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Seismic response from microtremors in Catania (Sicily, Italy)

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Abstract - A survey of environmental seismic noise (microtremors) was carried out within the Catania municipal area in May 1999. The aim of the data acquisition was to improve our prediction of the seismic ground motion locally, using Nakamura's approach. The seismic noise was recorded at 39 different sites. These sites were chosen according to the following criteria: 1) significance in terms of geological, geotechnical, or local characteristics; 2) presence of a lithological transition (e.g.: the transition from lava to sediments); 3) presence of other geotechnical or geophysical measurements; 4) alignment with some of the transects along which the ground motion had been simulated numerically. The data were acquired independently by two teams, who used different instrumentation. Measurements overlapped at seven locations. We have found that more than one half of the sites exhibit weak or no amplification. These sites are located either on lava (e.g., sites in downtown Catania and in the northern part of the municipal area) or on well-consolidated sedimentary soils (Western districts of the city). The only sites which bear evidence of some amplification are located either on soil fill lying over lava, or on the fine alluvial deposits of the Catania Plain. In the first case the H/V amplitude is usually moderate and the fundamental frequency is between 5 and 12 Hz, while the sites of the Plain have a much lower natural frequency (about 1.3 Hz) and larger H/V amplitude. Some sites displayed anomalous, though relatively small in most cases, H/V peaks, in the low frequency band 0.2-1 Hz. Our analysis, performed at some sites, comparing the measured H/V spectral ratios (HVSR) to those simulated numerically for an earthquake, supports the interpretation raised recently by other authors of an effect of the deep structure. Finally, the numerical simulations also predict an appreciable lateral variability of the HVSR, where the underlying structure is not a "plane layer model", rather usual in Catania. This implies that seismic noise

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measurements made at single, isolated points should be used with care in the interpretation.

1. Introduction

Estimation of local amplification of the ground motion caused by earthquakes is of fundamental importance for seismic microzonation studies. For the purpose of urban planning and retrofitting of existing structures, it is, in fact, important to make accurate estimates of the amount of ground motion amplification that can result from the occurrence of intermediate and large earthquakes within local and regional distances.

Existing methods for microzonation based upon instrumentally recorded ground motion have been reviewed by various authors (e.g., Field and Jacob, 1995; Kudo, 1995; Riepl et al., 1998; Bard, 1999). In recent years, in addition to the classic method that determines the spectral ratios between a reference site, generally located on rock, and other sites of interest (Borcherdt, 1970), the use of single station horizontal-to-vertical (H/V) spectral ratios (HVSR) of microtremor noise has become common. This technique is commonly referred to as Nakamura's method (Nogoshi and Igarashi, 1970, 1971; Nakamura, 1989). 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 and Chavez-Garcia, 1993). 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, 1999; Faeh et al, 2001) have confirmed the close connection between H/V spectral ratios and the ellipticity of surface waves (Nogoshi and Igarashi, 1971). In particular, these authors have shown that:

1. the lowest frequency peak of the H/V curve coincides with the fundamental resonance frequency of the site (if any!);
2. the peak occurs whenever the soil-bedrock impedance contrast exceeds a value of about 2.5, and
3. the H/V ratio does not provide an estimate of the entire bandwidth over which the motion is amplified.

The use of microtremors for site amplification studies has become quite popular in recent years because 1) it allows for significant reductions in field data acquisition time and costs, 2) it does not require an ongoing earthquake sequence, and 3) 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. Finally, there is some debate on the fact that this method should provide meaningful results for horizontally layered media only and the meaning of the results for sites featuring rough topography and/or 3-D structure complexity is still to be ascertained.

The city of Catania was destroyed twice following the 1169 and 1693 Catania earthquakes of magnitude between 7.0 and 7.2 (Azzaro and Barbano, 2000). In 1996, the National Group for the Defence against Eartquakes (GNDT), funded by the Italian Civil Protection Agency, started a research program aimed toward the determination of seismic risk scenarios for one of the two large earthquakes above (Faccioli, 2000). Thus, one goal of the program was the prediction of strong ground motion. To this purpose, and in order to have a structural characterization, in terms of geophysical and geotechnical parameters, the available geotechnical data were gathered together and additional measurements were also carried out (Faccioli, 1997). Subsequently, all the data were organized within a single database. As a result, a detailed map of the principal geotechnical units was compiled (Fig. 1). This map was used by various authors to generate synthetic seismograms along transects across the Catania municipal area (Priolo, 1999; Romanelli

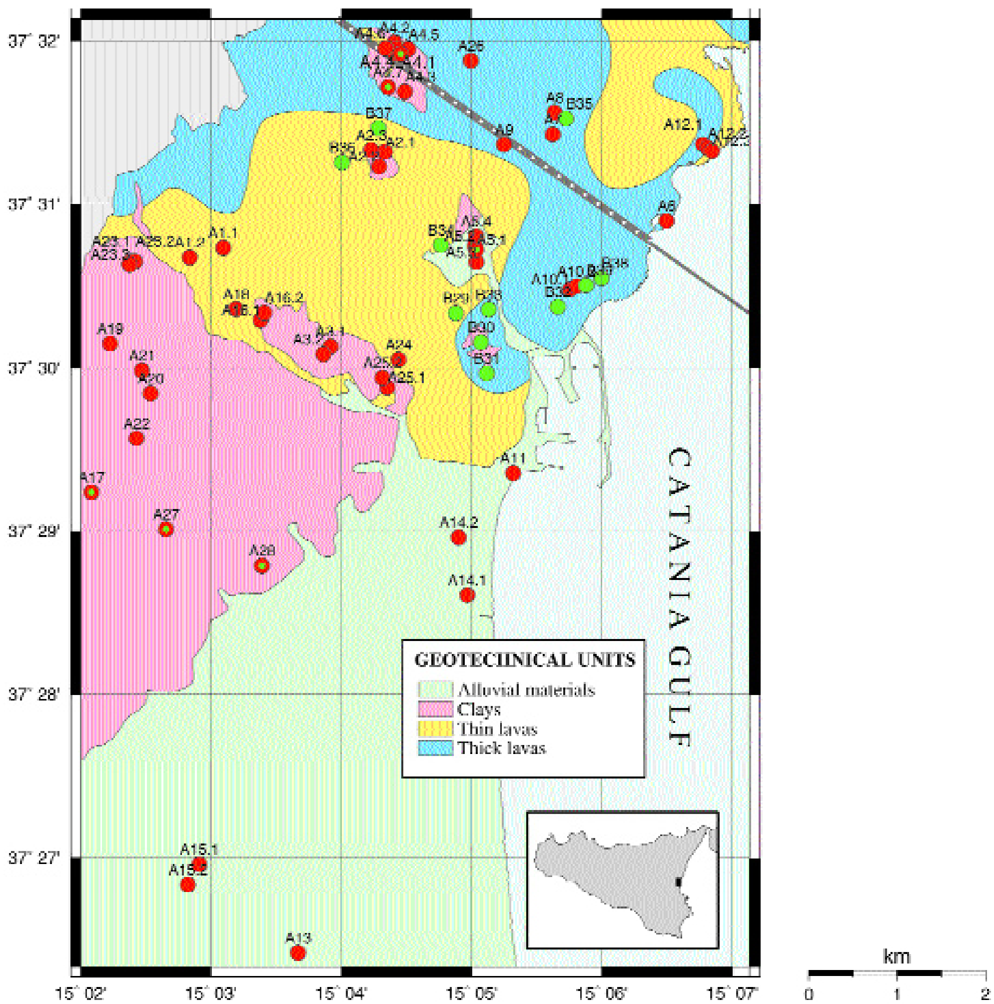

Fig. 1 - Base map of the Catania municipal area showing the location of the seismic noise acquisition sites and the simplified geotechnical zonation (courtesy of E. Faccioli and V. Pessina). Red and green circles indicate the measurements performed by teams A and B, respectively. Thin and thick lavas indicate lava thickness smaller and greater than 10 m in the upper 30 m of soil, respectively (Faccioli, 1997; Romanelli and Vaccari, 1999). The gray line in the northern area indicates the location of transect T3 used for the numerical simulation in Priolo (1999). White dots and thicker width indicate the part of the transect for which the results are presented and discussed (see also Fig. 14).

and Vaccari, 1999; Zollo et al., 1999; Faccioli, 2000).

In the last phase of the Catania project, a microtremor field acquisition was carried out with the goal of estimating the relative ground motion amplifications. These measurements were acquired at sites representative of the main geological units of the area (Fig. 1). In this paper, we describe and discuss the results of the microtremor survey.

In the past, other microtremor measurements were carried out in the area of Catania for purposes of site response estimation. In the eighties, Lombardo (1985) performed an analysis using the spectrum of seismic noise, while more recently Giampiccolo et al. (2001) and Lombardo et al. (this issue) based their analysis on the use of the HVSR technique.

In this paper, we first provide a detailed description of the various geological formations that outcrop in the studied area. Secondly, we describe the acquired data and their processing. Finally, we show the H/V ratios observed at all sites and discuss the main results also exploiting the information provided by the geotechnical study and the synthetic waveform modeling.

2. Geological setting

On the regional scale, the crustal structure of Eastern Sicily is quite complex. A simplified cross-section of the geological structure along the N-S direction is shown in Fig. 2.

