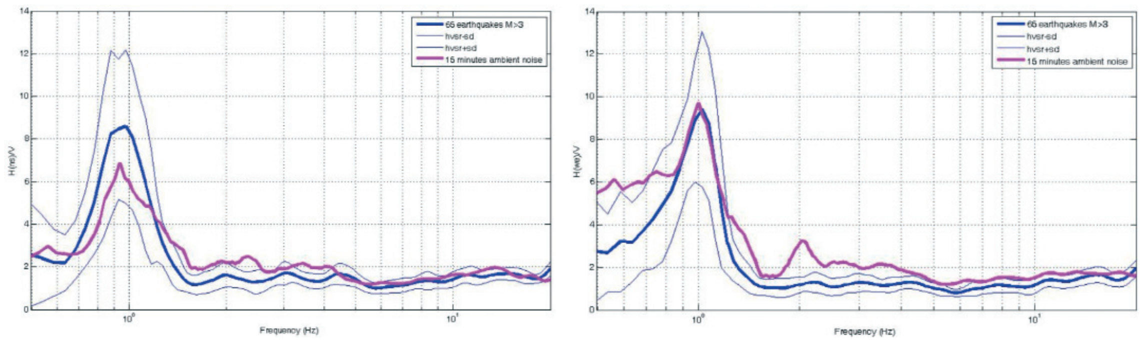

Fig. 8 - HVSR curves for the two components (N-S on the left and W-E on the right) of Castelnuovo by 65 earthquakes with M_L>3 and 15 minutes of ambient noise recordings.

a down-hole seismic profile, allowed us to determine if the constrained HVSR inversion is able to return a reliable estimate of the average V_S in the resonant layer or of its depth. The shear wave velocity increases monotonically with depth, from 200 m/s at the surface layer, to 600 m/s at a 30 meter depth and then, with V_{S30}=381 m/s, it can be classified as a B site according to EuroCode8 and the Italian Code NTC08. Fig. 6 reports the comparison between the HVNSR curve and the synthetic one obtained inverting the HVNSR curve according to the constrained inversion procedure proposed by Castellaro and Mulargia (2009). The constraint was put on layer thickness and velocity down to 30 m and to the velocity of bedrock set at 1150 m/s, as available from a borehole reaching bedrock in a nearby town (San Gregorio). The inversion returns a synthetic HVSR curve in good agreement with the observed one, thus, we can confirm that the resonance layer responsible for the main peak at 2 Hz is made of 75 meters of sand-silt-clay lacustrine deposits over limestone.

Castelnuovo is a severely damaged town, classified as IX degree MCS scale, while its neighbors do not exceed the VI degree. Based on the new geological map drawn for the Castelnuovo area at a 1:5,000 scale, the town is located at the top of a hill which morphologically represents the relict of a fluvial terraced surface and is made up mainly of silts, characterized by varying degrees of cementation. Nine ambient noise recordings were performed estimating a clear resonance peak at about 1 Hz. Although the thickness of the resonance stratum varies from 80 m on the top, to 20 m at the base of the hill, the peak frequency remains at 1 Hz while the amplitude value changes from site to site. The HVNSR curve estimated on the top of the hill has higher amplitude values than those of the base hill HVNSR. Fig. 7 shows HVNSR curves in different sites, in particular, we would like to focus the attention on the CTNV10 HVNSR curve: although this measurment was performed at the base of the hill, with small thicknesses of sand layers, the HVNSR curve has a peak at a 1 Hz lower amplitude with respect to the others. This variation in amplitude values and the stationarity in frequency of resonance peak could be a clue to the 2-3D effect attributable to the whole hill, as assessed in a work in progress (Costanzo *et al.*, 2011). To validate the HVNSRs, two ETNA-Kinemetrics accelerometers were installed the day after the main shock; one on the top of the hill and the other in the middle (Fig. 7). Also in

