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Information on subsoil geological structure in the city of Catania (Eastern Sicily) from microtremor measurements

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Abstract
Nakamura's technique, or the H/V spectral ratio method, has been applied to microtremor measurements carried out in the urban area of Catania (Eastern Sicily) to obtain information on the geological structure of some sites, and to make a hypothesis on their seismic response. In general, sites located on soft soils or anthropic debris fillings have shown greater amplification at high frequencies (above 1 Hz). However, a strong lateral variation was observed in the frequency band, thus a denser grid of measurement points is necessary for a precise mapping of the resonant frequencies. In the low frequency range, between 0.1 and 1 Hz, a common peak around 0.2 Hz was observed. The fundamental resonant frequency inferred from the main peak in the H/V spectrum has been used to calculate the depth of the interface between the clays and the main reflector on the basis of the shear-wave velocity: it has been estimated as about 700 m.

Key words *Catania (Eastern Sicily) – microtremors – H/V technique – site response – subsoil geological structure*

1. Introduction

Local site conditions are widely recognized as an important factor in the distribution of earthquake damage in urban areas. Very efficient trapping of energy in basins and/or focusing of seismic waves by irregular interfaces and topographies lead to significant spatial variations of ground motion in both amplitude and duration.

Among the many approaches to the site-effect estimation, an empirical trial is to use ambient seismic noise measurements. The application of microtremors to seismic zonation has been investigated since the early works of Kanai and Tanaka (1961) and Katz (1976) either through direct interpretation of Fourier amplitudes and power spectral density, or using computation of spectral ratios relative to a firm site reference station (Otha *et al.*, 1978; Kagami *et al.*, 1982, 1986; Field and Jacob, 1990). A further method which was first applied by Nogoshi and Igarashi (1970, 1971) and popularized by Nakamura (1989), is based on computation of spectral ratios between the horizontal components of motion and the vertical component obtained at the same site.

When applying the H/V spectral ratio method to noise data, it is assumed that the micro-

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tremor energy consists mainly of Rayleigh waves (Nogoshi and Igarashi, 1971; Lachet and Bard, 1994; Kudo, 1995) and that the site-effect amplification is due to the presence of a soft surficial soil layer overlying a half-space. The simplicity of this practice allows the sampling of many sites within alluvial fans or basins. Several applications of this technique have proved to be effective in estimating fundamental frequency of surficial soil layers (*e.g.*, Field and Jacob, 1993; Yamanaka *et al.*, 1994; Ohmachi *et al.*, 1994; Mucciarelli, 1998) or even building fundamental modes (*e.g.*, Mucciarelli and Monachesi, 1999; Mucciarelli *et al.*, 1999). The estimation of amplification factors was also attempted (*e.g.*, Lermo and Chavèz-Garcia, 1994; Konno and Ohmachi, 1995). Moreover, recent observations (*e.g.*, Ibs-von Seth and Wohlenberg, 1999) show that Nakamura's technique is the most suitable method to determine the thickness of soft cover layers from the measured resonant frequency of the main peak in the H/V spectrum, on the basis of the shear-wave velocity. This correlation is valid for a wide range, from tens of meters to more than 1000 m (Ibs-von Seth and Wohlenberg, 1999; Bodin and Horton, 1999). The application of microtremors for this purpose was initiated by Kanai and Tanaka (1961), who studied microtremors in a period range of less than 1 s and found a good correlation between the thickness of sediments and the predominant period of microtremors. A similar correlation was proposed by Otha *et al.* (1978) for the analysis of long-period microtremors (1-5 s). Conversely, Kagami *et al.* (1982) did not find any significant variation in the predominant period of long-period microtremors in relation to the thickness of the soil deposit in Niigata (Japan) or in the Los Angeles basin (U.S.A.). Further works, however, support the observation that microtremors can be used to infer information on thickness of cover layers (Tucker and King, 1984; King and Tucker, 1984; Field and Jacob, 1990; Morales *et al.*, 1991; Yamanaka *et al.*, 1994; Ibs-von Seth and Wohlenberg, 1999; Bodin and Horton, 1999). In this study we applied the horizontal to vertical ratio technique (HVSR) in the urban area of Catania (Eastern Sicily) to investigate the potential effects of local site conditions on seismic ground motion and to test the capability of microtremors in determining the subsurface structure.

A discussion of the experimental aspects relevant to the measurements like those presented here is given in Mucciarelli (1998) and for sake of brevity will not be reported here.