The main units are: 1) the carbonatic basement of the Hyblean Foreland (gray colored in Fig. 2); 2) the sedimentary formations of the Northern Chain (pink and orange), which underlie 3) the volcanic body of Mt. Etna (blue); 4) the Ibleo-Maltese escarpment running offshore in the NNW-SSE direction, and, at a smaller scale, 5) the Gela-Catania Foredeep, with the sedimentary basin of the Catania Plain (green). The geology and structural set-up of the region has been studied by a number of authors. A summary of references and a synthesis of the

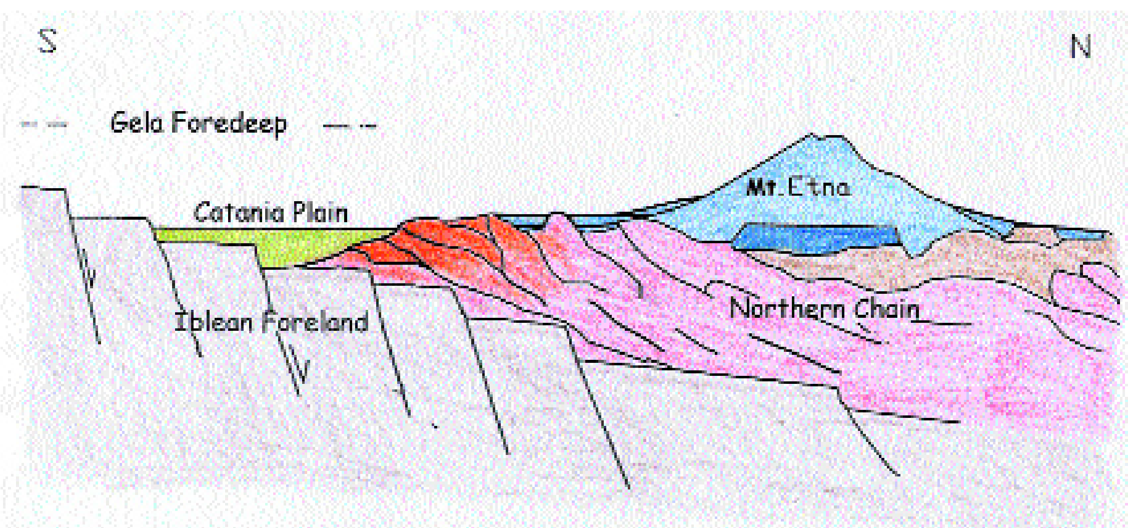

Fig. 2 - Simplified cross-section of the geological structure of the study area along the N-S direction (modified from Accaino, 1998). See more detail in the text.

results can be found in two papers of the Special Issue of the J. of Seismology devoted to the Catania Project (Faccioli, 1999), namely the papers by Sirovich and Pettenati (1999) and Priolo (1999). The most important features of the target area of this study are:

1. The carbonatic basement. As shown by several deep wells (AGIP, 1977), seismic profiles (Petronio, 1997; Accaino, 1998), and geological sections (Cristofolini et al., 1979; Lentini, 1982; Bianchi et al., 1987), it constitutes the deep structure and dips northward with an angle of 8-10 degrees. Beneath the area under investigation its depth may vary from several hundred meters to about 2000 m. This formation does not appear in Fig. 1 and is gray colored in Fig. 2;
2. the sedimentary formations of the Gela-Catania Foredeep, consisting of the recent alluvial deposits of the Catania Plain (in green, Figs. 1 and 2);
3. the sedimentary formations of the Northern Chain. They are mainly constituted by intercalations of sandstone, marls, sand, and conglomerates. These formations outcrop in the south-western part of Catania as the Terreforti Formation (pink in Fig. 1, and orange-to-pink in Fig. 2; see more details below), while in the remaining part of the study area these formations are covered by lava flows;
4. the Mt. Etna lava flows, which cover a large part of the city. Lava thickness increases going from the coastline toward Mt. Etna, and it varies from few meters in the southern part of the city (yellow in Fig. 1) to several tens of meters in the northern part (light blue in Figs. 1 and 2).

The surface geology of the Catania municipal area is even more complex. It features a strong spatial variability, even at the local scale (i.e., tens of metres), with the presence of both volcanic and sedimentary units (Pastore and Turello, 2000). The ages of these units range between the mid-lower Pleistocene and the upper Holocene. Fig. 1 shows only a simplified geotechnical map of the main lithological units, and it does not represent the soil variability adequately; Table 1 summarizes the geotechnical units defined for the area, while Fig. 3 shows the sequence of the geological formations and the relations among the geotechnical units. Below, we describe the geological formations of the area (Puglia et al., 1994) in detail:

Table 1 - Description of the geotechnical units (Faccioli, 1997; Pastore and Turello 1999).

1	R-Dt	Top soil and fill (R), debris and landslides (Dt)
2	M	Marine deposits
3	Alf	Fine alluvial deposits (silts and clays with subordinated sand lenses)
4	Alg	Coarse alluvial deposits (sands, gravels and pebbles)
5	X	Scoriaceous lavas, lavas in blocks, "rifusa" and volcanoclastic rocks
6	E	Fractured to slightly fractured lavas, with subordinated horizons of scoriaceous lavas, lavas in blocks, "rifusa" and volcanoclastic rocks
7	P	Pyroclastic rocks
8	SG	Yellow or brown quartzose sands and sandstone, gravels and conglomerates with pyroclastic alternation
9	ASg	Yellowish or brown clays and sandy silts, with sandy interbedding and pyroclastic alternation
10	Aa	Silty clays and grey-bluish marly clays

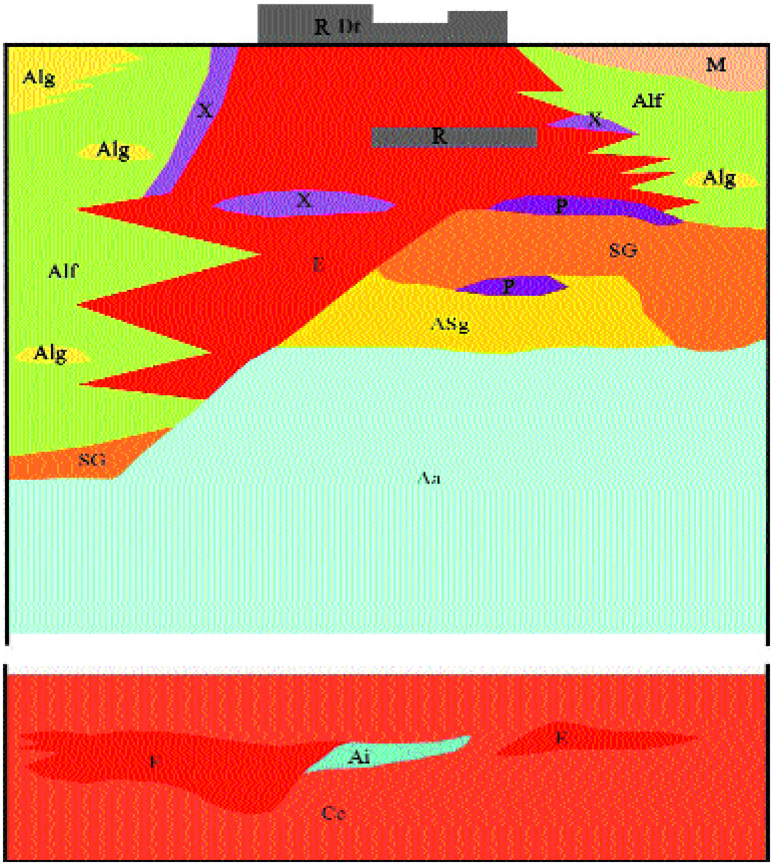

Fig. 3 - Schematic representation (cross-section) of the sequence of the geological formations and relations among the geotechnical units of the Etnean series (modified from Faccioli, 1997). Geotechnical units are the same as defined in Table 1, namely: 1) Top soil and fill (R), debris and landslides (Dt) (grey); 2) Marine deposits (M, pink); 3) Fine alluvial deposits (Alf, light green); 4) Coarse alluvial deposits (Alg, light yellow); 5) Scoriaceous lavas, lavas in blocks, "rifusa" and volcanoclastic rocks (X, magenta); 6) Fractured to slightly fractured lavas (E, red); 7) Pyroclastic rocks (P, violet); 8) Yellow or brown quartzose sands and sandstone, gravels and conglomerates with pyroclastic alternation (SG, orange); 9) Yellowish or brown clays and sandy silts, with sandy interbedding and pyroclastic alternation (ASg, yellow); 10) Silty clays and grey-bluish marly clays (Aa, light blue).

TERREFORTI FORMATION. - This consists of sandstone and conglomerate (SG, Table 1 and Fig. 3, pink in Fig. 1), and extends over a great part of the pink colored area of Fig. 1. The lower part of the unit consists of sandstone displaying cross layering sedimentation and slumping. Occasionally, these sandstones include small lenses of pebbles and/or a few centimeters of clay layers, or some "palle di argilla" (clay balls) and tufaceous levels (ASg). The upper and younger part of the formation displays layers of pebbles and conglomerates with increasing diameter of the constituting pebbles (i.e., from a few centimeters to 30-40 cm). The overall thickness of the Terreforti formation is thought to reach a few hundred metres. This formation represents the southernmost outcrop of the Northern Chain structural unit.

GREY-LIGHT BLUE CLAY. - These are sandy clays showing a grey-light blue color at fresh cuts (Aa). The age is low-middle Pleistocene (Wezel, 1967; Kieffer, 1971). The formation features plastic-like aspects at the base and sandy-clay alternations (or clayey sands) toward the top. The clays display mud-cracks at the surface. This formation belongs to the Northern Chain structural unit and underlies the Terreforti formation. For this reason it is not visible in Fig. 1.

TUFITI. - This unit (P) occurs within the sandy-conglomeratic unit above and displays lens-like shapes with clear stratification in most cases. The color goes from light to dark gray depending on the amount of effusive material within. In the historic part of Catania (i.e., in the area delimited by the Benedettini Convent, Monte Vergine and Via dei Crociferi), some volcanic sands (i.e., from a few meters to 20-25 m) inter-bedded with rare volcanic scoriae have been found recently, testifying increased volcanic activity in the pre-Roman age. This formation is one of the products of Mt. Etna's volcanic activity and, at the ground surface, it is scattered within the lavas (yellow and light blue in Fig. 1).

OLD ALLUVIAL TERRACES. - The origin of these deposits is linked to various and diverse agents. These include eustatic sea-level changes caused by the Quaternary glaciations, landslides and/or lava entrapments. The alluvial units (ASg) outcrop on the great part of the hills and of the areas which have not been filled by the lava. The alluvial terraces show some very clear horizontal and flat morphology which is to be attributed to continental margin terraces or to erosion surfaces. However, the same terraces can be found also between different lava flows and represent examples of fluvial valleys filled by the lava flows. This formation represents the southernmost edge of the Northern Chain structural unit (pink in Fig. 1).