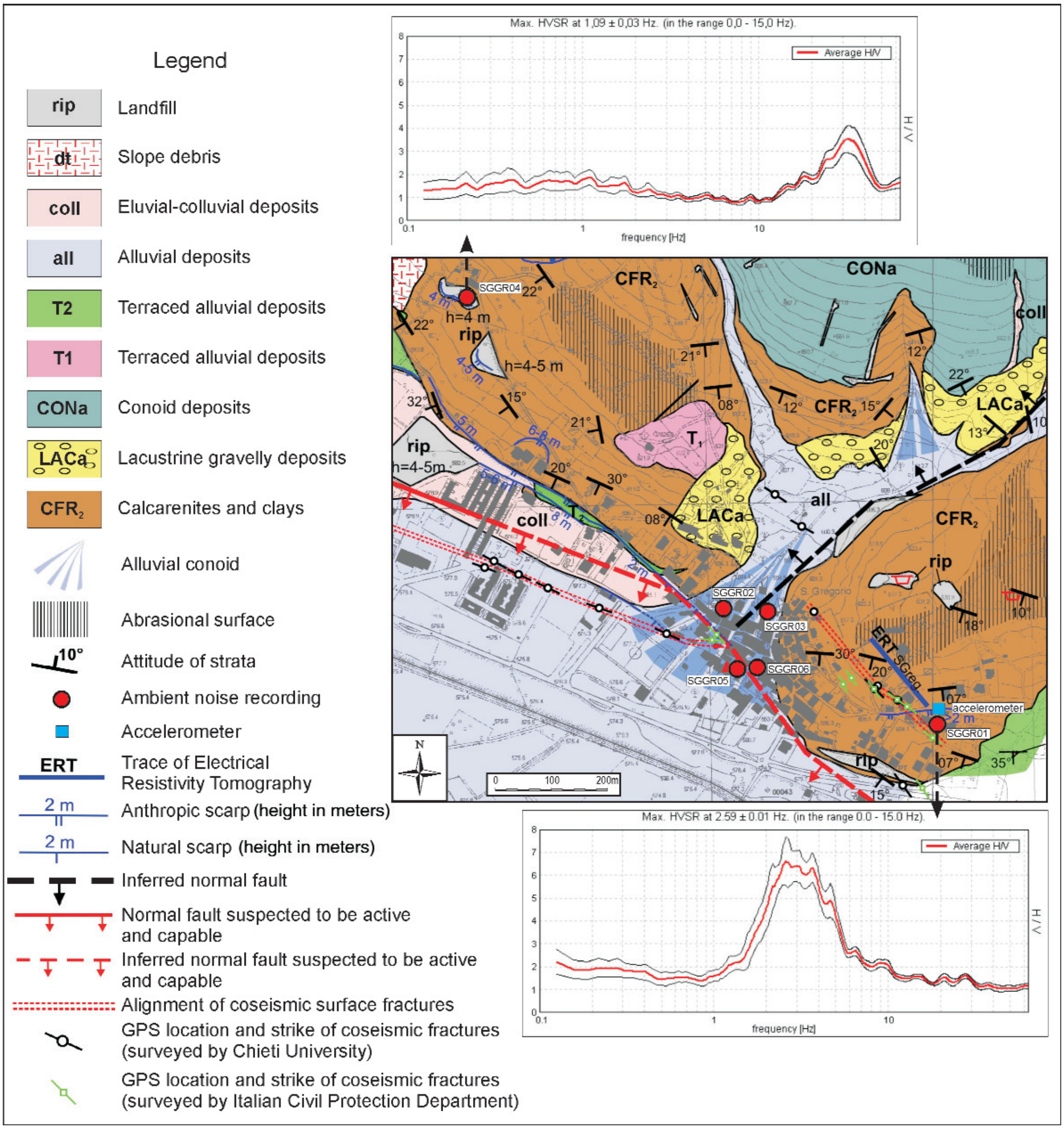

Fig. 9 - Geological map and HVNSR curves estimated on well-cemented Miocene calcarenites of San Gregorio town. The geological map is taken from the microzonation performed for the Civil Protection Department by the group chaired by P. Boncio (University of Chieti-Pescara).

Castelnuovo, hundreds of events with a magnitude ranging between 3-5.1 M_L were recorded. The comparison of HVSR curves for the two components with 15 minutes of ambient noise and 65 earthquakes with M_L>3, recorded on the top of the hill, is reported in Fig. 8. The agreement is satisfactory not only with the detection of frequency and amplitude of resonance peak (1 Hz) but also in the shape even considering the difference in the two components probably due to the above mentioned 2-3D effect.

