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Results of microtremor measurements in the urban area of Catania, Italy

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Abstract - More than 200 time histories of ambient noise have been recorded at 158 sites in the urban area of Catania. Among them, 144 sites are aligned along 15 profiles crossing the most representative lithologies outcropping in the study area. The standard Nakamura (1989) technique has been applied to compute the H/V spectral ratio along these profiles, where the upper-layer structure has been reconstructed in detail using surface geology surveys as well as data from available wells. The geological peculiarity of Catania is the presence of an extended, high-velocity lava cover of varying thickness that fills a large part of the urban area; lower-velocity sedimentary layers outcrop only in small windows in the northern part of the town, however, they predominate in the southern part. In such a complex geological setting, the application of the Nakamura technique provides results that do not correspond strictly to the expectation for usual hard and soft-site spectral shapes. Measurement results have indicated that, in general, the H/V amplitudes do not attain large values in the study area: only at 15 sites are the spectral peaks greater than 3 units, and this occurs predominantly on lava outcrops, where the maximum amplification occurs between 7 and 10 Hz. This frequency band is consistent with weathering processes of the lava flows. At soft sites the observation of significant amplitude (> 3) spectral peaks is limited to a few cases. The recordings of six broad-band stations laying on or near the selected profiles have been used for a preliminary comparison between microtremor results and amplifications observed during individual earthquakes. The H/V spectral ratios are generally similar for microtremor and earthquake data, microtremor tending to underestimate the amplitude of horizontal ground motions of earthquakes. But amplifications at sedimentary outcrops (with reference to a massive lava site) can be significant during individual earthquakes, and in some cases include frequency bands where no

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tendency to amplify was inferred from the microtremor H/V spectral ratios. Even though this comparison needs more data before reaching a stable conclusion, a preliminary analysis of earthquake data confirms that caution is required in using ambient noise for engineering purposes in complex and laterally sharply varying nearsurface geological structures such as those presented by the urban area of Catania.

1. Introduction

Eastern Sicily has a high seismic hazard. The seismicity affecting the area can be explained by post-collision processes between the African plate boundary and the Calabrian arc. These produce a peculiar tectonic setting with regional scale structures that intersect to give rise to the Mt. Etna volcano. The seismotectonic features of the area are illustrated by Scandone et al. (1992) and more recently by Azzaro and Barbano (2000), who propose a revised seismogenic model of southeastern Sicily. As a consequence of this tectonic setting, the contributions to the seismic hazard of Catania and its suburbs are from weak and moderate magnitude (up to $M \approx 4$) events due to the seismic activity of Mt. Etna and from larger earthquakes located to the south, generated by the regional scale tectonic structures of the Malta-Hyblean escarpment. It is along these structures that the most destructive events of the area took place, such as the 1169, 1542 and 1693 earthquakes whose intensities were equal to or greater than X. Moreover, the famous 1908 earthquake, in the Messina Straits, was felt in Catania with an intensity not lower than VII. More recently, the 1990 off-shore Augusta earthquake, in spite of its moderate magnitude ($M = 5.5$), caused considerable damage with an intensity of VI in Catania. It is therefore of primary interest to evaluate the seismic response of the urbanized area from moderate to strong seismic input, with particular attention to the effects that can occur on sites having topographical and/or lithological conditions favourable to large local amplifications of ground motion. The evaluation of seismic scenarios for the area of Catania has been discussed by several authors (e.g. Faccioli and Pessina, 2000) and modelling of ground motion was performed using different methodologies (Langer et al., 1999; Priolo, 1999, 2000).

This paper describes a detailed survey using ambient noise to predict potential variations of the seismic response at the scale of hundreds of metres. In the area of Catania, microtremor measurements have been performed since the late eighties (Cosentino et al. 1984; Lombardo, 1985, 1987), analysing seismic noise with the Kanai and Tanaka (1961) and Katz (1976) methodology. More recently, Giampiccolo et al. (1999, 2001) and Priolo et al. (2001) applied the Nakamura (1989) technique for a preliminary evaluation of site response in some test zones in Catania. We have applied the same methodology (Nakamura, 1989) recording microtremors at a dense distribution of measurement sites along fifteen representative profiles of the town. The goal is to test to what extent microtremor H/V spectral ratios are sensitive to strong lateral variations of nearsurface geology along profiles whose geological structure is mapped in detail. Finally, inferences based on microtremor measurements are compared with earthquake recordings of broad band, high dynamic range seismological stations installed in the urban area of Catania.

2. Geologic setting

The surface geology of Catania is mostly characterized by weathered lava flows. This situation is the result of several Etnean flows that in both pre-historical and historical times

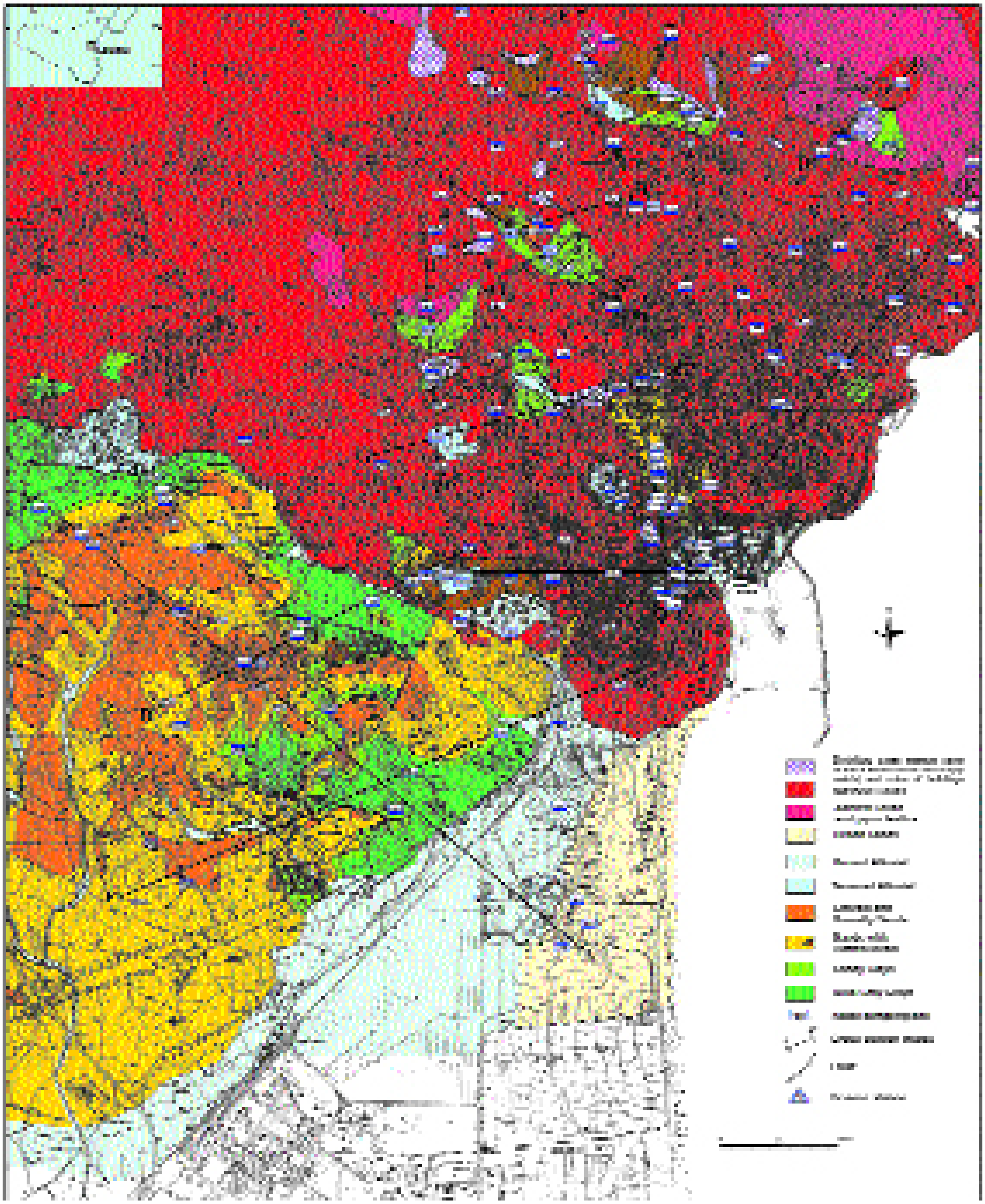

Fig. 1 - Geological map of the area of Catania.

covered the area. The volcanic rocks covered and re-shaped the original morphology of the sedimentary substratum that, at present, outcrops only in small areas in the northern part of the town, whereas it predominates south of the urban area and in the alluvial plane of the Simeto river.