LAVA FLOWS. - These cover a great part of the Catania downtown area (E and X, yellow and light blue in Fig. 1) and their great majority is to be attributed to the volcanic stratigraphic unit of the late Mongibello (Romano et al., 1979; Romano and Sturiale, 1981). The remaining lava date back to the ancient alkaline eruptive phase.

COASTAL DEPOSITS. - These refer to the coastal sands (M) that make up the shoreline (light green in Fig. 1). The sand itself consists of medium to fine quartz grains continuously reworked by the action of the waves. The same sand can be also found beneath the lava flows as a result of an ancient sedimentation process (i.e., the paleo-shores beneath the area of Castello Ursino), but it can be also found above the lava, testifying a still active and nearly continuous sedimentation process. This formation characterizes most of the shoreline of the Catania Plain (light green in Fig. 1).

RECENT AND ONGOING ALLUVIAL DEPOSITS. - These spread over a large part of the Catania Plain (Alf, light green in Fig. 1) and over the existing and extinct river beds (Alg, not visible in Fig. 1). The alluvial deposits are made of marl and clay inter-bedded with gravel and sands of diverse grain size. Overall these deposits are rather heterogeneous.

REWORKED SOILS. - These (R-Dt) spread over the whole territory although they occur more often within the most urbanized areas.

3. Data acquisition and processing

The seismic noise was recorded at 39 different sites. These sites were chosen according to the following criteria: 1) significance in terms of geological, geotechnical, or local characteristics; 2) presence of a lithological transition (e.g., the transition from lava to sediments); 3) presence of other geotechnical or geophysical measurements; 4) alignment with some of the transects along which the ground motion had been simulated numerically (e.g., Priolo, 1999). The data were acquired by two teams independently - Teams A and B - using different instrumentation. Noise measurements were acquired by both teams at seven sites. The two teams adopted different processing schemes.

Team A's data acquisition was performed using three portable Orion Nanometrics digital seismographs and 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 0.2 Hz. At each site, microtremor acquisition lasted for a minimum of thirty minutes of continuous recording time. The sampling interval was set at 100 Hz, guaranteeing reliable spectral estimates up to 30 Hz. Much attention was paid to avoid, as much as possible, the introduction of near instrument transient and coherent signals (e.g., operator induced, cars) and, whenever possible, the geophone-soil coupling was improved by burying the sensor into the ground. To keep track of all the variables involved (e.g., instrument, sensors, time of recording), all survey operations were accurately logged.

Team A estimated the mean H/V ratio by averaging the HVSR computed on a set of running time windows. At the pre-processing stage, outliers were manually removed (e.g., near impulsive sources caused by cars; trains passing nearby; ...), 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 or Burg methods, that are implemented as MATLAB functions (The MathWorks, 2000), and no smoothing is applied in the spectral ratio computation (step 5). The first method is based on averaging and scaling the modified periodograms for sections (i.e., time windows) of the signal (Welch, 1967). Periodograms are computed through FFT. The second (Kay and Marple, 1981) is an autoregressive (AR) spectral estimation by minimization of linear prediction errors. In our tests, using a high order of the AR model equal to $p = 128$, the two methods result in very similar estimates. The HVSR shown in this study were all computed using the Burg method and a spectrum length of 512 samples.

Team B (Gallipoli, 1999) used a sensor similar to that used by team A, namely a three-component 1 Hz Lennartz 3D-Lite (1 Hz natural frequency). However, it was connected to a different acquisition unit, specifically a 24 bit PRAXS-10 unit coupled permanently to an Intel 486, 100 MHz personal computer. These units are assembled within a portable suitcase box. The sampling interval was set at 125 Hz. At each site, microtremor acquisition lasted about eight minutes. Data used for the HVSR computation consisted of at least five one minute time series.

The data processing performed by team B involved the same first two steps performed by Team A, followed by 0.1 to 20 Hz band-pass filtering, and cut-off frequencies located at 0.05 and 25 Hz (Gallipoli, 1999). Fast Fourier transforms were applied to compute spectra for 25 predefined values of frequency, equally spaced in a logarithmic scale between 0.1 and 20 Hz, and selected "in order to preserve energy" (Castro et al., 1990). The function H/V was estimated by averaging all the H/V results computed separately for the one-minute time windows. Full details of the methodology and its shortcomings are given by Mucciarelli (1998). Team B data were also processed independently by team A using their own processing procedure.

We have analyzed the acquisition and processing methodologies by comparing the HVSR estimated and processed independently by the two teams at common sites. In particular, we compare the HVSR that have been 1) acquired and estimated by team B; 2) acquired and estimated by team A, and 3) acquired by team B and estimated by team A. In general, the HVSR agree well in the medium frequency band 1-12 Hz. See for instance the case of site A/B27 (Fig. 4a), where the A/B indicates that both teams acquired the data. However, in a few cases, we have found some inconsistencies in the results obtained by the two teams. In our opinion, the causes of these discrepancies lie mainly in the acquisition procedure. For site A/B4.7 (Fig. 4b), for example, the two measurements were taken at about 10 m from each other, and while team A's sensor was installed in a quiet position and in a hole dug into the soil, team B's station was installed on a nearby concrete platform located close to a passageway. Both acquisition sites were close to a two-story reinforced concrete building, whose fundamental frequency of about 4-5 Hz shows up well in the HVSR of Team A and not in those obtained by Team B data. This observation, however, raises some questions on where the microtremor measurements should be taken when the goal of the survey is to identify anomalous amplifications of the ground motion. Our suspicion is, in fact, that microtremor measurements should be taken (if possible) at some distance from buildings. Attention should also be paid not to place the sensors on man-made

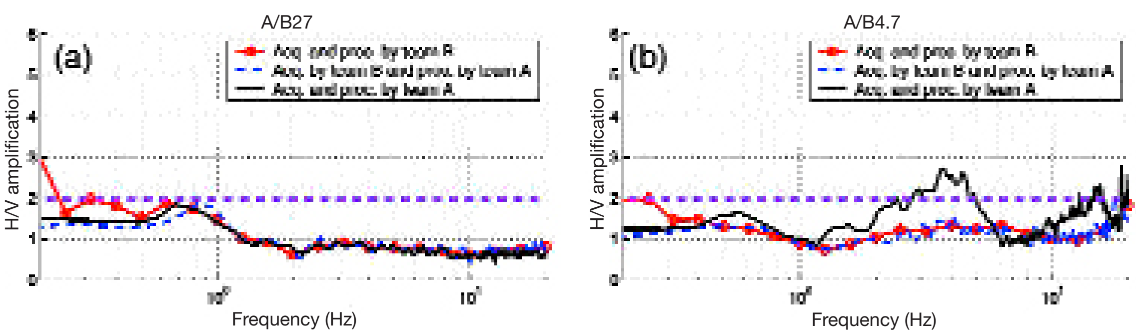

Fig. 4 - Comparison of HVSR estimated from data acquired independently and simultaneously by team A and B, respectively. Sites are (a) A/B27 and (b) A/B4.7.

constructions or appendices because these can mask the true ground motion or respond to it according to their own natural frequency (Guéguen and Bard, 1999).

A summary of different measurements performed at all sites and the HVSR determined using the procedures described above are shown in Fig. 5 and Table 2, respectively.

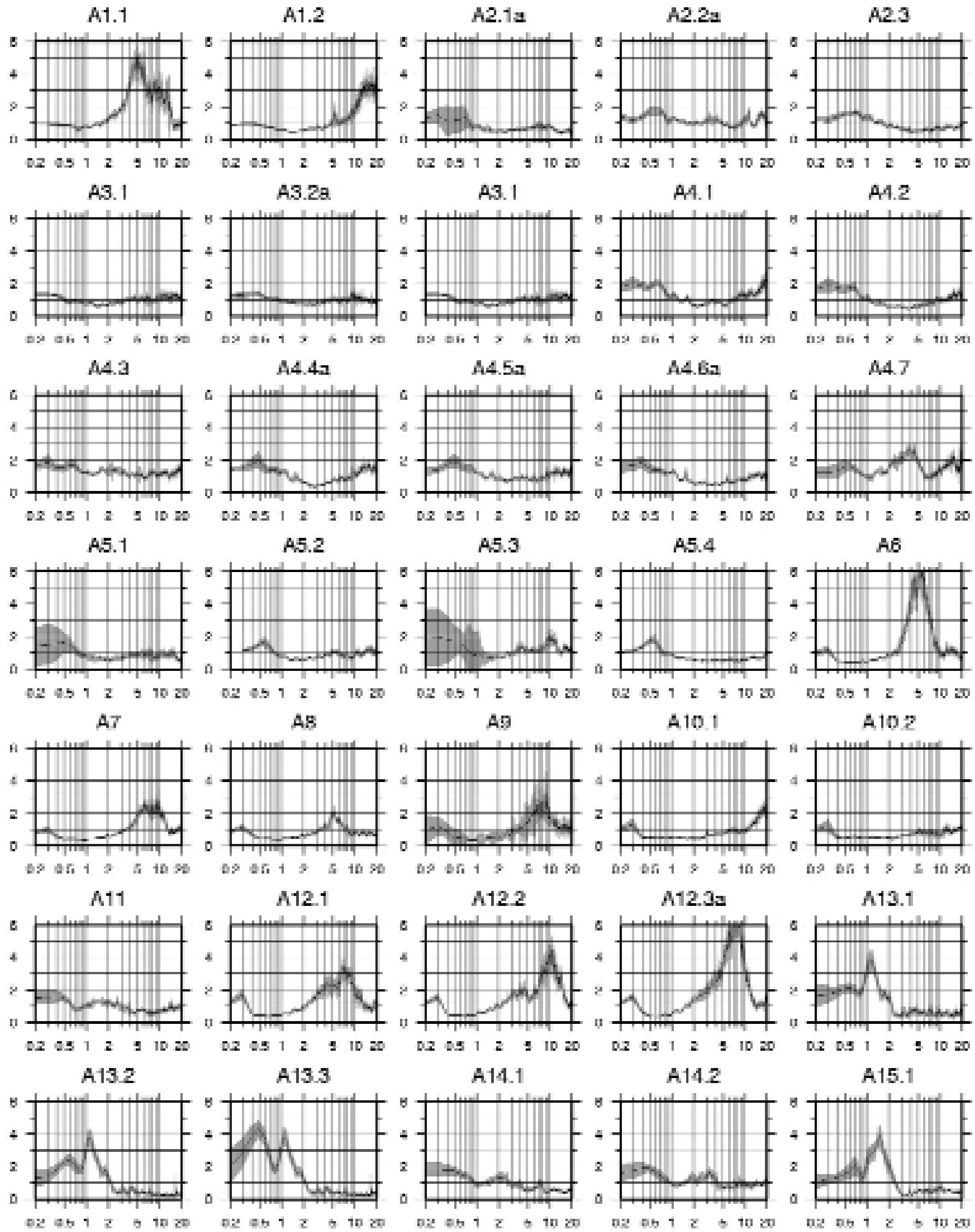

Fig. 5 - HVSR estimated at all measured sites using the processing of team A. Thick curve: average value. Shaded area: average plus/minus the first standard deviation. Abscissa represents frequency in Hz.