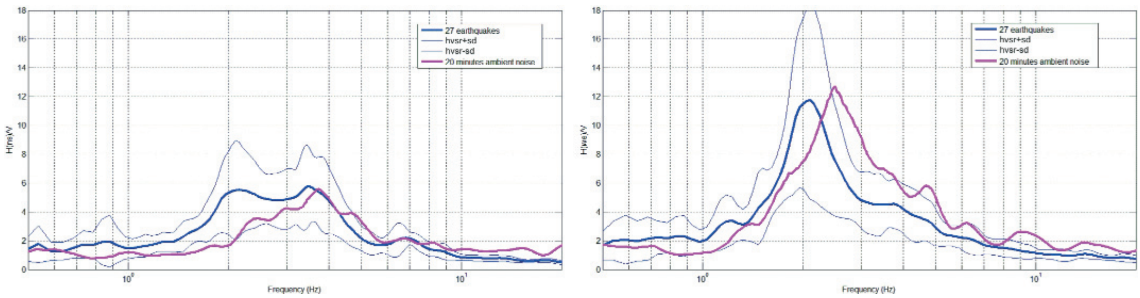

Fig. 10 - HVSR curves for the two components (N-S on the left and W-E on the right) of San Gregorio by 27 earthquakes and 20 minutes of ambient noise recordings.

Another site, where we have validated the ambient noise HVNSR with earthquakes, is San Gregorio. Our attention was caught there because of heavy damage on a reinforced concrete building, caused probably by site amplification. Although this building suffered total collapse of the first floor, the surrounding buildings with similar characteristics reported little or no damage. To understand if the soil effect could be a possible cause of damage, we have performed ambient noise and earthquake recordings, a detailed geological survey and some surface geophysical prospecting. The new geological map at scale 1:5,000 carried out in the San Gregorio territory, a few weeks after the main shock, shows that the surrounding area of the damaged building is characterised by the outcropping of well-cemented Miocene calcarenites which are cut by co-seismic fractures (Fig. 9). We performed ambient noise recordings on these well-cemented Miocene calcarenites: contrary to expectations, the HVSR curve (SGGR01 in Fig. 9) shows a clear resonance peak at about 2.6 Hz. This HVSR ambient noise has been validated by 27 earthquakes HVSR (Fig. 10). It is interesting to note the satisfactory agreement between the two HVSR curves, not only in the detection of the frequency and amplitude of resonance peak but also in the shape. Moreover, even the HVSR ambient noise curves show a clear directional effect as highlighted by earthquake HVSRs. We are studying, in more detail, the peculiar geological situation responsible for such a clear directional effect and to understand the disagreement with a detailed geological map.

These examples highlight the fact that the HVNSRs, are in good agreement with the HVSRs obtained by earthquakes, both in simple (Navelli) as in complex geological conditions (L'Aquila, Castelnuovo, San Gregorio). Therefore, these results lead us to argue that the HVNSR curves are correct and are markers of information on the subsoil seismic layering. This comforts us in saying that the 200 HVNSRs estimated in all the towns of the epicentral area carry useful information about site effects. Thus, the disagreement between the HVNSR curves and the lithological maps can not be attributed to the unreliability of the HVNSR. Instead, the large scale at which the geological survey was performed did not allow for a correct attribution of lithology, or the outcropping soil is not a sufficient criterion to explain the presence/absence of amplification, but a more comprehensive geological model is needed.

2.2. Does the geological classification have the appropriate scale for a right attribution of lithologies?

A striking example of how incorrect mapping of the outcropping lithologies do not explain the