In order to get a reference geo-lithological map, geological information from available wells, surficial surveys and data from the literature were gathered (Kieffer 1971; Catalano et al., 1998; Monaco and Tortorici, 1999). A revised version of the preliminary map presented by Azzara et al. (1999) is shown in Fig. 1. This map includes additional checks of the previous data and new geological observations. The peculiar geo-lithological feature of the area is the complex litho-stratigraphic sequence formed by soft sediments interbedded between a clayey basement (bedrock) and upper volcanic layers composed of lava flows and pyroclastics.

The lowermost levels that characterize the area are a Lower-Middle Pleistocene succession with about a 600 m thick layer of grey-blue marly clays. These clays include thin layers of fine sands that became more frequently interbedded, gradually grading to a sandy clay formation upward.

A sandy formation, several tens of meters thick, unconformably lies upon the sandy clay. The sands are rich in quartz and often include silty layers. In some localities in the surveyed area they also include tuffitic and pumice layers with thickness of a few metres. Intercalations of gravels and conglomeratic lens are often observed especially in the topmost, part of the sandy formation. The gravels and gravely sands constitute the higher part of the sedimentary lithology, and are composed of pebbles of poligenic origin, having a diameter ranging from a couple to about twenty centimetres. They are terraced in some cases while sometimes are etheropic with the sands. We did not investigate this difference in sedimentary formations in detail since we are more interested in the lithological variability of the different terrains present in the Catania area. Similar considerations pertain to the alluvial deposits as well, which are separated into two classes only, terraced or loose alluvium. Loose alluvium is more unconsolidated and thinner than terraced alluvium.

The lava flows that overlay the urban area are generally of basaltic type, often formed by alternating massive lavas and more or less weathered scoriae levels, characterized by an extremely variable thickness of both lithologies. A detailed description of prehistoric and historic lava flows in the area of Catania is given by Sciuto Patti (1872) who performed a “geological survey” when the area was not heavily urbanized as it is at present. Due to the focus of the present study, we were not concerned with the exact temporal sequence of the flows or to their composition, but our goal was rather to discriminate the weathered and/or scoriaceous lavas, called altered lavas, from massive lavas. However, this was not an easy task and we have tried to make this classification by assembling information from a visual survey of both natural and man made scarps, and by collecting descriptions of surveys made by other authors (Catalano et al., 1998; Monaco and Tortorici, 1999; Monaco et al., 2000). It is also important to realize that, due to the different ways the lava can flow and cool over the existing morphology, the youngest lavas are not always fresh and compact. As a consequence of this, the classification adopted in the map is not always unique and, as is described later, some further tests have been made in order to find an explanation for the results obtained from the microtremor measurements on lavas.

Also, horizons of several meters thick detritus outcrop in different zones of the study area. Intentionally, we have mapped as the same unit, slope detritus, archaeological materials, and ruins of buildings struck by the last destructive earthquake of 1693.

3. Methodology

Seismic site response can be assessed in different ways. The experimental methods using earthquake data are used in areas with sufficient seismicity; an alternative approach is numerical modelling of idealized situations. Among the former methods, the spectral ratio technique is very popular using either a reference rock station or taking the horizontal-to-vertical component ratio. In recent times many authors have demonstrated that the H/V spectral ratios from microtremor measurements are consistent in shape with H/V spectral ratios from earthquake recordings, and with earthquake spectral ratios using a reference bedrock station (see Bard, 1999, for an exhaustive review in this issue). Even though there is no unanimous agreement about a theoretical explanation of the observed similarity (Bard, 1999), the use of ambient noise is very attractive because it is both fast and cheap. Moreover, many papers (Arancio and Lombardo, 1986; Koyama et al., 1996; Lachet et al., 1996; Seo, 1998) have shown that sites where amplifications of damage occur during earthquakes are also often characterized by an increase of the microtremor amplitude on the horizontal components. For these reasons, the H/V spectral ratio of microtremors (the Nakamura technique) is widely used for microzoning and engineering purposes. The best performance of the method is achieved when there is a strong velocity contrast between the bedrock and the soft upper layers. Moreover, the features of the layering of sediments itself strongly affect the frequency band and the shape of the dominant peaks in the H/V spectra (Fäh et al., 2001). Because of its sensitivity to spatial variations of nearsurface geology, the method is particularly attractive in urban areas where the nature of the outcropping geological units is masked by anthropic intervention on the surface geology and city growth.

We have applied the conventional Nakamura (1989) technique in the urban area of Catania. More than 200 time histories of microtremors have been recorded at 158 measurement sites. Among them, 144 are aligned along 15 profiles. These profiles were chosen in order to satisfy the twofold purpose of crossing many measurement sites and to reflect the most representative lithological and structural features of the study area. Measurement sites had an average spacing of a few hundred metres. Time histories of ambient noise were recorded using a three-component 1-Hz Mark L4C 3-D seismometer connected to a 12 bit analog-to-digital converter and a PC notebook. Sampling frequency was 100 Hz, two antialiasing filters cut higher frequencies with a 10 db/oct slope. The response curve of the three components was estimated through the output-to-input ratio using sinusoidal voltage inputs in the frequency range 0.1 to 12 Hz.

At each site eight time series were recorded of 60-s length. The time series were base-line corrected in order to remove spurious offsets and low-frequency trends. After the application of a 10% cosine-tapered window, a Fast Fourier Transform algorithm was applied to obtain spectra in a frequency band 0.5 - 15 Hz. The lower limit of 0.5 Hz was assessed through the low-frequency cut off where the microtremor standard deviation becomes equal to the natural noise fluctuation of the 12-bit digitizer. Amplitude spectra of the three components were corrected for their instrumental response. For each time history the amplitude spectrum of the horizontal components was divided by the vertical component spectrum. A running smoothing function of 0.1 Hz was also used, both on the spectra of each single component and on the final ratio, to reduce spectral fluctuations. Finally, the arithmetic average operation provides the mean H/V spectral ratio at each measurement site.

The stability of the adopted processing method was checked by changing the length of the windowed time series (a single time series of 8 minutes or 8 time series of 60 s each). Figs. 2a and 2b depict an example of this test, respectively. No significant differences can be observed in the spectral shapes. Similarly, negligible differences are found by dividing the arithmetic average of the horizontal-component spectra by the arithmetic average of the vertical-component spectra (Fig. 2c). The standard deviation evaluated for H/V spectra at clayey sites produces spectral fluctuations of ± 0.5 units, around mean amplitude values not exceeding 2