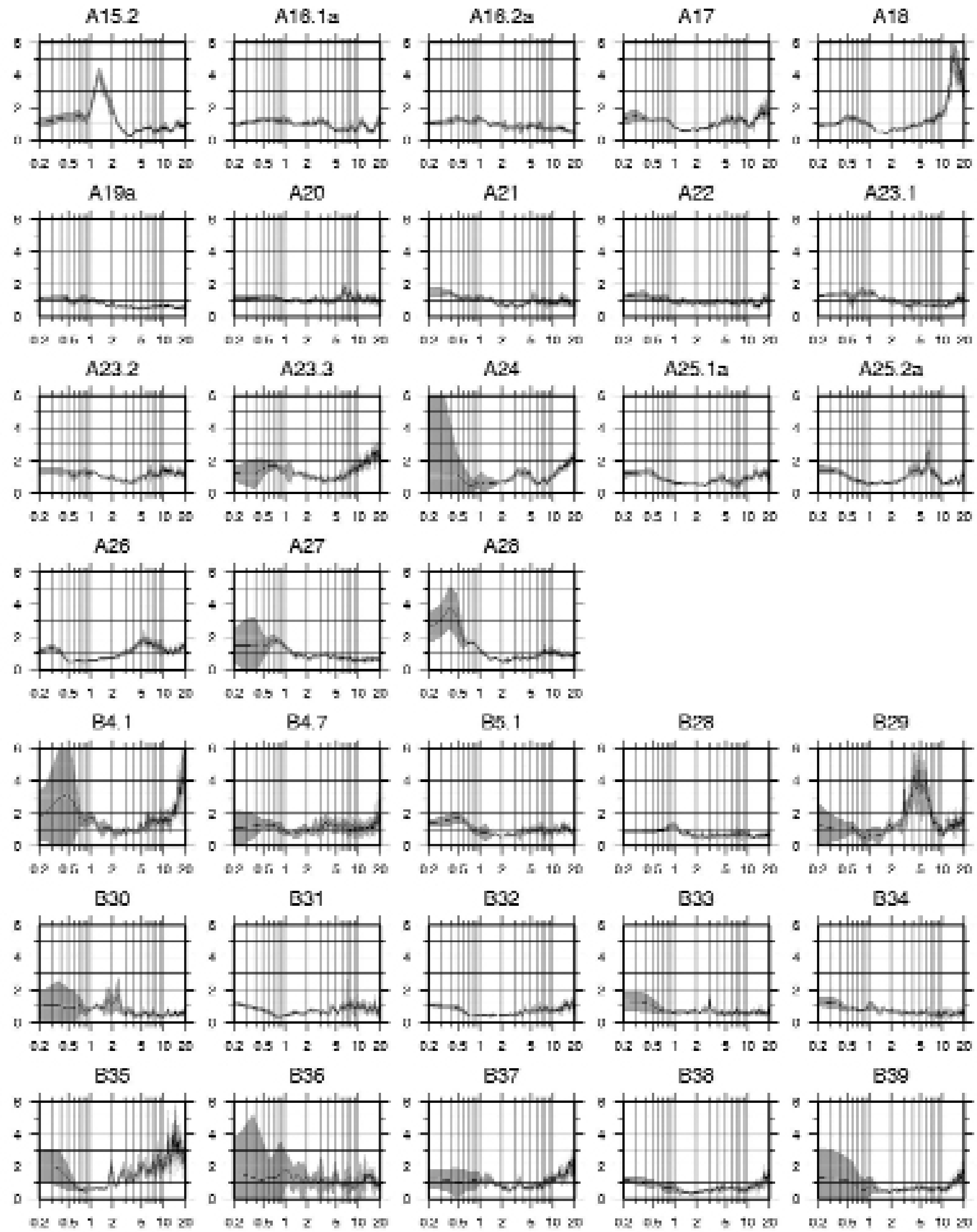

Fig. 5 - continued.

4. Results and discussion

The amplitude of the seismic noise recorded at all sites in the Catania municipal area was large, as a result of anthropic activities (e.g., working equipment, cars, etc) and ocean waves. Also, the power spectral densities (PSDs) of the data did not display constant levels with

Table 2 - Description of the acquisition sites. Geotechnical units are defined in Table 1. Other data (fifth column) are identified by the following abbreviations: GB = Geotechnical borehole; DH = Down-hole velocity measurement; CH = Cross-hole; SASW = Seismic Analysis of Surface Waves, T# = geotechnical or modelling transect number (e.g., T1 = Transect n. 1).

Sites	Area	Lithology [Geotechnical Units]	Notes	Other data
A1.1	Nesima Superiore	Fill over lava [R-Dt, E]	About 5-10 m of fill. Large building yard at 200 m.	
A1.2	”	Fill over lava [E]	On the ground bottom of a former lava quarry.	GB(198)
A2.1	Via S. Sofia	Fill over lava [E]	Cultivated lands at the edge of lava flow.	
A2.2	”	Sedimentary soil (clays) [Aa]	At the base of a small hill within a sedimentary area.	
A2.3	”	Fill over lava [R-Dt, E]	Within the Gandhi Park	
A3.1	S. Leone	Fill over sedimentary soil [R-Dt, SG]	Cross-roads between Viale Indipendenza and via Nervesa della Battaglia	GB(133). 150 m from T1.
A3.2	”	Same as A3.2	Via Pisacane. At the base of a 5-10 m high escarpment	250 m from T1.
A/B4.1	University Campus	Cultivated soil over lava [R-Dt, E]	Within the grove at SE edge of the lava bank.	GB(350). T3.
A4.2	”	Same as A/B4.1	Same as A/B4.1, but NE edge	GB+DH(358)
A4.3	”	Sedimentary soil (clay and sandy silt) [ASg]	Near the Student House	
A4.4	”	Same as A/B4.1	Same as A/B4.1, but within the grove.	GB+DH(356). T3.
A4.5	”	Same as A/B4.1	Same as A/B4.1, but at the NE edge of the lava bank	GB+DH(352). T3.
A4.6	”	Same as A/B4.1	Same as A4.2, but SW farm side	GB+DH(360). T3.
A/B4.7	University Campus (Policlinico)	Same as A4.3	Institute of Pediatrics.	GB(68). About 20 other GB in the neighborhood. T3.
A/B5.1	Villa Bellini Park	Coarse alluvial deposits [Alg]	Play-ground area in the centre of the park. Measurement taken in the flowerbed under about 10 m tall trees	GB(1093, 1097), and others in the neighborhood. Near T4
A5.2	”	Same as A/B5.1	About 20 m from A/B5.1, but measurement taken in an undisturbed area.	Same as A/B5.1
A5.3	”	Fine alluvial deposits [Alf]	South side of the Park. Geophone on concrete along a foot path.	
A5.4	”	Same as A/B5.1	North side of the Park	T4.
A6	Railway embankement	Fill [R-Dt]	At least 10-15 m tick soil. Boundary of the sailing port.	
A7	Borgo	Fill and soil over lava [R-Dt, E]	Square between viale Raffaello Sanzio and via La Spezia, North side. About 300 m from A8.	At about 100 m from GB(57,158)
A8	Borgo	Same as A7	Inner courtyard of Lombardo Radice school. Partially cultivated soil.	Near to GB(159, 160, 272)
A9	”	”	Via Signorelli's railway station (Circumetnea line). The site is located above the underground railway tunnel, at some distance from it.	GB(1036) and near to GB(1034, 1035, 1037). T3.
A10.1	Corso Martiri della Libertà	Thin fill over lava [R-Dt, E]	Square between Corso Martiri and via Marchese di Casalotto, SW corner.	SASW(1). GB(235, 236) at about 100 m.
A/B10.2	”	Same as A10.1	Same as A10.1, but NE corner. Strong traffic noise.	
A11	Playa	Shore sand [M]	Beach at the S edge of harbour.	
A12.1	Tricolore Square	Lava [E]	North side, at the corner between via Borghetti and viale De Gasperi, at about 120 m from the cliff edge.	GB(176, 1005)
A12.2	”	Scoriaceous lava [E,X]	At the edge of the lava flow, at about 80 m from the cliff edge.	Near to GB(176, 1005)
A12.3	”	Lava [E]	At the edge of the lava cliff.	

Table 2 - continued.