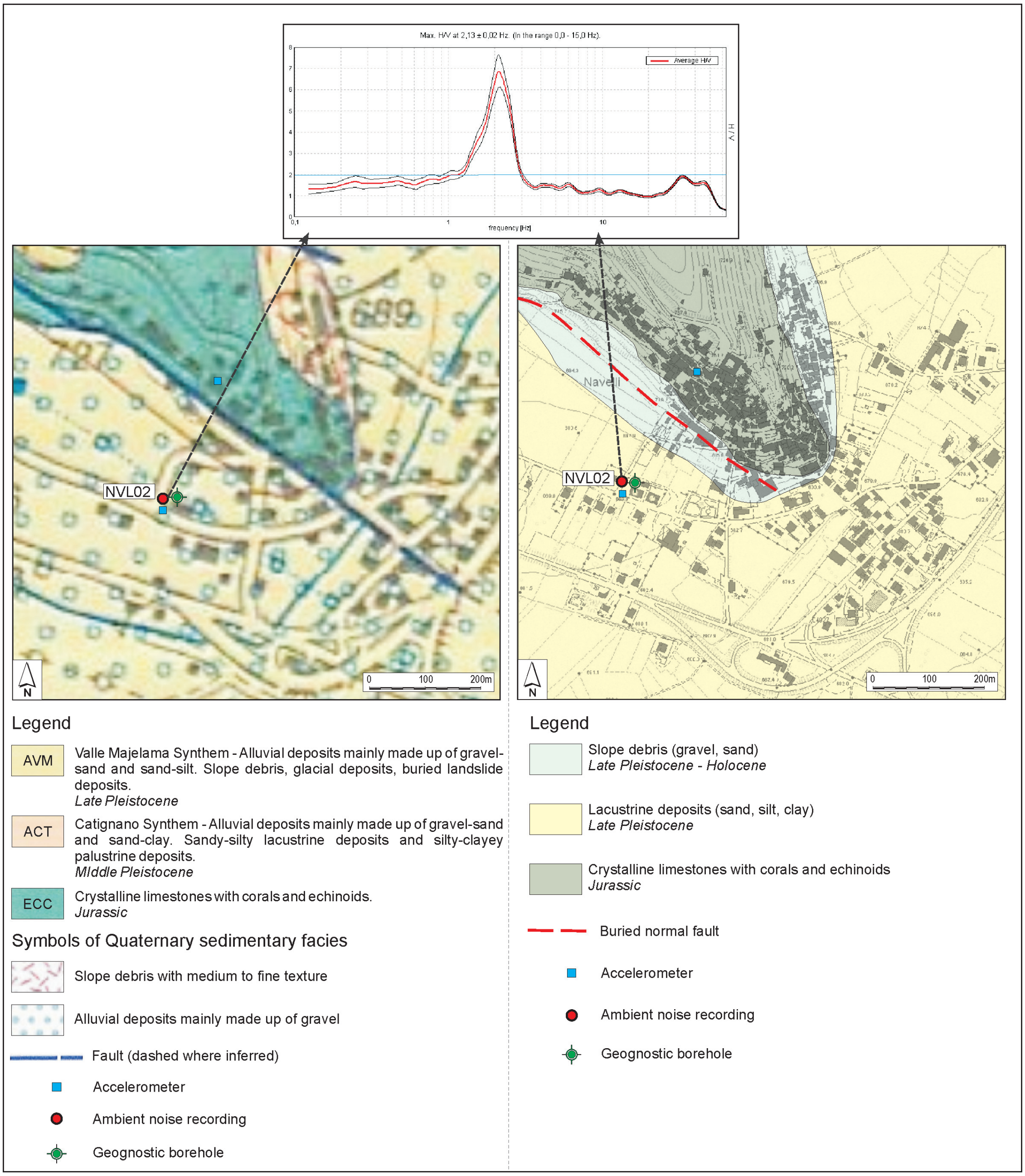

Fig. 11 - The CARG geological map at scale 1:50,000 scale (left), geological map at 1:5,000 scale (right) and HVNSR Navelli.

HVNSR shape is given by the towns of Navelli and Civitaretenga.

The CARG geological map, at scale 1:50,000, shows that the southern sectors of these towns are located on two very similar Pleistocene formations, which are both described in the legend as "alluvial deposits made up mainly of sand-gravel" alternated with "slope debris" respectively,