2. The geology of Catania

The area investigated is located in the southeastern part of Sicily where the seismic potential is not well known but rather high. Several centers of seismic activity are well described all around the city in the catalogue of historical data (*i.e.*, Boschi *et al.*, 1995). The most severe damage was produced by the 1169 and 1693 earthquakes which in Catania reached a IX MCS intensity. Understanding the seismic response in and around the city of Catania is thus important.

The geological setting of Catania is the result of three combined effects related to: i) the volcanic and tectonic processes; ii) the Late Quaternary sea-level changes, and iii) human activity. The backbone of the urban area (figs. 1 and 2) is represented by a sedimentary slope carved by a flight of marine terraces. This substratum is made up of a Lower-Middle Pleistocene succession (Wezel, 1967) consisting mainly of up to 600 m thick marly clays which, in the top 10 m, evolve to coastal sands and fluvial-deltaic conglomerates. These strata are covered by terraced deposits of coastal alluvial or marine origin (Kieffer, 1971; Chester and Duncan, 1982).

The sedimentary substratum is dissected by entrenched valleys filled with lava flows, which form the most representative rocks outcropping in the city. The lava flows consist mainly of basaltic material that, on its way downhill from Mt. Etna, invaded the urban area in prehistorical and historical times (*e.g.*, 252, 1381, 1669 A.D.), repeatedly modifying the geology of the area. In the ancient part of the city the uppermost stratigraphic horizons are represented by several meters of «detrital material», *i.e.*, the material of buildings destroyed by the 1693 earthquake. The resulting geological framework is thus strongly featured by both vertical and lateral heterogeneity.