A13.1	Industrial Area	Alluvial deposits [Alf]	Close to the ST factory. Geophone-soil coupling test. Sensor on asphalt (good coupling).	GB(1407-1416); GB(1417-1420) and two CH about 200 m away. T2.
A13.2	”	Same as A13.1	Same as A13.1, but geophone buried in a hole (good coupling).	Same as A13.1
A13.3	”	Same as A13.1	Same as A13.1, but geophone resting at the soil surface (bad coupling).	Same as A13.1
A14.1	Playa	Shore sand [M]	Courtyard of the professional school. At about 250 m from the coast.	At about.700 m from T5
A14.2	”	Same as A14.1	Riding training.	At about 200 m from GB(418-425, 1046), SASW(2).
A15.1	Industrial area	Alluvial deposits [Alf]	Northern side of ENEL plant (Strada III).	At about 100 m from ENEA-ENEL accelerometric station. T6.
A15.2	”	Same as A15.1	Same as A15.1, but southern side (cross-roads, side of Strada I).	At about 150 m from ENEA-ENEL station. Above GB+DH(1406), and near GB(1303). T6.
A16.1	Nesima Inferiore	Fractured lava [E]	At the lava flow edge. Corso Indipendenza, NW side of the Sport Hall.	Near to GB(99-109) T1.
A16.2	”	Fill over lava [R-Dt, E]	Corso Indipendenza, n. 162. Square in front of IACP building.	GB(182). T1.
A/B17	S. Giorgio	Sedimentary soil (sand) [SG]	Strada Bummacaro. At the top of the edge of a sand quarry.	At about 100 m from GB(1326-1328). T5.
A18	Nesima Inferiore	Fill over lava [E]	Via Palermo. Lava quarry. 2-4 m of fill over lava.	100 m from T1.
A19	Stradale Cravona		Via degli Olmi. Large excavated area. Sedimentary soil (conglomerate and sand) [SG]	Geotechnical site of type C. SASW(3)
A20	”	Fill over sedimentary soil (sand) [R-Dt, SG]	Via del Biancospino. At the edge of a 30 m high escarpment of fill.	Near GB(1193) and GB(1090, 1323).
A21	”	Sedimentary soil (conglomerate and sand) [SG]	Via degli Olmi. “Masseria dei Sorci”	
A22	S. Giorgio	Sedimentary soil (clay and sand) [SG,ASg]	“S. Giorgio sand”.	Geotechnical site of type B. At about 100 m from GB(113)
A23.1	Villaggio C.E.P. Monte Po'	Sedimentary soil (clay and sand) [SG, ASg]	Hill at the southern side of Don Luigi Sturzo school. Site under investigation for landslide.	GB+DH. T1.
A23.2	”	Same as A23.1	Same as A23.1, but NW hill side	GB(407-409). T1.
A23.3	”	Same as A23.1	Same as A23.1, but W hill side.	GB and DH (Addia). T1.
A24	Palestro square	Fill over lava [R-Dt, E].		GB(1427) and DH(GNDT n. 2). T1
A25.1	Fortino	Fill over sedimentary soil (sand) [R-Dt, SG]	2-3 m thick fill.	
A25.2	”	Sand [SG]	Building yard with working machinery. 5-7 m thick sand. About 150 m from site A25.1	Near GB(1059-1060).
A26	Parco Gioeni	Lava [E]	Via Musco. Northern park entrance.	
A/B27	Librino	Possible fill over sedimentary soil (sand) [R-Dt, SG]	Viale Moncada, between C and B blocks. Highly urbanized area with tall buildings (at least 8 floors).	At about 100m from GB(1177-1178). T5.
A/B28	”	Sedimentary soil (clay and sandy silt) [ASg]	Viale Castagnola, block A.	At about 100m from GB(200-203). T5.
B29	City centre	Reworked filling material over lava [E]	Dante square.	
B30	”	Probable sandy deposits [E, M]	Cross-roads between via Garibaldi and via Castello Ursino	

Table 2 - continued.

B31	”	Lava [E]	Castello Ursino, Southern side	
B32	”	Lava [E]	Piazza Majorana	At about 100m from GB(234)
B33	”	Lava [E]	Cross-roads between via Crociferi and via Di Sangiuliano	GB(1063,1064,1065)
B34	”	Possible alluvial deposits or lava [Alf, E]	Via Lago di Nicito	GB(1050, 1051)
B35	Picanello	Fill and soils over lava [R-Dt, E]	Via Vagliasindi	GB(159, 160)
B36	Cibali	Lava [E]	Cross-roads between Via Galermo and via S. Paolo	
B37	”	Lava or scoriaceous lava [E, X]	Free-way at the crossroads with via S. Sofia	GB(154)
B38	Corso Martiri della Libertà	Same as A10.2	In the neighborhood of A10.2	GB(163, 276, 341, 279, 278, 281, 277, 280, 212)
B39	”	Same as A10.1	In the neighborhood of A10.1	GB(163, 276, 341, 279, 278, 281, 277, 280, 212)

frequency (i.e., white noise). With the exception of a few sites (i.e., alluvial and/or reworked soil on lava), the impedance contrast between the surface layer and the seismic bedrock beneath (when it exists) is generally lower than 2-3 (Puglia et al., 1994; Faccioli, 1997; Pastore and Turello, 2000), so that, the local amplification is also small (Bard, 1999). It follows that the resonant frequencies of the site can hardly be estimated from either the PSD alone or the HVSR.

In order to visualize possible geographical patterns of the HVSR of Fig. 5, we have identified the fundamental frequency and the H/V amplitude value of each site. As it will be shown below, we have found that several sites exhibit an anomalous amplification within the frequency band 0.2-0.8 Hz. Thus, we have subdivided the results into two groups according to two different frequency bands, 0.2-1.0 and 1-20 Hz, respectively.

Fig. 6 displays the estimated H/V amplitude in the frequency range 1-20 Hz (i.e., the most important for seismic engineering purposes). We see that more than one half of the sites exhibit moderate or weak amplifications (lower than 2) and these sites locate either on lava (for example, the sites in the center of Catania or in the northern part of the municipal area) or on well-consolidated sedimentary soils (i.e., the “Terreforti” formation outcropping in the Western districts of the city). While this behavior of the HVSR is to be expected for those sites lying on the lava outcrops, it is to some extent unexpected for the “Terreforti” formation. Our findings suggest no relevant acoustic impedance contrast at depth down to several hundreds of meters, as indicated by the well data, and geological and geophysical studies (see section “Geological Setting”). This interpretation is supported by a similar investigation performed by Giampiccolo et al. (2001) and, for what concern the uppermost portion of soil, by the results of the short SASW (Spectral Analysis of Surface Waves) profiles performed in the area of site A19 (Nunziata et al., 1999).

The camera pictures shown in Fig. 7 (site A27) show the conglomerate, clay and sands which make up the “Terreforti” formation (Faccioli, 1997). Fig. 8 displays another site in this area (site A22). The field measurement was taken at about 20 m from the edge of a 30 m high escarpment formed by well consolidated filling materials. To explain the flat frequency response, we have to assume that the acoustic impedance ratio between the consolidated fill and the sedimentary soil of the underlying escarpment is not large.

The only sites which bear evidence of some amplification are located on either fillings/soils lying on the top of the lava, or on the fine alluvial deposits of the Catania Plain. In the first case the H/V amplitude level is usually moderate (< 6) and the fundamental frequency is between 5 and 12 Hz. In the second case, the sites of the Plain have a much lower natural frequency (about 1.3 Hz) and H/V amplitude of about 4-5 (see also Fig. 11).

Fig. 9 shows some examples of the HVSR found in the northern part of the area under

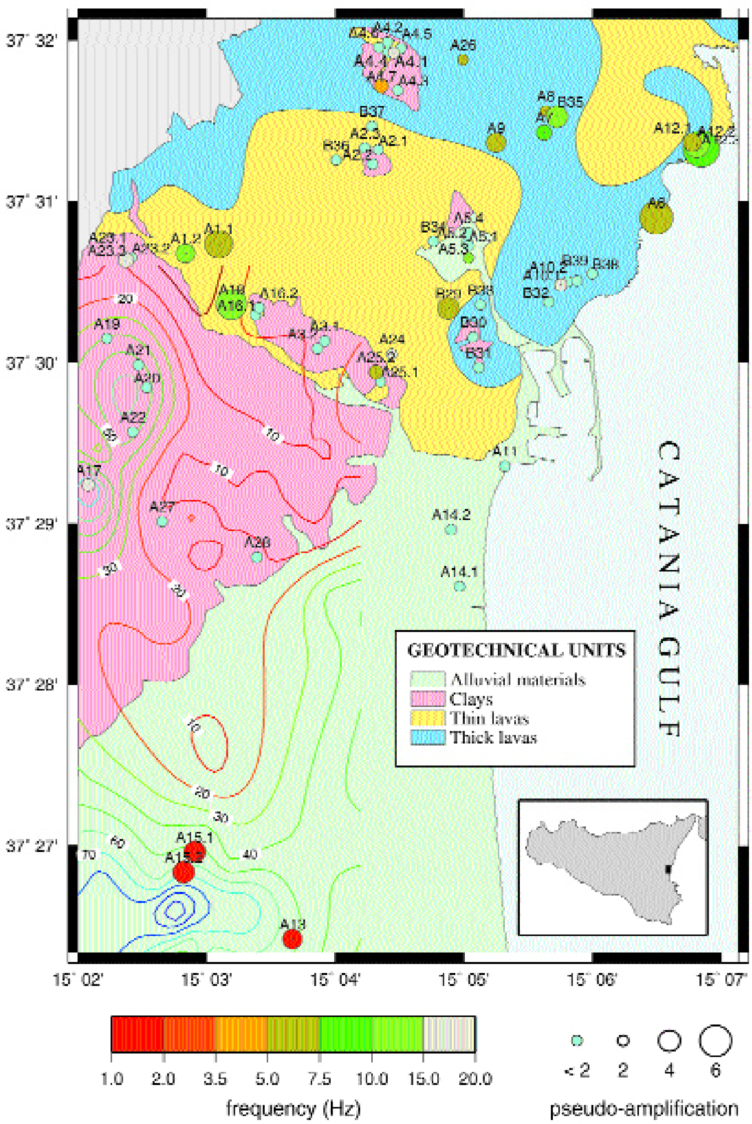

Fig. 6 - Estimated peak H/V amplitude in the frequency range 1-20 Hz. The color and size of the circles indicate peak frequency and amplitude of the HVSR, respectively. Blue circles indicate sites with very low H/V amplitude or flat response. Contour lines indicate the depth of the top of the light-blue clay formations, which some authors assumed as a possible seismic bedrock (Faccioli, 1997). See Fig. 1 for additional details.