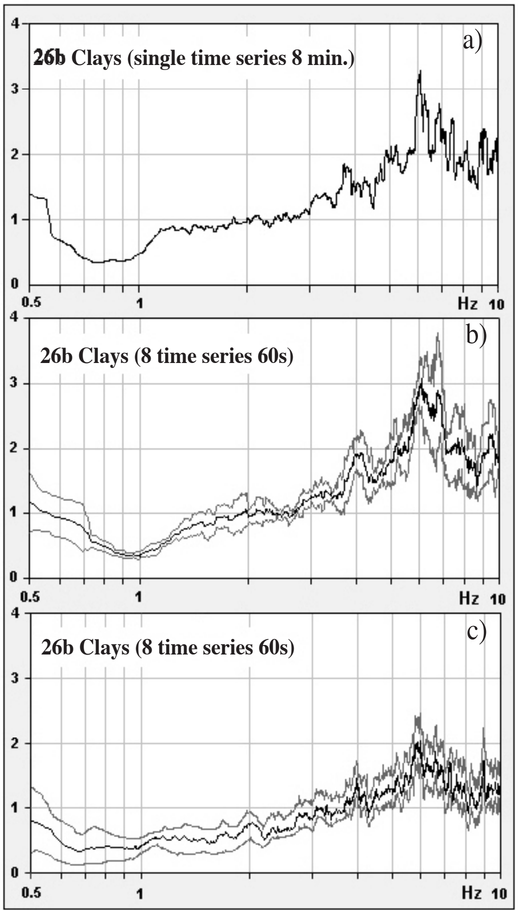

Fig. 2 - Examples of H/V spectral ratios obtained through different methods of analysis: a) spectral ratios obtained by processing a single 8-min time history; b) spectral ratios obtained by averaging the H/V ratios over 8 time histories of 60 s each; c) spectral ratios obtained dividing the average horizontal component spectrum by the average vertical component spectrum, the average being made over 8 time histories of 60 s each. The mean spectral ratio is the dark curve; in (b) and (c) the upper and lower light curves represent the ± 1 standard deviation interval.

units (see the example in Fig. 2). Based on these fluctuations only spectral peaks higher than 3 units were taken into account as statistically significant.

4. Results

Since noise measurements in Catania were made in densely urbanized areas, the preliminary step of our analysis was devoted to a test evaluating to what extent the presence of nearby buildings could affect microtremors in the study area. Three tests were made around tall buildings. One building is five-stories tall and is built on massive lavas; the second one is nine-stories tall and is built on a clay formation; the third building is four-stories tall and is built on gravelly sands. These lithologies predominate downtown Catania. In Fig. 3, the

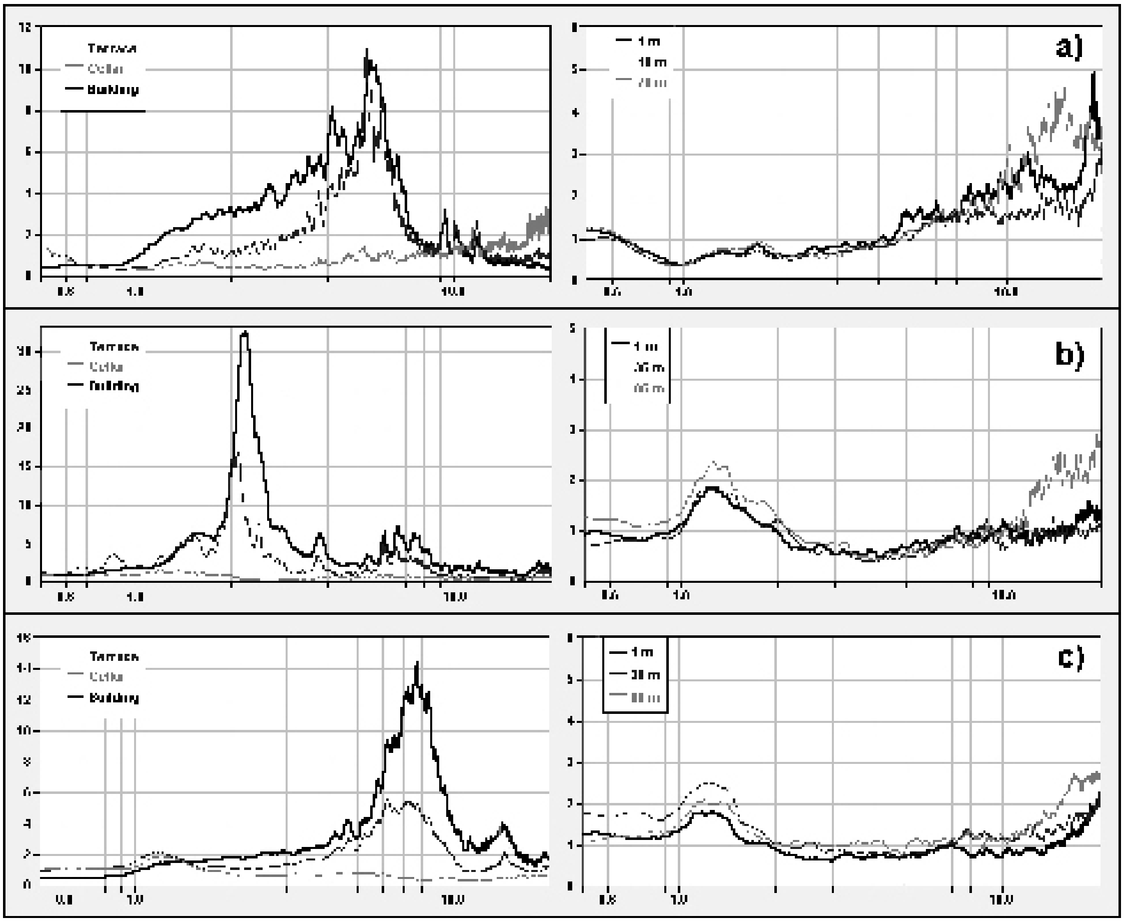

Fig. 3 - H/V spectral ratios on reinforced-concrete buildings: a) five-stories tall building founded on massive lavas (site 32m in Fig. 1); b) nine-stories tall building founded on consolidated clays (site 55m in Fig. 1). c) four-stories tall building founded on gravelly sands (site 38b in Fig. 1). Cellar and Terrace indicate the H/V spectral ratios from measurements performed in the lowest and highest part, respectively, of each building. The thick curve is their spectral ratio: the peak indicates the natural frequency of buildings. The panels on the right-hand side show the result of measurements performed at increasing distance outside of buildings: there is no evidence of soil-structure interaction even at small distances.

measurements performed inside the three buildings (on the left hand side) and at increasing distance from the buildings (right hand side) are shown. The three components of motion were recorded in the lowest floor of each building (cellar) and in the highest part (terrace). The natural frequency of the two buildings was assessed through the ratio $\frac{(H/V)_{terrace}}{(H/V)_{cellar}}$ (thick curve in Fig. 3).

In the three cases of Fig. 3 the natural period of buildings does not significantly contaminate the ground response in the surrounding area. Measurements were performed installing instruments at increasing distances perpendicularly to the larger side of each building. Independently of the terrain lithology, measurement results show dominant peaks significantly different from the building’s natural frequencies (Fig. 3). This suggests that soil-structure interaction does not affect, at least in these observations, the peak response at sites. This observation is particularly important since the microtremor data recorded in the historical part of Catania could have been affected by interference of surrounding man-made structures. However, all measurements inside buildings were performed in the lowermost structural level and, when available, inside cavities at archaeological sites (e.g., underground circle of the Roman theatre, catacombs of ancient churches, Roman and Greek age thermae). The resulting microtremor H/V spectral ratio along the selected geo-lithological cross-sections are plotted in Figs. 4-7. The fifteen profiles were reconstructed on the basis of the geological data used to draw Fig. 1, with the addition of information about the layer thickness obtained from available well data. Figs. 4-7 do not show evident strong differences in the H/V spectral ratios within the urban area. The microtremor H/V spectral ratios at sites located on clay, which constitute the bedrock of the area, show practically a flat shape in the frequency band 2-10 Hz. Surprisingly, a similar behaviour is observed even for many sites located on the sandy clay lithotypes as well as on sand and gravel. In the same frequency band, 27 sites show an H/V amplitude equal or higher than a threshold of 3; the largest part of them is classified as detritus, terraced alluvial, and both massive and weathered lava. Amplifications usually are in the frequency band from 6 to 10 Hz.

5. Interpretation of results and comparison with earthquake data

The general features of the microtremor measurements in the urban area of Catania indicate a complex situation. However, some systematic behaviour can be recognized.