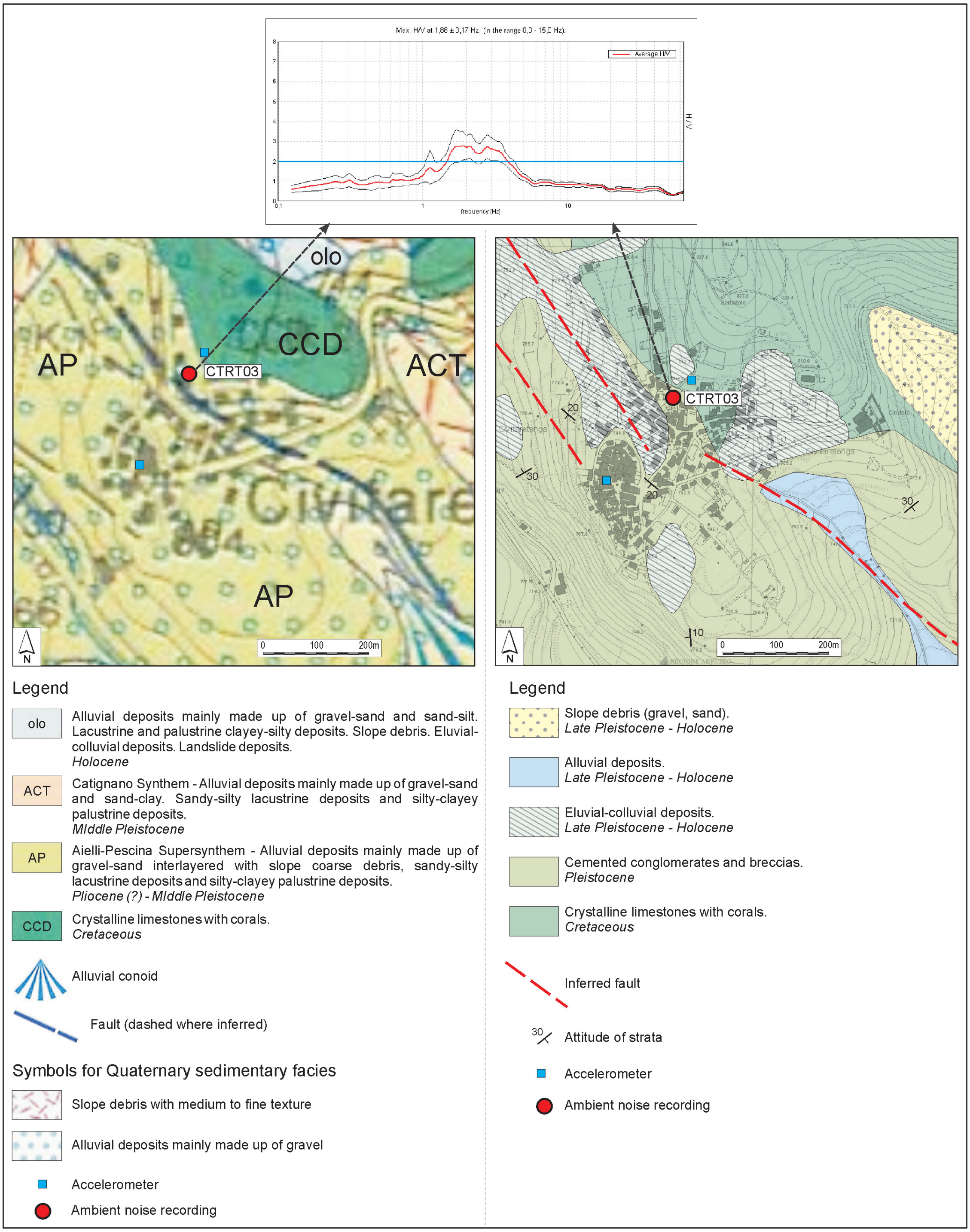

Fig. 12 - The CARG geological map at scale 1:50,000 scale (left), geological map at 1:5,000 scale (right) and HVNSR Civitaretenga.

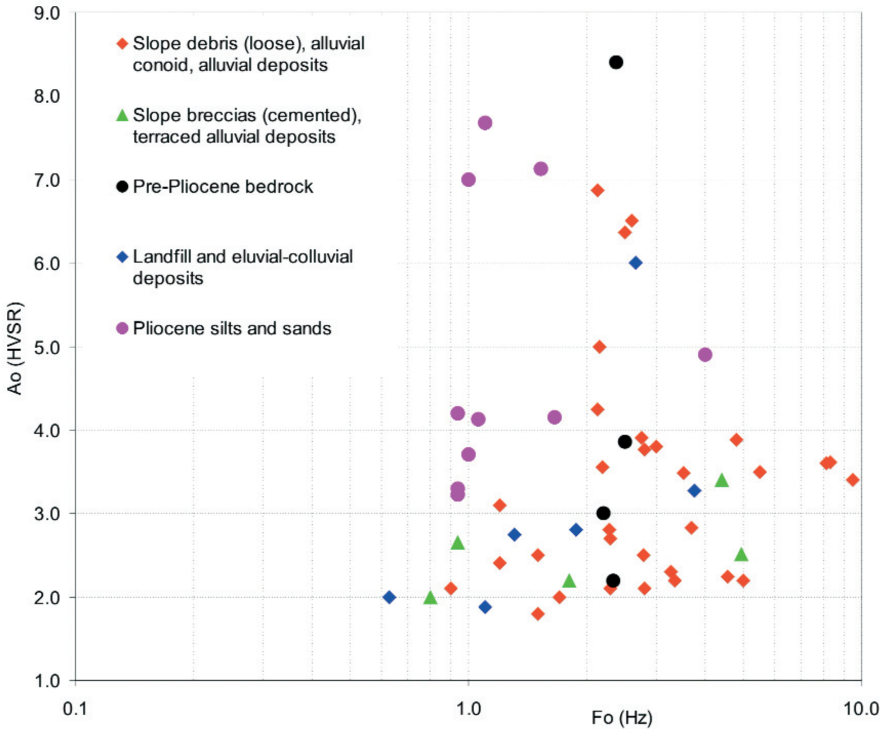

Fig. 13 - F_0 vs A_0 values of the first resonance peakof the HVNSR for each measurement marked at its relative soil class.