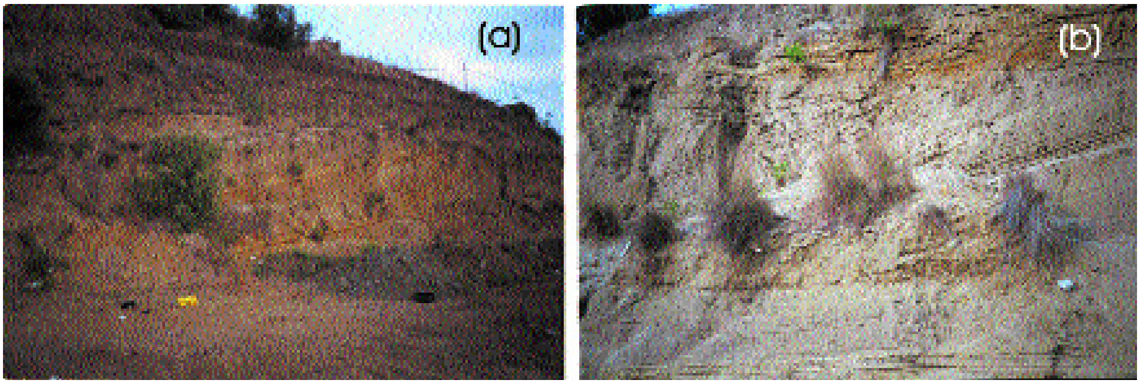

Fig. 7 - Site A27. The two pictures give an idea of the sedimentary soil made by conglomerate, clay and sandy silt characterizing most of the western part of the municipal area.

investigation. Site A6 (Fig. 9a) is a good example of large amplification. The site is located on the top of a 10-15 m high embankment consisting of re-worked filling material. The fundamental frequency of about 5.5 Hz is in good agreement with a shear wave velocity of the filling soil ranging between 220-250 m/s.

Site A7 (Fig. 9b) is an example of moderate amounts of local site amplification. It is located on filling material overlaying lava, but, when compared to A6, the thickness of the fillings is much thinner and the soil appears more consolidated. The fundamental frequency displays values as high as 8 Hz, whereas the H/V amplitude does not exceed the value of 3.

Fig. 9c has been included to show how a coherent noise source - working machinery at a distance of 150-200 m – does not show up in the HVSR. We can see that, at the frequency corresponding to the strong PSD peak produced by the working machinery, the HVSR is stable whereas the relative standard deviation is slightly larger, due to temporal variation of the source. This site (A1.1) is located on a 10-15 m thick fill over lava.

Fig. 9d displays the effect of a particular morphology and it refers to site A12.3 located on the edge of a 10-15 m lava cliff (Fig. 10). The HVSR show a significant amplitude increase as the measurement site approaches the edge of the cliff (Fig. 5a, sites A12.1 to A12.3). Thus, we

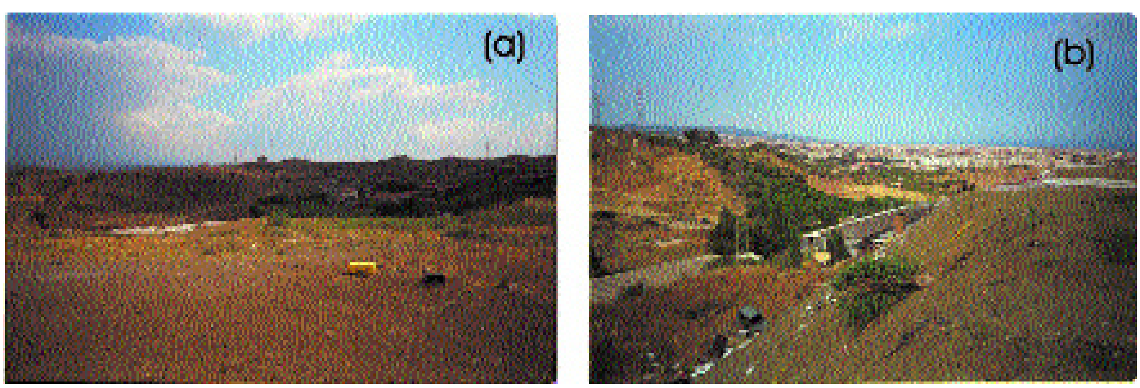

Fig. 8 - Site A22. The measurement location is at the top of an escarpment (a, view to north) apparently made by filling material (b, view to east). The seismic response estimated from HVSR was flat.

interpret the frequency peak at about 7.5 Hz as an effect of a fundamental mode of vibration of the cliff wall. Finally, we note that all signals recorded on lava in the northern part of the municipal area, that is sites A6, A7, and A12.3, although recorded at different times, but within a few hundred meters distance, nearly all feature the same energy and frequency content (bottom panels of Fig. 9a, b and d, respectively).

Fig. 11 displays the ground response near the Catania ENEA-ENEL (National Institute for Alternative Energy – National Electric Energy) strong motion station. The two measurement sites lie at a distance of about 100 m toward the north and south of the accelerometric station, respectively. The sites are located on fine alluvial material. The two HVSR are very similar to each other. The fundamental frequency is about 1.4 Hz. Note also that the signal measured at site A15.1 features a strong monochromatic component at 4 Hz, generated by a factory located at about 400 m from the measuring site. This demonstrates again that coherent seismic sources do not generally affect the HVSR, with the exception of short (frequency dependent) source-receiver distances.

Several sites display amplification in the low frequency band 0.2-1 Hz (Fig. 12). This behavior was found by both teams A and B. With the exception of two sites, namely A13.3

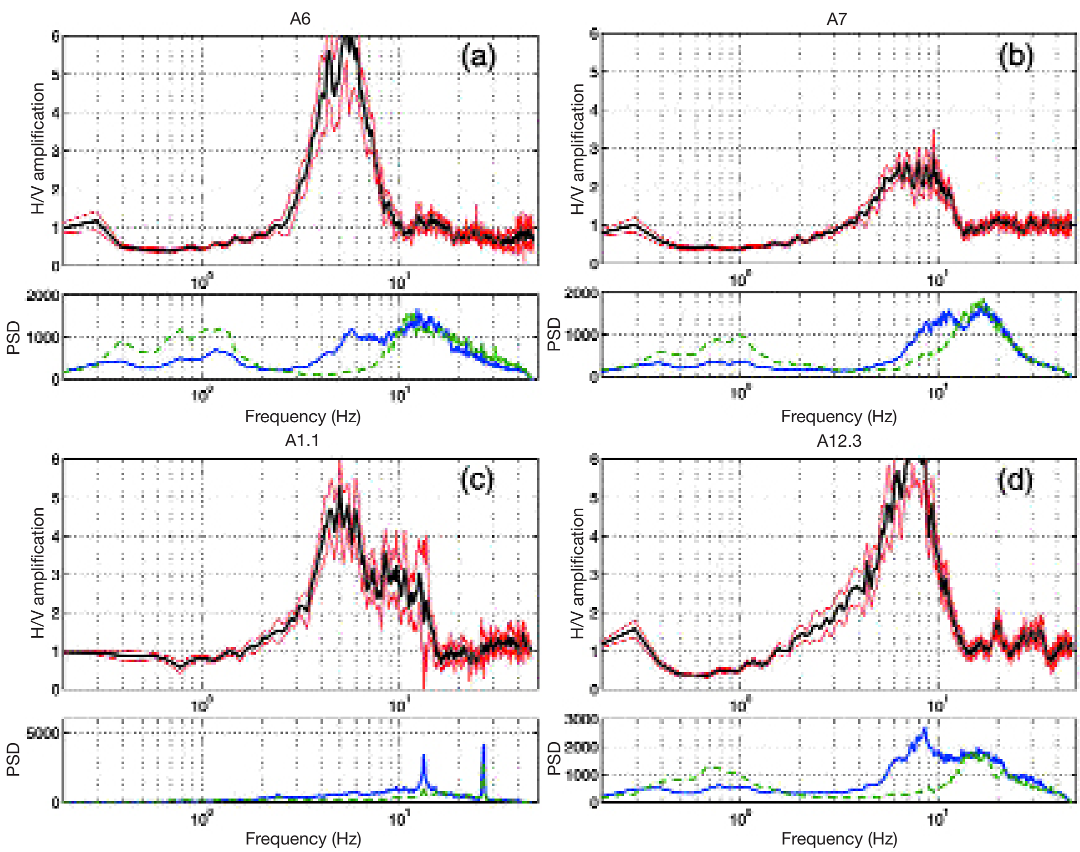

Fig. 9 - HVSR estimates at four sites characterized by the occurrence of some amplification. Displayed sites: (a) A6, (b) A7, (c) A1.1, and (d) A12.3. For each site the two panels show (top panel) the HVSR estimate (thick line) and the same plus/minus the first standard deviation (thin lines), and (bottom panel) the average power spectral density of the horizontal (solid line) and vertical (dashed line) components, respectively.