First, the general tendency of sites on massive lavas is not to show particularly enhanced frequency peaks (sections H-H', M-M', N-N', O-O' and P-P’), however contrasting effects are observed in other sites having an apparently similar lithology (see sections B-B', F-F', L-L' and Q-Q'), where a tendency for amplifications to peaks of near 6-7 Hz is observed. To further investigate this ambiguity microtremors were recorded at natural or man-made scarps, where it was easy to identify the presence of either massive or weathered lavas. The results (e.g., see Fig. 8) confirm that massive lavas are characterized by a substantially flat H/V spectrum as expected,

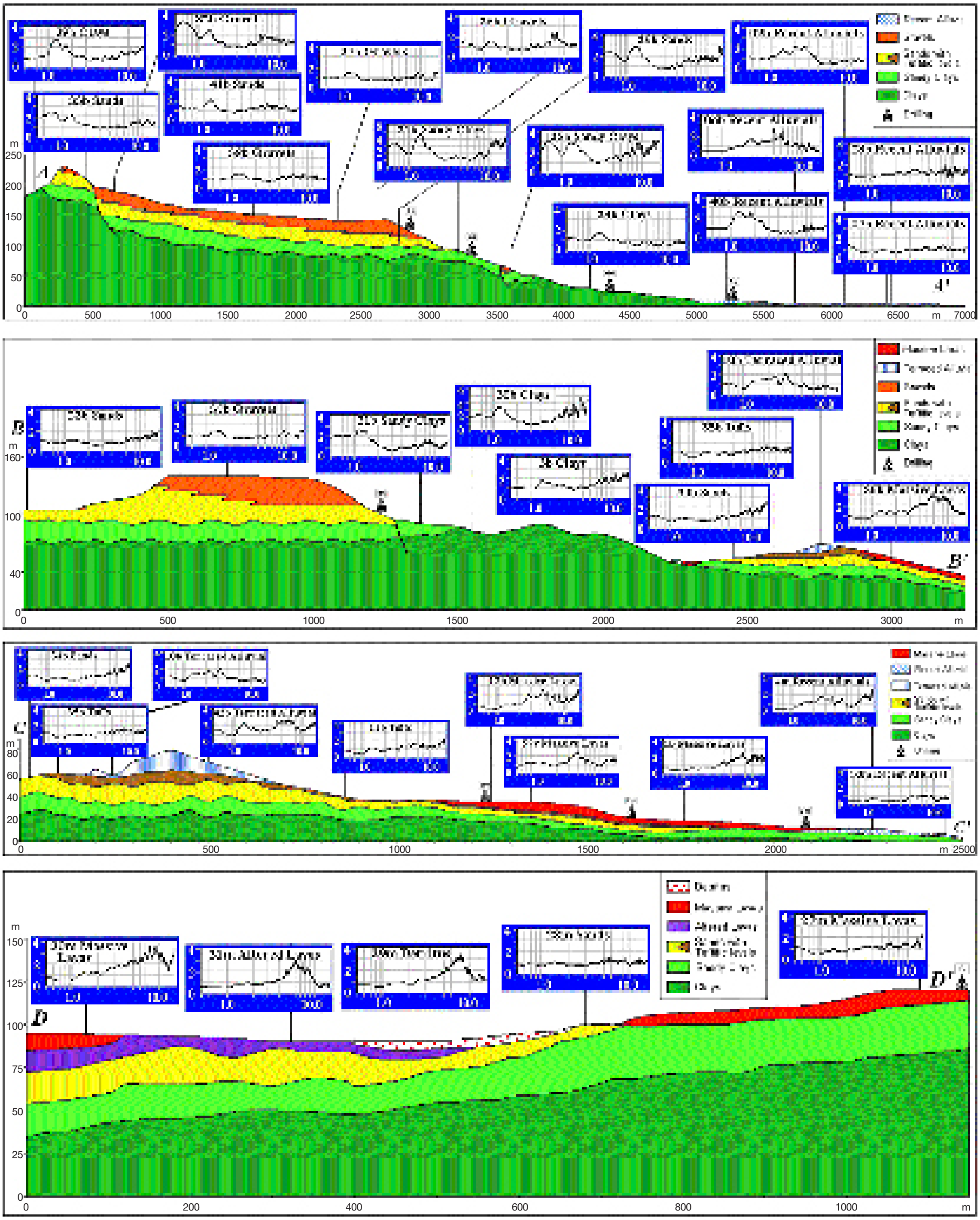

Fig. 4 - Geo-lithological cross-sections of profiles AA', BB', CC', and DD' (Fig. 1) and resulting H/V spectral ratios at measurement sites.

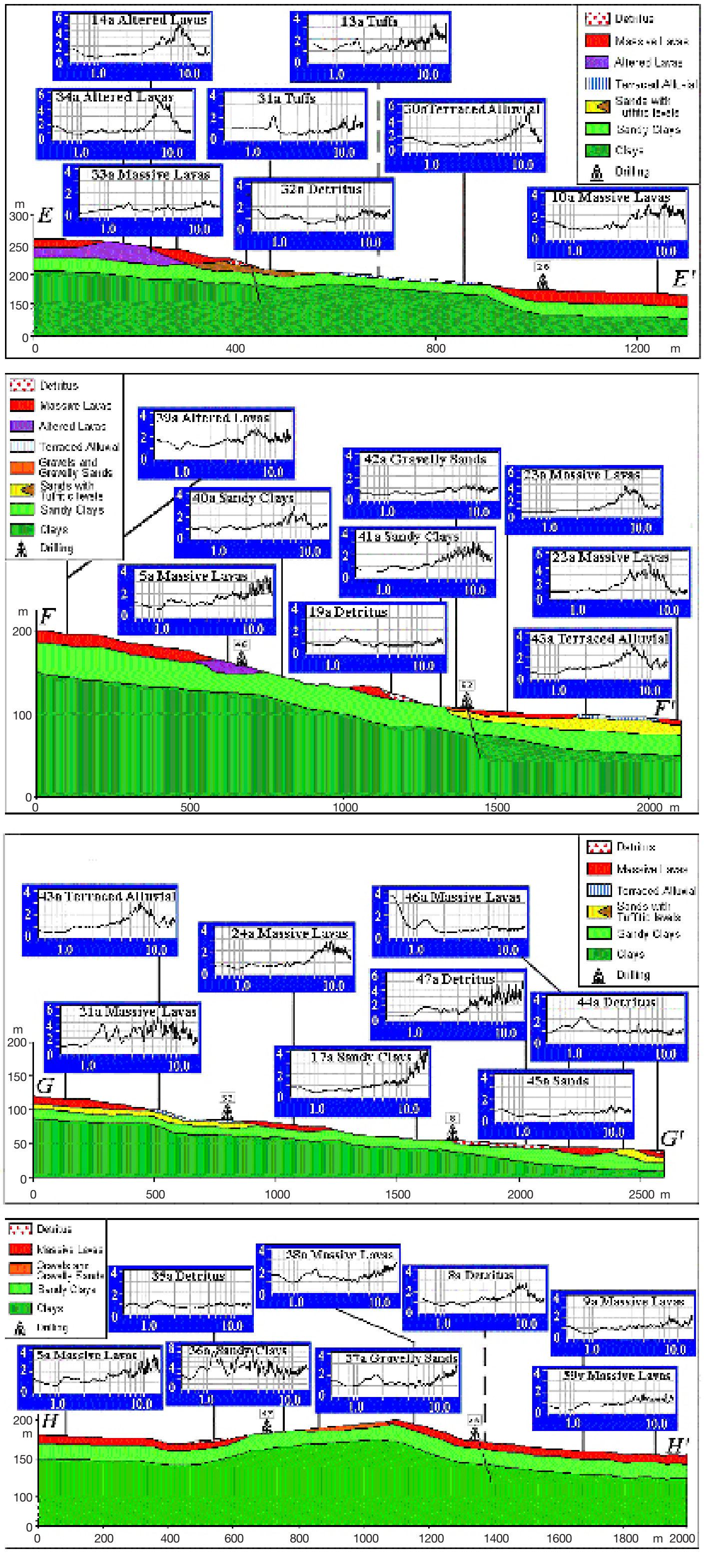

Fig. 5 - Geo-lithological cross-sections of profiles EE', FF', GG', and HH' (Fig. 1) and resulting H/V spectral ratios at measurement sites.