whose cementation degree is not specified. Indeed, also the same graphic symbol superimposed on the map representation of both the (lithologically rather similar) formations is for "mainly gravel alluvial deposits" (Fig. 11 for Navelli and Fig. 12 for Civitaretenga). Performing two ambient noise recordings on these two apparently similar geological lithologies, in the southern sectors of Civitaretenga and Navelli, respectively, the two HVNSR curves show different shapes (Fig. 11 for Navelli and Fig. 12 for Civitaretenga); moreover, the HVNSR curves have been validated by earthquakes at both sites. The Navelli HVNSR has a clear peak at 2 Hz and the Civitaretenga one shows an amplification band ranging between 2-3 Hz with a low amplitude level compared to the Navelli one. A new geological map at a 1:5,000 scale (Fig. 11 for Navelli and Fig. 12 for Civitaretenga), integrated with the stratigraphic log from a 30-m deep geotechnical borehole drilled close to the Navelli investigated site (Fig. 3), instead shows that the Civitaretenga site is located on well-cemented strata of slope breccias overlying the Mesozoic crystalline limestones, which are characterized by a thickness ranging from 1-2 m beneath the ambient noise recording CTRT03 to about 3-5 m on the southern slope of Civitaretenga, whereas the stratigraphic succession at the Navelli site is characterised by at least 30-m thick lacustrine deposits made up mainly of silt and fine sand. Both these two rather different lithologies overlie the seismic bedrock represented by Mesozoic limestones. This new geological classification is certainly more appropriate to justify the different shapes, of the HVNSRs.

Another example, where the lithology does not match the amplification function, is a site at San Gregorio. We performed two ambient noise recordings on these well-cemented Miocene calcarenites: as expected one HVNSR (SGGR04 in Fig. 9) is flat, except for a peak at about 30 Hz due to 2-3 m of landfill but, contrary to expectations, one HVNSR (SGGR01 in Fig. 9) shows a clear resonance peak at about 2.6 Hz, a clear clue of impedance contrast at medium depth. Again, the HVNSR in the amplifying site has been validated by earthquake recordings as described in the previous section (Fig. 10). Despite the availability of a new detailed geological map, this case has claimed for “nanozonation”, because the difference in recorded amplification and observed damage varies dramatically over a few tens of meters, in fact, the neighboring sites do not present the same characteristics either in HVNSR curves or in the damage.

While our former attempt to correlate lithologies and HVNSRs using the CARG geological map did not provide any correlation, this comparison between more detailed geological mapping and HVNSR curves brought a good agreement in Civitaretenga and Navelli but not in San Gregorio. In the light of these opposite results, we wanted to investigate a larger sample, examining the correlation between 72 HVNSRs and the outcropping lithologies mapped at detailed scales 1:5,000 in the new geological maps for microzonation.

The use of a uniform geo-lithological legend, particularly accurate in differentiating the Quaternary continental deposits, makes these new maps much more accurate and suitable for these types of correlations than the previous CARG maps.

Most of the HVNSRs are located on 8 different Pliocene-Quaternary lithologies, whereas only a few measurements were performed on the pre-Pliocene bedrock. Based on similarity in age, lithology and inferred mechanical characteristics, the 7 Pliocene-Quaternary lithologies and the pre-Pliocene bedrock have been grouped into the following 5 distinct soil classes:

- Class 1 – landfill and alluvial-colluvial deposits;
- Class 2 – slope debris (loose), alluvial fan, alluvial deposits (Aterno River);
- Class 3 – pliocene silts and sands;
- Class 4 – slope breccias (cemented), terraced alluvial deposits;
- Class 5 – pre-Pliocene bedrock.

Fig. 13 reports the F_0 and A_0 value of the first resonance peak for each measurement marked at its relative soil class. While some clusters now appear, again the correlation is not significant: there are bedrock sites which have unexpected clear resonance peaks, and the HVNSRs for each class do not have a pattern, either in frequency or in amplitude, as it would be expected if the thickness of strata in an 1D model were the only unexplained variable. Most of the resonance frequencies fall between 1-5 Hz and the amplitude 2-4, regardless of the outcropping soil.