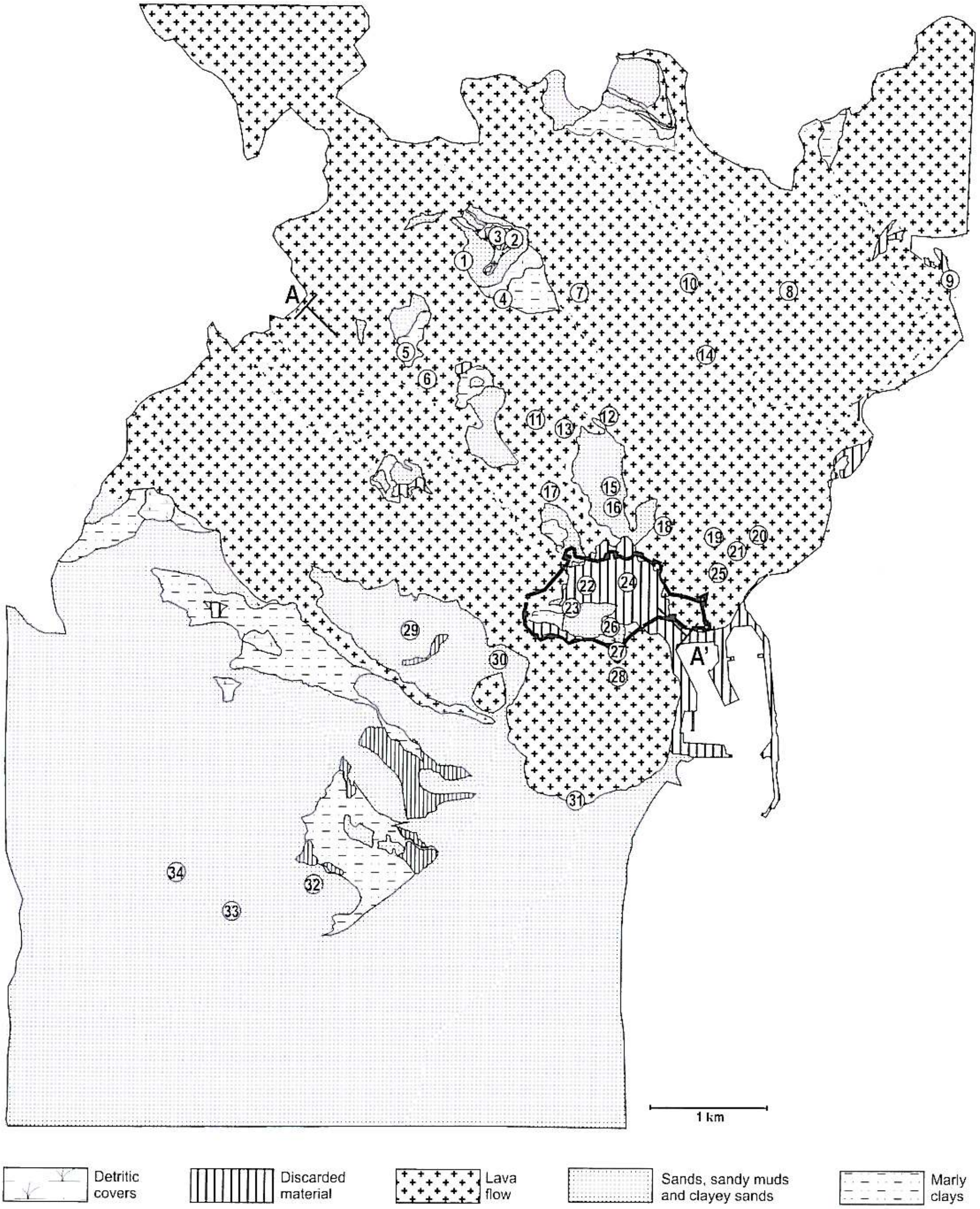

Fig. 1. Geological overview of the study area (Monaco *et al.*, 2000). Locations of sites where microtremor measurements were performed (white numbered circles) are also reported. A-A′: trace of the cross section shown in fig. 2.

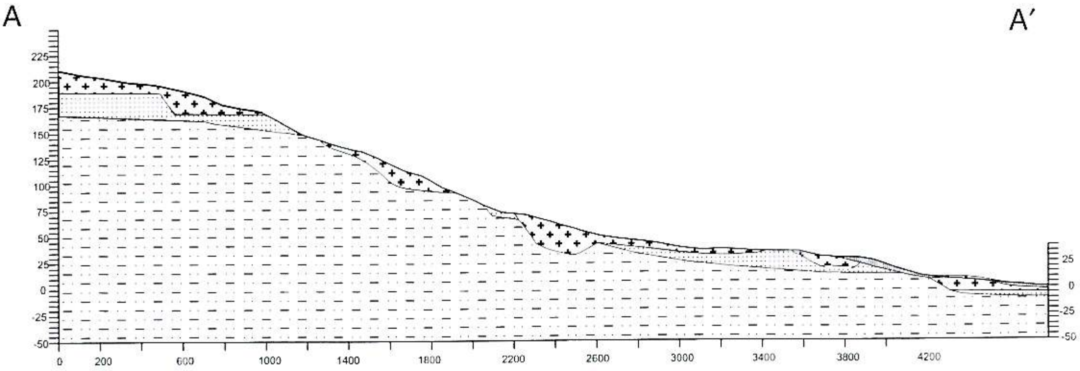

Fig. 2. Cross section showing the main geological units outcropping in and around the city of Catania (after Monaco *et al.*, 2000).

Many geotechnical and geophysical data are available for the urban area of Catania (Catalano *et al.*, 1998). The typical geophysical parameters of the subsurface and deep geological units are listed in table I. The subsurface geology varies from site to site, whereas the parameters of deeper units are supposed to be constant across the area.

3. Observation and instruments

Microtremor measurements were carried out at the ground surface of 34 sites that would best differentiate ground motion on the major geologic units in the city (fig. 1). Many of them were made in coincidence or very close to drilling sites where detailed information on the subsurface structure, for example the thickness of sedimentary and volcanic covers, are available (fig. 3).

The noise signals were recorded with a tridirectional sensor Lennartz 3D-Lite (1 Hz frequency), connected with a 24 bit digital acquisition unit PRAXS-10 and a personal computer board 486 (100 MHz). The sensor has the same characteristics on the three axes. Great care was taken to avoid problems that may arise during *in situ* measurements in a town, such as environmental factors (*e.g.*, wind, sea), anthropic noise, concrete or asphalt coverings and soil-structure interaction.

Table I. Geophysical parameters of subsurface layers and deeper units.

Subsurface layers	
Layer	*S-velocity*
Lavas	1000 m/s
Sands	400 m/s
Terraces/alluv.	300 m/s
Detritic	100 m/s
Deeper units	
Layer	*S-velocity*
Clay	600 m/s
Claystone	1500 m/s
Marls	1700 m/s
Limestone	2600 m/s
Basement	3500 m/s

The site transfer functions were computed as follows. First, a set of at least 5 and a maximum of 15 time series of 60 s each, sampled at 125 Hz, were recorded. Time series were corrected for the base-line and for anomalous trends, tapered with a cosine function to the first and last 5% of the signal, and bandpass filtered from 0.1 to 20 Hz, with cut off frequencies at 0.05 and