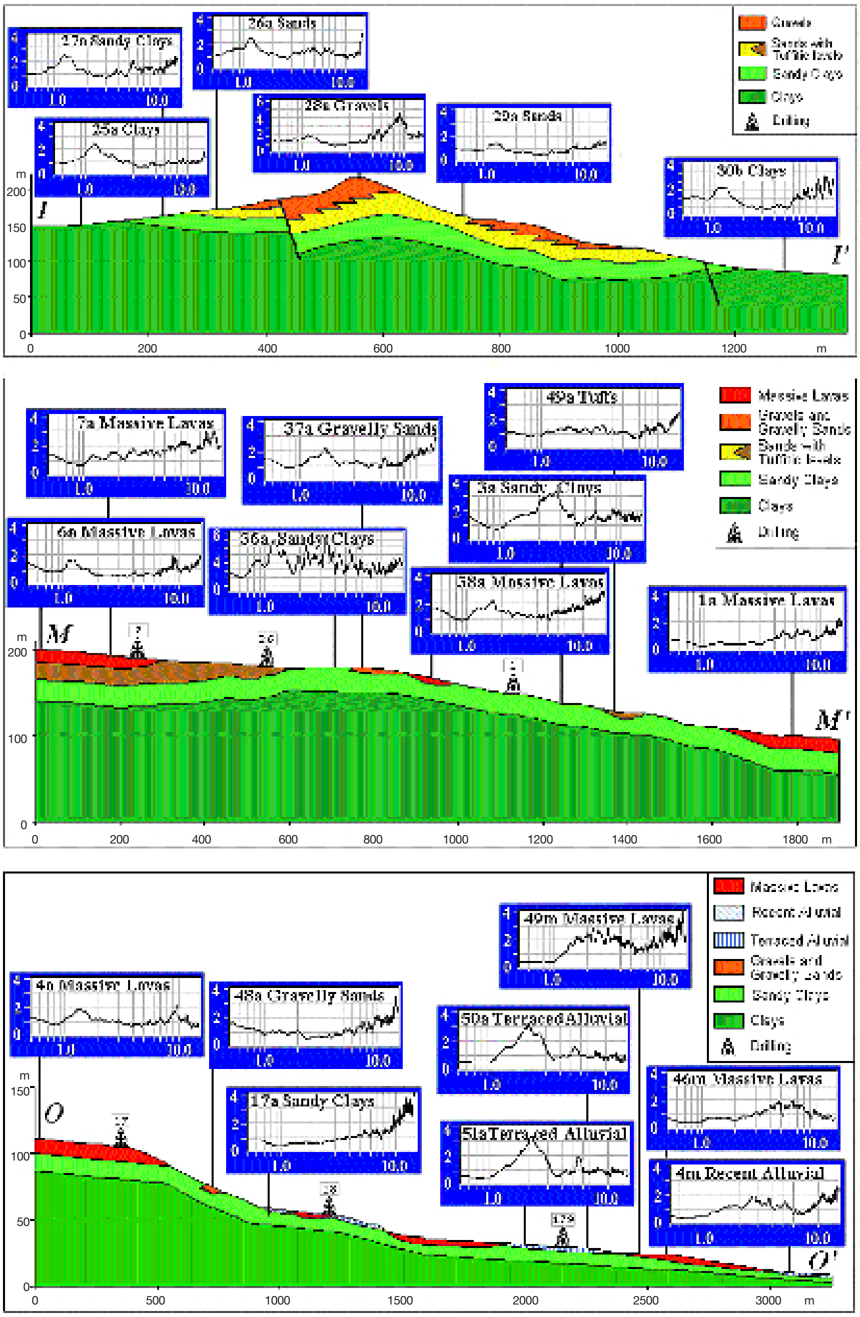

Fig. 6 - Geo-lithological cross-sections of profiles II', MM', and OO' (Fig. 1) and resulting H/V spectral ratios at measurement sites.

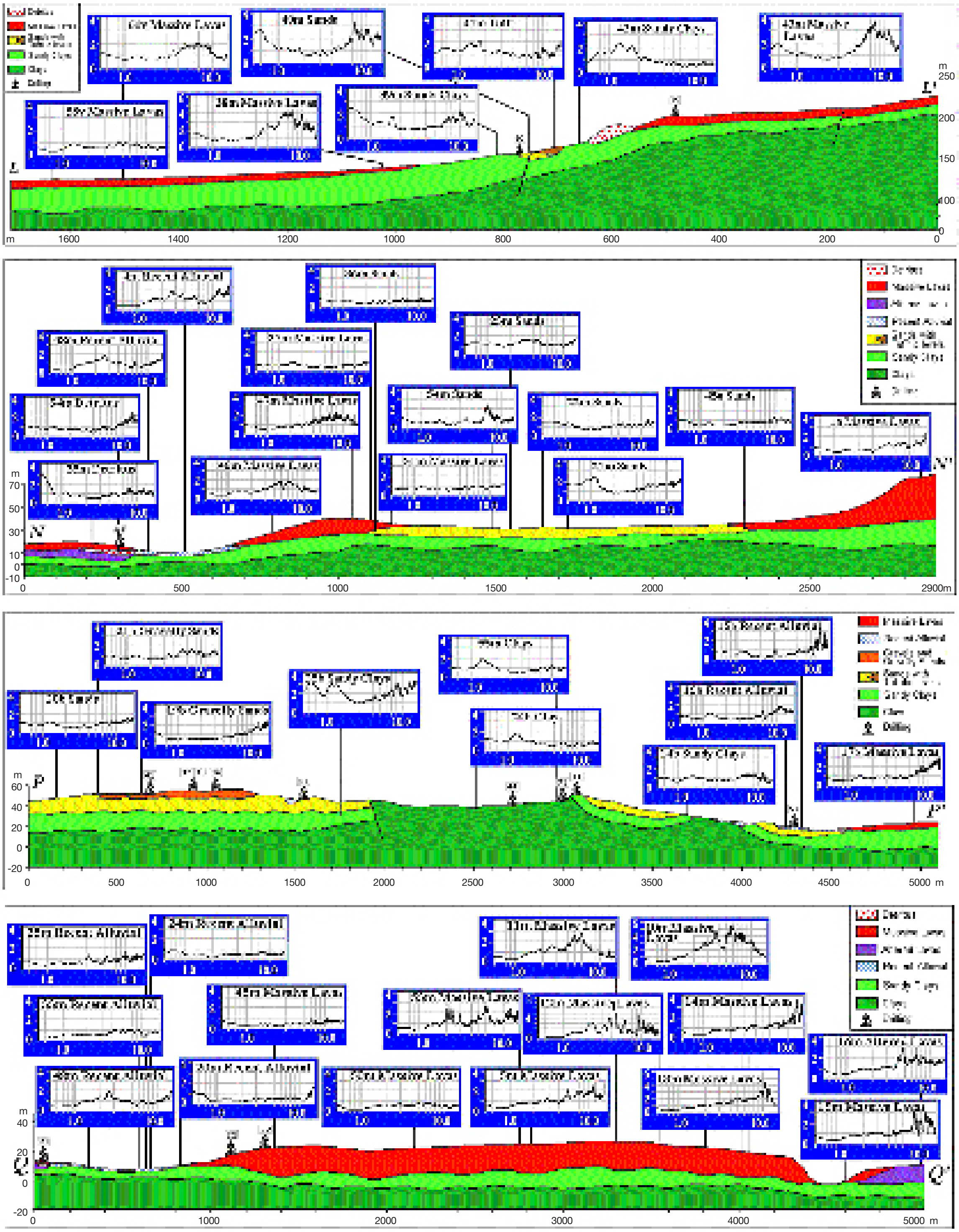

Fig. 7 - Geo-lithological cross-sections of profiles LL', NN', PP', and QQ' (Fig. 1) and resulting H/V spectral ratios at measurement sites.