This disagreement leads us to think that the outcropping soil is not a sufficient criterion to explain the presence/absence of amplification, but a more comprehensive geological model is needed.

2.3. Is the outcropping soil a sufficient criterion to explain the presence/absence of amplification?

Extensive literature highlights the fact that simple classification approaches, like outcropping lithology or V_{S30}, in most cases fail to identify the amplification-prone areas. Many authors have studied sites classified as A, having amplification due to the presence of different degrees of rock fracturation with consequent velocity contrast between the bedrock and the weathered/fractured

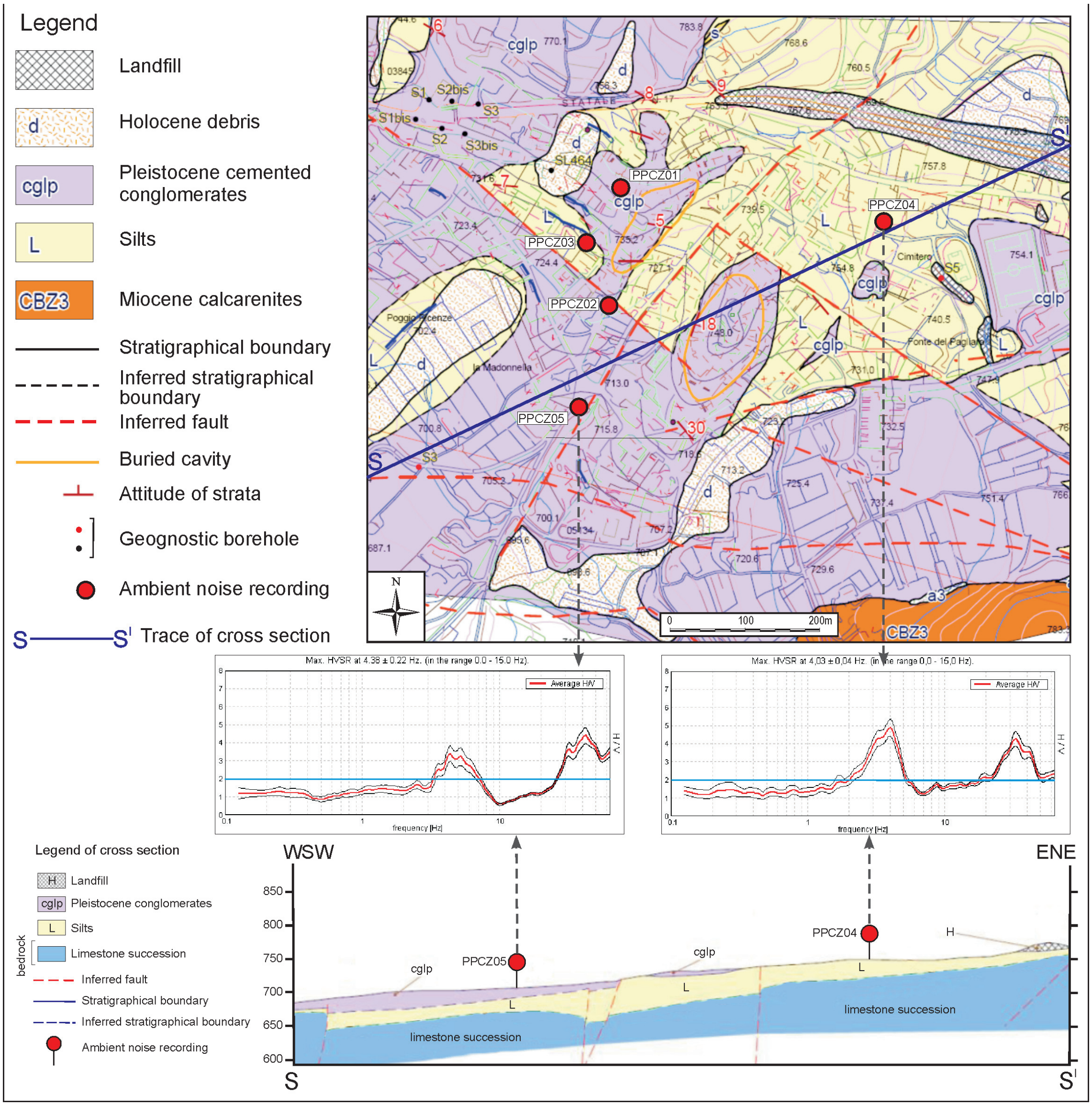

Fig. 14 - The geological map and geological section with HVNSR (PPCZ04 and PPCZ05) of Poggio Picenze. The geological map and section are taken from the microzonation performed for the Civil Protection Department by the group chaired by L. Martelli (Emilia Romagna Region).