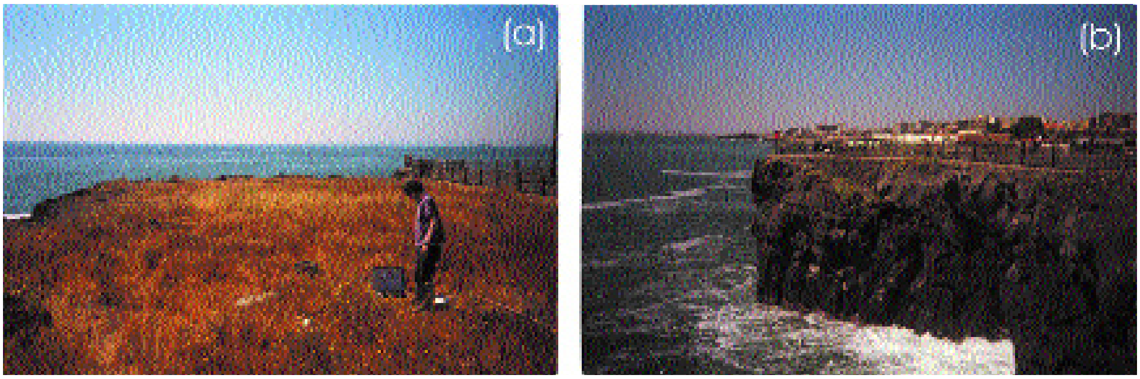

Fig. 10 - Site A12.3. The acquisition site (a) was at about 10 m from the edge (b) of a 10-15 m lava cliff.

and A28 (Fig. 13), the H/V amplitude is rather low (a factor of 2). We are still evaluating some hypotheses that can explain the 'anomalous' behavior at these two sites. These include the effects caused by ocean wave motion, wind, instrumental anomalies, deep geological structure, poor sensor-soil coupling, or the method used for the estimation of the power spectral density. So far, however, we have found no correlation between the observed low-frequency peaks and the distance of the site from the sea, the wind occurrence, and the instrumentation used. The effect of the geological structure has been claimed by other authors (Giampiccolo et al., 2001), and it is supported also by the fact that the sites where the low-frequency amplification occurs are all clustered together within restricted areas, located either within or near the Plain or where the sedimentary formation outcrops from beneath the lava flows. Further support to this hypothesis is given by the following analysis.

In Fig. 14, we compare the measured HVSR to those predicted by spectral element numerical modeling along transect T3 (Priolo, 1999). The reference source simulates the catastrophic $M \geq 7$ earthquake of January 11, 1693, with hypocenter located along the Iblean-Maltese fault. Transect T3 crosses the northern part of downtown Catania with direction SE-NW

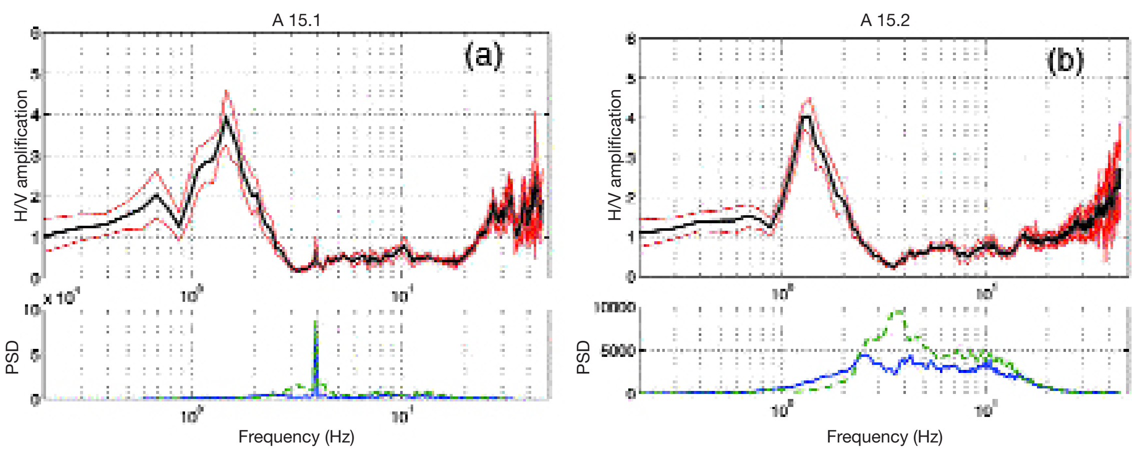

Fig. 11 - HVSR estimated at the two sites located in the vicinity of the Catania ENEA-ENEL accelerometric station. (a) A15.1, and (b) A15.2. The power spectral density at site A15.2 features a narrow band energy peak at about 4 Hz corresponding to the vibration induced by 400 m - distant factory.

(Fig. 1). Inland, the surface section of the transect features two bulky lava banks (Fig. 14a), whose thicknesses range from 20-30 m to 60-80 m for the bank close to the coastline and that located inland, respectively.

The section shown in Fig. 14a accurately reproduces one of the sections produced by the geotechnical study, i.e. section n. 3 in Faccioli (1997). In this context, the term “accurately” is used to mean that only the structural detail with scale lengths larger than about 5 m is reproduced, while a smaller size detail is either omitted or averaged out. Note also that, the geotechnical data allow us to accurately identify only the uppermost part of the structure, i.e., the thick lava bank inland, down to a depth of about 80 m, and the sedimentary formations and the lava bank close to the coast down to a depth not exceeding 30 m. It follows that several

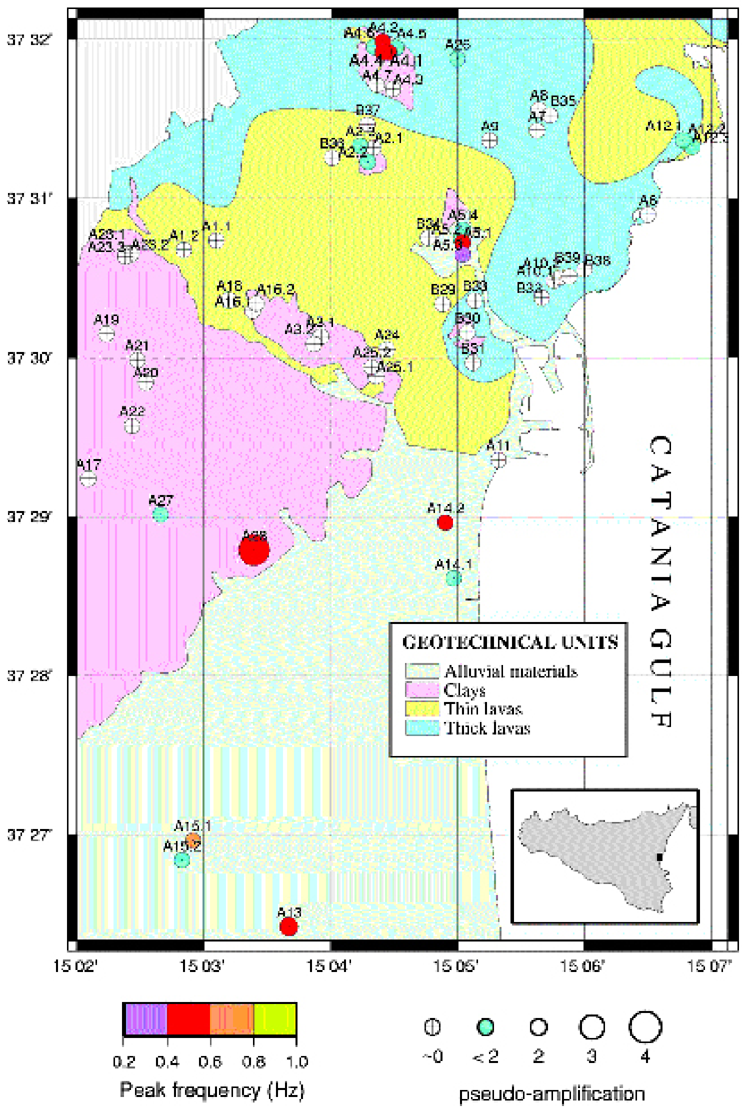

Fig. 12 - Estimated *H*/*V* amplitude in the frequency range 0.2-1 Hz. Here, blue and white circles with crosses indicate sites with weak and flat response, respectively. Other details as in Fig. 6.

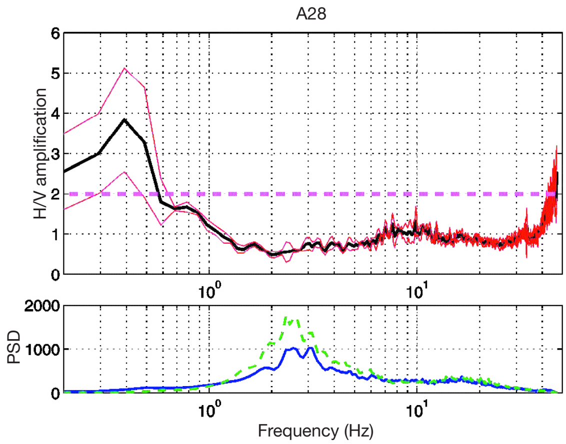

Fig. 13 - Example of HVSR displaying amplification in the low frequency range. Site is A28.

features of the deep section (e.g., the continuous extension of the light blue clay layer (Aa3), the sequence of the pliocenic sediments and alloctonous (Spa) beneath, as well as the values of the physical parameters) may not be completely realistic.

Fig. 14b shows the HVSR predicted by spectral element modeling along the whole length of transect T3. Receiver spacing is 25 m. The nearly horizontal stripes of peaks at frequencies of about 0.3-0.5 Hz, 1.5-1.9 Hz, 2.3-2.7 Hz, and 3-3.4 Hz represent the fundamental and higher modes of vibration. The decrease of the resonant frequency from the coastline inland results from the increasing thickness of the layers. In the middle of the section (i.e., at abscissa of about 3-4 km), where the underlying sedimentary formations outcrop and are covered by a thin layer of soil, we see some clear high amplitude peaks at a frequency of about 3-5 Hz. In addition, the numerical simulation predicts a strong lateral variability of the HVSR, especially in the medium-high frequency range (2-6 Hz). This implies that seismic noise measurements made at single isolated points should be used with care in the interpretation.

In Fig. 14c-h we compare the HVSR predicted at three sites located along the transect to those actually measured at sites located near the transect (e.g., site A4.7) or very close to it (e.g., sites A9, and the group of sites A4.1-6 located within the University Campus). At site A9 (Fig. 14c-d), the measured HVSR displays a clear peak at frequency 7-8 Hz, while the simulated HVSR does feature several smaller peaks (at 05-0.9 Hz, 1.6-1.9 Hz, 4-4.5 Hz and 8-9 Hz), but the amplitude of those peaks is so small that we interpret the response as flat. Site A9 (Fig. 1) is located above the tunnel of the Circumetnea underground railway, at some distance from it, and at about 100 m from the Borgo Station. The tunnel goes through the lava bank at a mean depth of 15 m, and it has a diameter of about 9 m along the line and 13 m at the Borgo Station (Ardita, 1997). The lava covering, from the tunnel roof to the surface, has a thickness of about 8 m. We interpret HVSR peak at 7-9 Hz as resulting from the resonant frequency of the tunnel. However, while we found some studies which identify the resonant modes or scattering effects of an underground cylindrical cavity, we found no references confirming this interpretation in terms of HVSR.