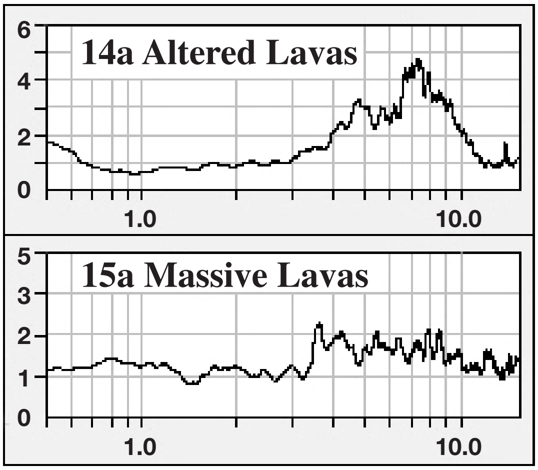

Fig. 8 - Examples of H/V spectral ratios obtained from microtremor measurements performed in test sites where massive or weathered lavas are unequivocally identified.

whereas the spectral ratios on weathered lavas show amplifications in the frequency band 6 to 10 Hz. Moreover, data from available mechanical sounding and down-hole measurements show that in areas mapped as massive lavas at the surface, lack of velocity homogeneity, indicating buried weathered lavas, is frequently observed (Fig. 9b). This observation supports the need for a multidisciplinary approach including both surficial geological surveys and geophysical and geotechnical measurements.

At soft sites, amplification of the microtremor H/V spectral ratios tend to be smaller than those usually reported in the literature for similar soils. The only exceptions are observed in sites located on detritus (sections DD', GG', and HH') where amplifications in the frequency range 7 - 8 Hz are found, and on terraced alluvial (sections EE', FF', and OO'), where there is a tendency to amplify at 2 Hz and 8 - 10 Hz. However, in this study soft site measurements were not performed in alluvial valleys or similar situations with a high impedance contrast. The available downhole data (Fig. 9a) indicate that shear-wave velocities range from 300 to 500 m/s from the top of the sedimentary sequence (gravel) to the uppermost part of the clayey basement. A moderate impedance contrast of sand and gravel deposits with respect to the basement clay formations may lie hypothesized as a possible explanation for the diffuse low-amplitude H/V spectral ratios at soft sites.

Another interesting feature, that is common to several H/V spectra, is the amplification in the range of frequencies between 1 and 2 Hz. It is particularly evident in almost all of the cross sections in the southern part of the studied area (AA', BB', II', PP'), where sedimentary layers are extensively present.

A final test is based on the comparison between microtremor and earthquake recordings. In the framework of an agreement between INGV and the Department of Geological Science of the University of Catania, ten sites were instrumented with broad-band seismometers in the urban area. Six of them (see Fig. 1) lie along or near the profiles investigated in this study. Stations 1, 2, 3, and 5 are located on sedimentary formations while station 4 is sited on lava and pyroclastic

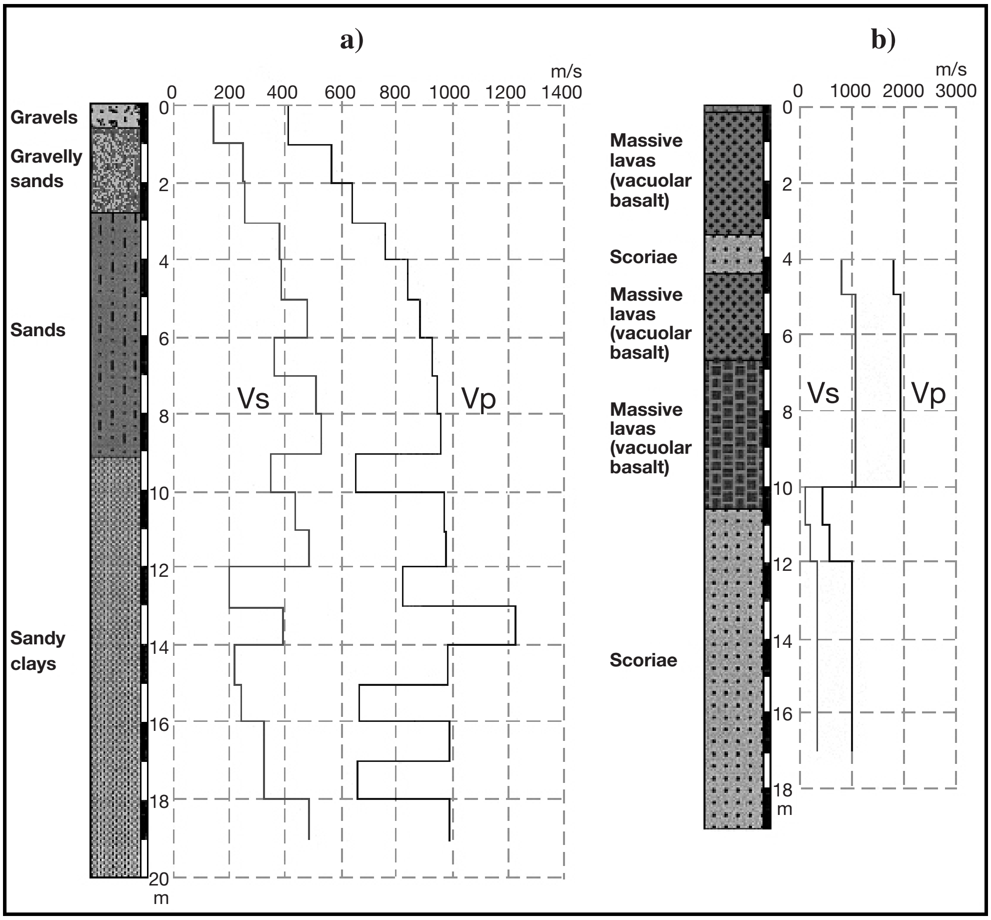

Fig. 9 - Stratigraphy and down-hole in situ measurements of P and S wave velocities in two wells: a) sedimentary formation, b) lava flow.

materials. Station 6, located on massive lavas overlaying the clay formation, was chosen as the reference site.

The continuous recordings of the permanent stations are used both to validate the microtremor results at nearby measurement sites along the profiles and to compare earthquake with microtremor results.

In Fig. 10 the results obtained through the analysis of microtremors recorded by portable stations, using short duration (8 min) measurements (red curves), are compared with the H/V spectral ratios averaged over a 1-day microtremor acquisition at the permanent stations. The black and blue curves represent the upper and lower bound of 1 standard deviation around the mean spectral ratio, respectively. In general, moving and permanent station measurements provide similar microtremor results and do not show systematic variations that could be related with the receiver type, measurement duration, and processing algorithm. The small differences that are observed for stations 1 and 5 can be ascribed to the different smoothing between spectra of portable stations and spectra of permanent ones. The high frequency behaviour of station 5 is probably due to the large distance (300 m, approximately) between the permanent