overburden (Rovelli *et al*., 2002; Martino *et al*., 2006); unexpected amplification due to velocity inversion [ancient settlements took place on slices of rigid material overlying soft sediments; Di Giacomo *et al*. (2005)]; sites B and C without amplification or with amplification at a frequency lower than expected because located on very deep basins (h>300 m) with a probable low impedance contrast at the sediment-bedrock interface (Park and Hashash, 2004). Gallipoli and Mucciarelli (2009) estimated that 35% of the cases they examined showed amplification that was not expected by V_{S30} classification or vice versa, or if the amplification occurs at frequencies lower than expected. This non correlation, already evident between V_{S30} and HVNSRs worsens when we consider the outcropping lithology only and HVNSRs as discussed in the previous paragraph.

During this microzonation study, we have observed some interesting cases where the outcropping soil class at detailed scale is not a sufficient criterion to explain the presence/absence of amplification but a more complex geological model is necessary.

An example is the Poggio Picenze town: a detailed geological map shows that part of the town lies on silts over bedrock, while the other part lies on a more stratigraphically complex succession made up of (from top to bottom) Pleistocene cemented conglomerates - silts - bedrock (Fig. 14, geological and section map). As expected the impedance contrast between bedrock and silts gives a clear peak at 4 Hz (Fig. 14 PPCZ04 HVNSR) where silt outcrops, but it remains clearly visible also on outcropping Pleistocene cemented conglomerates (Fig. 14 PPCZ05 HVNSR) due to the velocity inversion with silt over bedrock. On the mountainside, where conglomerates overlie limestone, the HVNSR becomes flat.

In this and other cases, the presence of the HVNSR peak on a high stiffness outcrop helped the geologists to draw more precise sections pinpointing the areas where the velocity inversion is present between silts underling the Pleistocene cemented conglomerates.

3. Conclusions

The experience of survey activities carried out in the area damaged by the April 2009 Abruzzo earthquake has provided useful indications about the feasibility of HVNSR surveys combined with detailed geological surveys. During the first level of microzonation activities, geological surveys alone have not proved sufficient to identify areas where seismic amplification is expected or vice versa to exclude or limit the area where further *in situ* tests are more urgent. In this frame, it becomes clear that coupling geological surveys with passive seismic prospecting techniques would have represented an improved tool for fast and cheap microzonation activities. In HVNSRs particular, the deduced by single station measurements of ambient noise (HVNSR) have been considered in many cases as an important tool not only to prepare detailed geological maps but also to identify and quantify where the local seismic response is expected, pinpointing sites where possible seismic resonance phenomena may occur as an effect of the local stratigraphic structure and to evaluate, at least qualitatively and comparatively, the amount of such effects, providing preliminary depth estimates of the resonant layer.

In particular, when used correctly, in the frame of a coherent geological interpretation and even without drillings, HVNSR measurements turned out to be a tool of basic importance in the development of emergency seismic microzonation maps. In fact, HVNSR allows:

1. to identify sites where possible seismic resonance phenomena may occur as an effect of the local stratigraphic structure: this is true also in the case of sites apparently characterised by stiff outcrops when velocity inversions are present;
2. to evaluate, at least qualitatively and comparatively, the amount of such effects;
3. to provide preliminary depth estimates of the resonant layer in a 1D situation;
4. to provide a map of the resonance frequency of sedimentary covers, helping geologists to refine on formation limits and for identification of the areas with a danger of soil-structure

resonance.

All these estimates are provided extensively without any limitation due to the fast application of the method and the use of very portable instruments. Finally, a following comparison with down-hole measurements showed that constrained HVNSR inversion is able to return a reliable estimate of the average V_S in the resonant layer or of its depth, according to which one of the two data is used to constrain the other.

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Corresponding author: Maria Rosaria Gallipoli
Istituto di Metodologie per l'Analisi Ambientale, C.N.R.,
85050 Tito Scalo (Pz), Italy
Phone: +39 0971 427260; fax: +39 0971 427264 e-mail: gallipoli@imaa.cnr.it