The agreement between computed and measured HVSR is rather good at site A4.7 (Fig. 14e-f). Here, a weak peak is found in both HVSR at the frequency of 3-5 Hz. This frequency

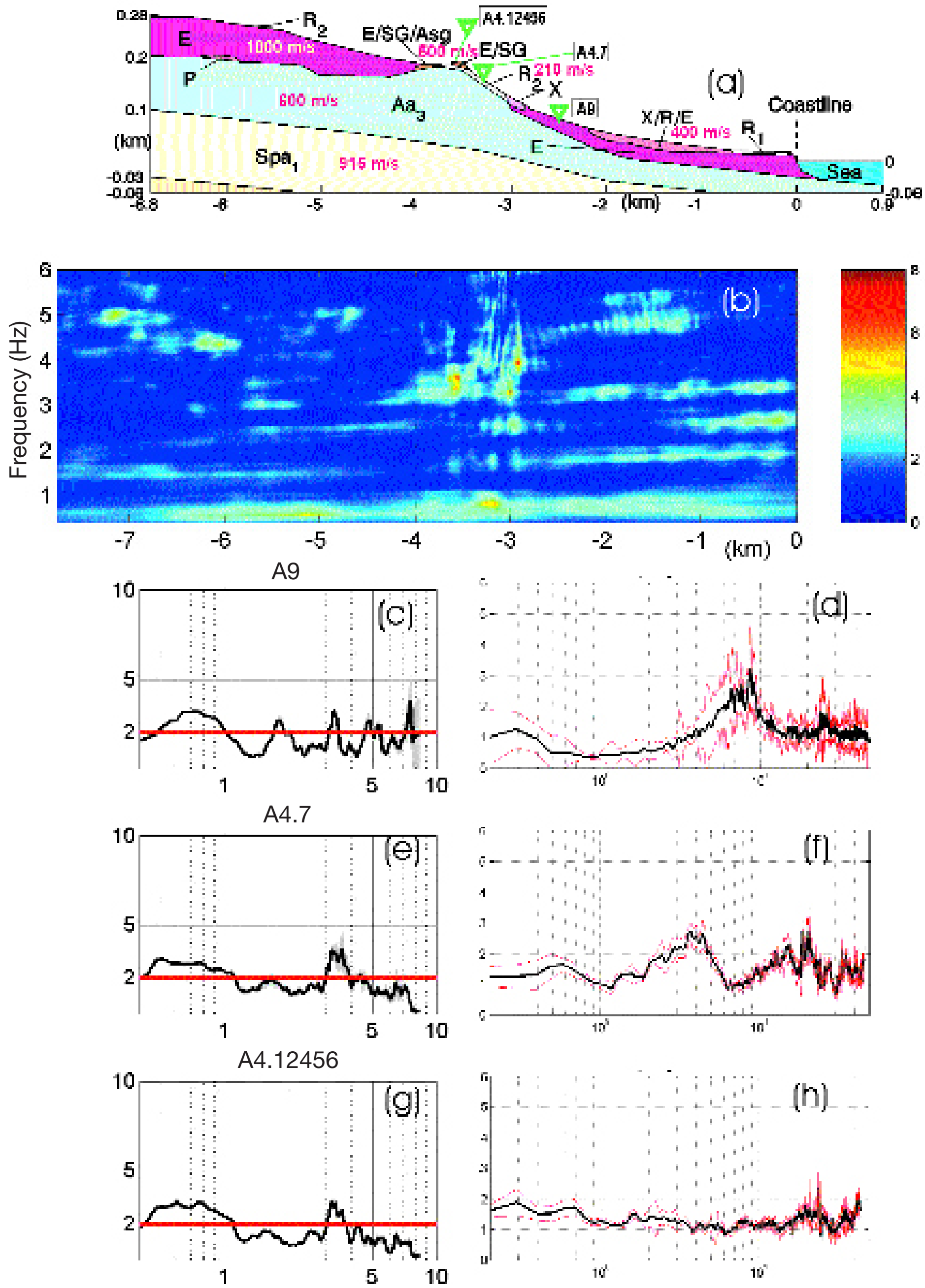

Fig. 14 - HVSR predicted by spectral element numerical simulation along transect T3 for an earthquake occurring along the Iblean-Maltese fault (Priolo, 1999). (a) Geological section near the surface. The geotechnical units of the regions are specified in Table 1. For each region the shear wave velocity is specified. Green triangles indicate the location of the three sites where the HVSR are shown in panels (c-h). (b) HVSR along the transect surface. HVSR (c) predicted and (d) measured at site A.9. (e, f) Same for site A4.7. (g, h) Same for sites within the University Campus. Panel g displays the average of predicted HVSR for a distance range of about 300 m, while panel (h) is the HVSR measured at site A4.3, taken as representative of all lava sites located within the University Campus. In this case, the coordinate of the site for the predicted HVSR corresponds to a mean location of sites A4.1, A4.2, A4.4, A4.5, and A4.6, which were close to each other and located at a short distance from the transect. Note, also, that the predicted and measured HVSR (panels (c, e, g) and (d, f, h), respectively) are represented using two different graphic scales.

band corresponds to the first resonant frequency of the top layer of soil (R_2 in Fig. 14a) in the simulated model, which has the velocity V_S = 210 m/s, thickness h = 12 m, and velocity contrast of about 3 with the layer below.

At the lava sites, located within the University Campus (A4.1, A4.2, A4.4, A4.5, and A4.6), the measured HVSR features a flat response, while that predicted by numerical modeling features a weak peak at 3-4 Hz, similar to site A4.7. This weak inconsistency is explained by the simplified model used to defined the surface structure of the numerical model at the top of the hill (Fig. 14a), where a complex sequence of units consisting, from top to bottom, of lava (E, about 8 m thick), yellow sand (SG, 2-3 m), a mixture of clay and silt (Asg, 2 m), and, beneath, light blue clay (Aa) (Faccioli, 1997) has been merged into a stiff soil unit (E/SG, with a shear wave velocity of 550 m/s).

It is important to note that both predicted and measured HVSR feature a weak but clear increase of amplitude in the low frequency range (0.2-1 Hz), similar to that observed at site A28 (Fig. 13). This range corresponds to fundamental frequencies of the sequence of sedimentary layers defined in the model of transect T3 down to carbonatic basement at a depth of about 2000 m (Priolo, 1999), and supports the arguments given by Giampiccolo et al. (2001) who interpret the HVSR amplitude increase in the low frequency range as an effect of the deep structure. For instance, the fundamental frequencies of three different stacks of layers down to the bottom of units Aa_3 (mean shear wave velocity and thickness of 580 m/s and 165 m), Spa_2 (715 m/s and 420 m), and Spa_7 (1310 m/s and 2300 m, which corresponds to the top of the carbonatic units) are 0.88 Hz, 0.43 Hz, and 0.14 Hz, respectively.

Finally, the inconsistency featured in the low frequency band 0.2-1 Hz concerns the uncertainty of the estimate (i.e., the standard deviation) more than the mean value (see for instance sites 4.1, 4.7, and 5.1 measured by both teams A and B, in Fig. 5).

5. Conclusions

The results of this study indicate that the amount of local site seismic amplification in the Catania municipal area, as determined from the HVSR of microtremors, is generally low. We have found that, in more than half of the measured sites, the HVSR has no clear peak and it is nearly constant with frequency. Overall, the pattern of the HVSR indicates the presence of three zones which closely reflect the simplified geotechnical map. The first zone, lies north of the center of town and consists of massive lavas. The second is located west of the downtown area and is made up of thick sedimentary units (conglomerate, sandstone and loosely compacted gravel). The third area is the Catania Plain, south of the city, which features thick and fine alluvial, often unconsolidated, sand and clay deposits.

In the first area, the level of HVSR amplification is generally moderate (i.e., < 2.5) with only a few sites, by the sea cliffs and on sites having thin - soil layers and manmade deposits, where the local amplification exceeds values of six (e.g., A12 and A1.1) in the medium/high frequency range (5-15 Hz). However, the interpretation of the results should be made with caution because the geology of the area is quite complex. For example, some localized areas featuring outcropping sediments – the University Campus (A4), the St. Sofia/Cibali area (A2) and the Villa Bellini Gardens (A5) - display no HVSR amplification. This would indicate that these formations are probably thick and did not juxtapose upon recent lava.

In the second area, where the "Terreforti" formation outcrops, the HVSR are always almost constant. This would suggest that the sedimentary cover is thick and little or no impedance contrast exists at depth.

In the Catania Plain, only sites south of the airport showed some amplification. The fundamental frequency of these sites is much lower (1-2 Hz).

We have found that in some places HVSR amplification peaks occur between 0.2 and 0.8 Hz. They are difficult to explain thoroughly at this stage of the work, and we cannot exclude technical reasons, such as poor sensor-soil coupling. However, the analysis performed at some sites comparing the measured HVSR to those simulated numerically for an earthquake, might support the hypothesis of an effect of the deep structure, as recently claimed by other authors. The numerical simulations also predict a strong lateral variability of the HVSR, where the underlying structure is not a "plane layer model", rather usual for Catania. This implies that seismic noise measurements made at single isolated points should be used with care in the interpretation.

Finally, this study leaves some issues still open, e.g., 1) there are some doubts on the general applicability of Nakamura's technique to areas featuring lateral heterogeneities such as those found in Catania; 2) the low frequency peaks need a more thorough investigation. We think that a great part of this criticism can be addressed using a larger dataset than the one employed here. In fact, other groups (e.g., Giampiccolo et al., 2001; Lombardo et al., 2001) have also acquired microtremor data which we would like to merge with our dataset, in the near future, to improve the spatial resolution and verify the consistency of the results.

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