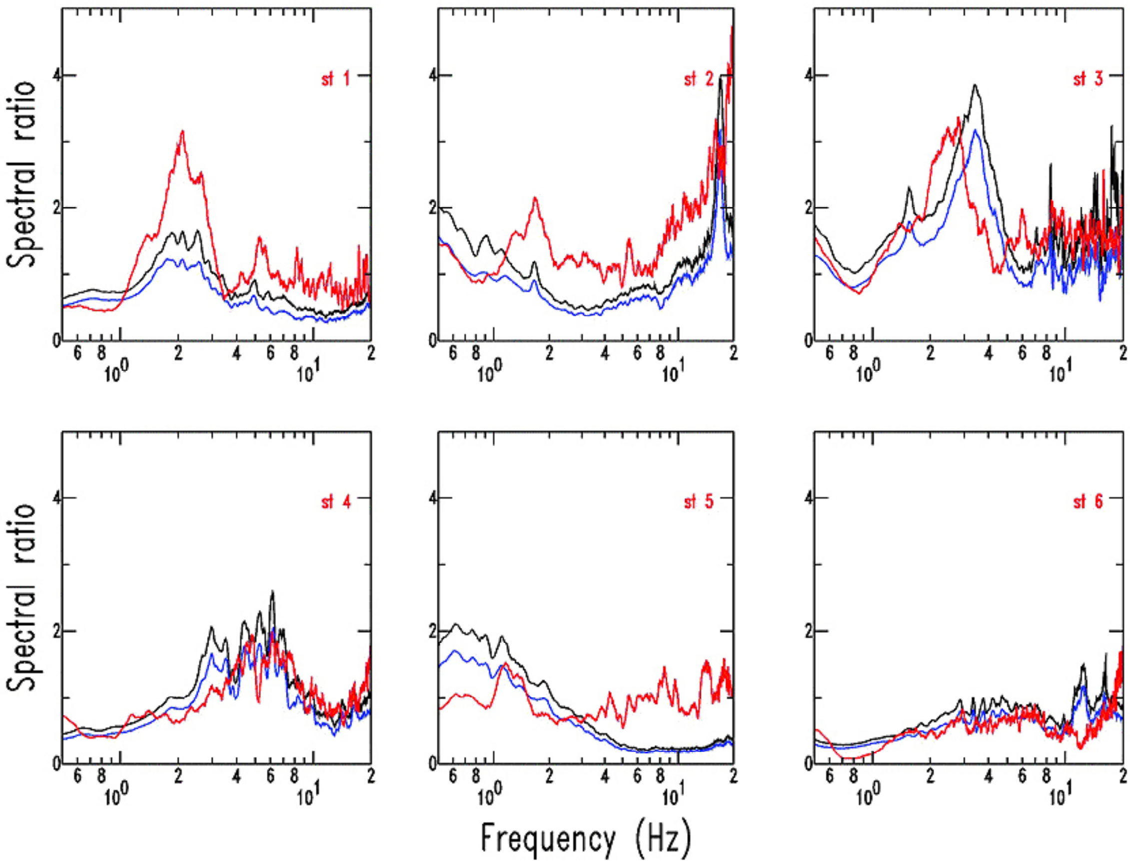

Fig. 10 - Microtremor H/V spectral ratios estimated at fixed stations (numbers from 1 to 6 refer to the location of stations shown in Fig. 1) compared with moving station microtremor measurements. The blue and black curves represent ± 1 standard deviation of the mean spectral ratio averaged over a 1-day acquisition; red curves are relative to 8-min measurements.

station and the moving measurement site. This station is sited on gravelly sands. This lithotype is characterized by a pronounced lateral heterogeneity, and this can significantly affect the shape of the H/V spectra. However, the generally good agreement suggests stability of the results that are presented in Figs. 4-7.

In addition to the permanent station microtremor results, H/V spectral ratios computed from earthquake recordings are plotted in Fig. 11. These curves (red lines) are from the average over two earthquakes that had the best signal-to-noise ratio at each station. Three of the fixed stations (n. 1, 3, and 6) show a fairly good agreement between microtremor and earthquake H/V spectral ratios. For the remaining stations the disagreement is limited to specific frequency bands: for instance, at station 5 the microtremor trend is substantially flat while the H/V spectral ratio shows a pronounced peak around 3 Hz when earthquake data are used. A larger disagreement with microtremor results is found when the horizontal component spectra of stations 1 to 5 are divided by the horizontal component spectrum of station 6 that is used as the hard-site reference station. These conventional reference-station spectral ratios are shown as green curves in Fig. 11. This figure indicates that sedimentary formations and lava-pyroclastic terrains have ground

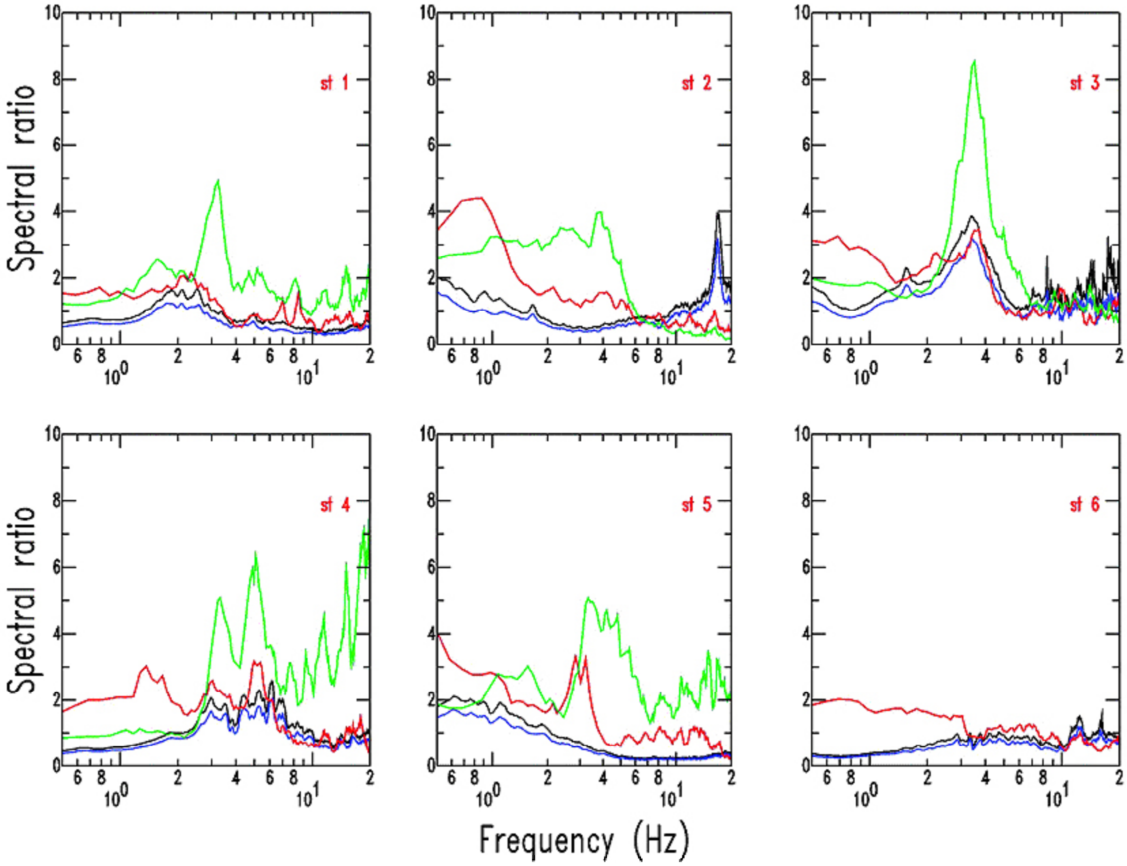

Fig. 11 - Microtremor H/V spectral ratios estimated at fixed stations (the blue and black curves represent ± 1 standard deviation of the mean spectral ratio averaged over a 1-day acquisition) are compared to earthquake H/V spectral ratios (red curves). For stations from 1 to 5 spectral ratios referred to a massive lava site (station 6) are overimposed (green curves).

motion amplitudes during earthquakes that are systematically larger than those of the massive lava reference site. Only at station 3 is the frequency band of earthquake amplification fit well by microtremors, with a spectral ratio larger than 3. A rough similarity between the earthquake amplification and microtremor H/V spectral ratios is found for station 1 but the peak frequency has shifted from 2 to greater than 3 Hz. For station 4 there is a fair agreement in shape but the microtremor H/V spectral ratio only attains a factor of 2, that is less than the statistical significance. For stations 2 and 5 microtremors do not predict any amplification. Both these sites are on gravelly sands, that are not characterized by a high velocity contrast and do not represent the optimal conditions for the application of the Nakamura technique (see also Fäh et al., 2001).

Of course, such a preliminary earthquake data analysis is not enough to get stable conclusions about the earthquake shaking effects and decide to what extent sediments amplify or lavas deamplify. However, we have verified that the earthquake amplification observed in the spectral ratios at stations 1 to 5 are not due to spectral holes of the reference station, confirming the presence of peaks in the horizontal component spectra, at the five analyzed sites.

6. Conclusions

Microtremor H/V spectral ratios have been computed along 15 profiles crossing the most representative lithologies of the urban area of Catania. The average spacing between measurement sites was a few hundred metres.

After a careful reconstruction of the 2D geological structure beneath the selected profiles, an attempt has been made to interpret variations of microtremor H/V spectral ratios in terms of the local site geology. The experimental results indicate that, in general, the correlation of spectral shapes with nearsurface geology is poor since it is not always able to separate the geology on the basis of a rough classification into two (hard and soft) site categories. This can be interpreted as a consequence of the moderate shear wave velocity contrast between soft sedimentary formations and the clayey basement. Even though there is a tendency for lava sites to have H/V spectral ratios around unity, in many cases a significant amplification is observed in the frequency band between 7 and 10 Hz. This observation is independent of geometry, age and chemical composition of the lava flows, but is systematically found when the upper lava layers have a high percentage of interbedded scoriaceous levels. In contrast, at soft sites the microtremor H/V spectral shapes do not frequently produce peaks that are greater than 3. Only at sites located on detritus and terraced alluvial, a tendency to amplifications in the frequency range 7 - 10 Hz is observed.

As a general conclusion, it seems that the Nakamura technique has to be carefully tested before intensive applications for microzoning purposes and engineering studies in the urban area of Catania are made. At a very preliminary step of the analysis, a comparison with results obtained from individual earthquake recordings indicates that large variations of the horizontal ground motion can occur between sites that differ by no more than a factor of 2 in the microtremor H/V spectral ratios. However, a much larger number of earthquake records is needed to reach stable conclusions.

References

AGIP; 1977: *Temperature sotterranee*. F.lli Brugora, Milan, Italy.

Arancio S. and Lombardo G.; 1986: *Elementi di microzonazione sismica dell'area dello Stretto di Messina*. Boll. Soc. Geol. It., **105**, 87-98.

Azzara R., Coco G., Corrao M., Imposa S., Lombardo G., Rovelli A. and Scamarda G.; 1999: *Valutazioni preliminari sulla risposta sismica nell'area urbana del comune di Catania*. In: XVIII Convegno Nazionale GNGTS, Rome, Italy, pp. 234-236.

Azzaro R. and Barbano M.S.; 2000: *Analysis of the seismicity of Southeastern Sicily: a proposed tectonic interpretation*. Annali di Geofisica, **43**, 171-188.

Bard P.Y.; 1999: *Microtremor measurements: a tool for site effect estimation?* In: Irikura K., Kudo K., Okada H. and Sasatani T. (eds), The Effects of Surface Geology on Seismic Motion, Balkema, Rotterdam, pp. 1251-1279.

Catalano S., De Guidi G., Di Grande A., Giandinoto V., Gresta S., Monaco C., Scamarda G. and Tortorici L.; 1998: *Il contributo della geologia per la definizione del rischio sismico in aree urbane: l'esempio di Catania e Augusta (Sicilia orientale)*. LXXIX Congresso Nazionale della Società Geologica Italiana, Palermo, Italy.

Cosentino M., Fallico F. and Lombardo G.; 1984: *Approccio alla microzonazione sismica dell'area di Catania*. In: III Convegno Nazionale GNGTS, Rome, Italy, pp. 781-797.

Faccioli E. and Pessina V.; 2000: *The Catania Project: earthquake damage scenarios for high risk area in the Mediterranean*. In: CNR - Gruppo Nazionale per la Difesa dai Terremoti, 225 pp.

Fäh D., Kind F. and Giardini D.; 2001: *A theoretical investigation on H/V ratios*. Geophys. J. Int., **145**, 535-549.

Giampiccolo E., Gresta S., Langer H., Mucciarelli M. and Gallipoli M.R.; 1999: *Risposta di sito nell'area urbana di Catania, mediante l'utilizzo di dati sperimentali e simulazioni numeriche*. In: XVIII Convegno Nazionale GNGTS, Rome, Italy, pp. 781-797.

Giampiccolo E., Gresta S., Mucciarelli M., De Guidi G. and Gallipoli M.R.; 2001: *Information about subsoil geological structure in the city of Catania (Eastern Sicily) from microtremor measurements*. Annali di Geofisica, **44**, 1-12.

Kanai K. and Tanaka T.; 1961: *On microtremors*. Bull. Earthquake Res. Inst., **39**, 97-114.

Katz L.J.; 1976: *Microtremor analysis of local geological conditions*. Bull. Seism. Soc. Am., **66**, 45-60.

Kieffer G.; 1971: *Depots et niveaux marins et fluviatiles de la regione de Catane (Sicile)*. Mediterranee, **5-6**, 591-626.

Koyama S., Okawa I., Kashima T. and Kitagawa Y.; 1996: *Characteristics of ground motion in Kobe area*. In: Proc. of the X World Conf. Earthq. Eng., Acapulco, Mexico. Elsevier Sci. Ltd., 1070 pp.

Lachet C., Hatzfeld D., Bard P.-Y., Theodulidis N., Papaioannou C. and Savvaidis A.; 1996: *Site effects and microzonation in the city of Tessaloniki (Greece). Comparison of different approaches*. Bull. Seism. Soc. Am., **86**, 1692-1703.

Langer H., Catalano S., Cristaldi M., De Guidi G., Gresta S., Monaco C. and Tortorici L.; 1999: *Strong ground motion simulation in the urban area of Catania on the basis of a detailed geological survey*. In: Oliveto G. and Brebbia C.A. (eds), Earthquake Resistant Engineering Structures, WIT Press, pp. 343-352.

Lombardo G.; 1985: *Approach to the seismic microzoning of the area of Librino (Catania, Italy)*. Boll. Geof. Teor. Appl., **27**, 25-40.

Lombardo G.; 1987: *Applicazione di metodologie di microzonazione sismica in alcune aree della Sicilia orientale*. In: Boschi E. (ed), Aree Sismogenetiche Rischio Sismico in Italia, Galileo Galilei, Lausanne, pp. 463-482.

Monaco C. and Tortorici L.; 1999: *Carta geologica dell'area urbana di Catania*. S.E.L.C.A., Firenze, Italy.

Monaco C., Catalano S., De Guidi G., Gresta S., Langer H. and Tortorici L.; 2000: *The geological map of the urban area of Catania (Eastern Sicily): morphotectonic and seismotectonic implications*. Mem. Soc. Geol. It., **55**, 425-438.

Nakamura Y.; 1989: *A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface*. Q.R. Railway Tech. Res. Inst., **30**, 25-33.

Priolo E.; 1999: *2-D spectral element simulations of destructive ground shaking in Catania (Italy)*. J. Seism., **3**, 289-309.

Priolo E.; 2000: *2-D spectral element simulations for a catastrophic earthquake*. In: Faccioli E. and Pessina V. (eds), The Catania Project: earthquake damage scenarios for high risk area in the Mediterranean, In: CNR-Gruppo Nazionale per la Difesa dal Terremoti, pp. 67-83.

Priolo E., Michelini A., Laurenzano G., Addìa R. and Puglia A.; 2001: *Seismic response from microtremors in Catania (Sicily, Italy)*. Boll. Geof. Teor. Appl., **47**, 337-362.

Scandone P., Patacca E., Meletti C., Bellatalla M., Perilli N. and Santini U.; 1992: *Struttura geologica, evoluzione cinematica e schema sismotettonico della penisola italiana*. In: Atti Convegno Nazionale GNDT, Pisa, Italy, 25-27 June 1990, **1**, pp. 119-135.

Sciuto Patti C.; l872: *Carta geologica della città di Catania e dintorni di essa*. Atti Accademia Gioenia Sc. Nat., **3**, 23-52.

Seo K.; 1998: *A joint microtremor measurement in the Fukui basin to discuss the effects of surface geology on seismic motion during the 1948 Fukui, Japan, earthquake*. In: Proc. of the XI Europ. Conf. Earthq. Eng., Paris, France, Balkema Ltd., 12 pp.