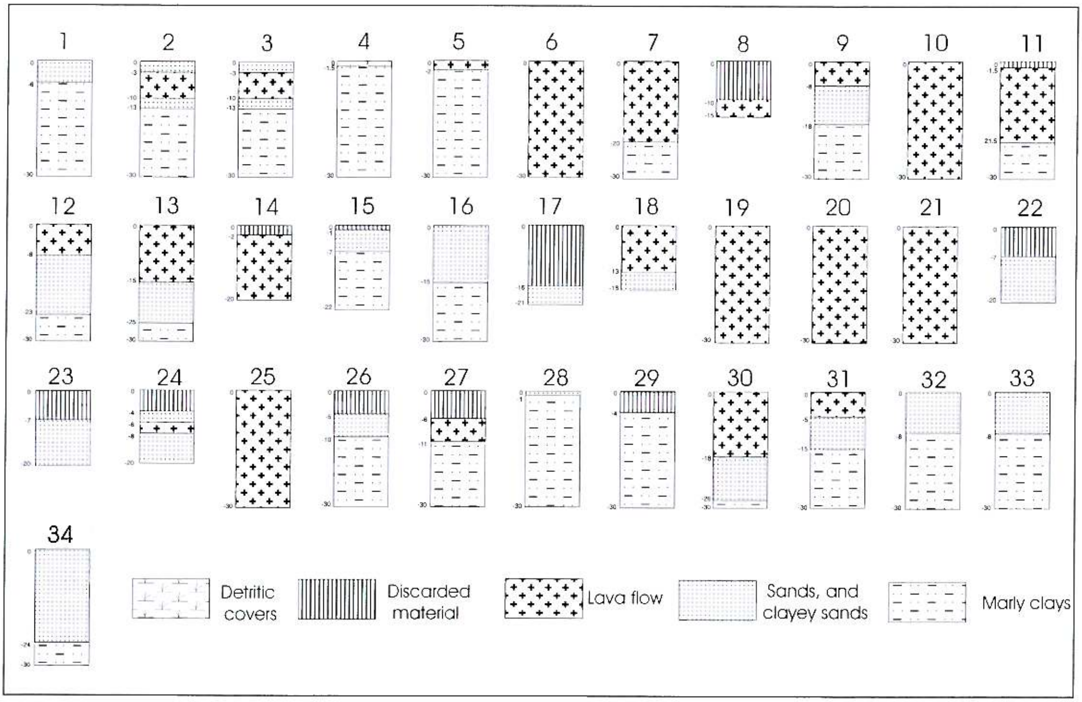

Fig. 3. Thickness of volcanic and sedimentary covers as inferred from drillings ($0 < h < 30$ m).

25 Hz. Fast Fourier Transforms were applied in order to compute spectra for 25 predefined values of frequency, equally spaced in a logarithmic scale between 0.1 and 20 Hz, selected in order to preserve energy and avoid spurious maxima due to unrealistic low vertical spectra (see Castro *et al.*, 1990). Furthermore, the H/V spectra were computed for all sites and components. The arithmetical average of all horizontal to vertical component ratios have been taken to be the amplification function. Full details on the methodology and its limits are given in Mucciarelli (1998).

4. Data analysis

Figure 4 reports an example of Fourier spectra for a single measurement. The ramp due to instrumental sensitivity is equal in all three components (thus it does not affect the ratio).

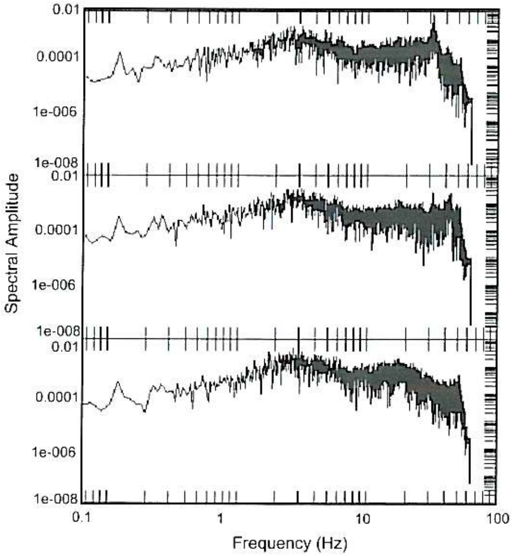

Fig. 4. Example of Fourier spectra for a single measurement.

Table II. Amplification values at each site, in the frequency range 0.1-20 Hz.

Freq.	0.10	0.13	0.16	0.20	0.25	0.32	0.40	0.50	0.63	0.79	1.00	1.26	1.58	2.00	2.51	3.16	3.98	5.01	6.31	7.94	10.00	12.59	15.85	19.95
n. 1	1.48	1.98	2.58	1.92	1.98	1.47	1.48	1.31	1.24	1.07	0.88	0.75	0.87	1.04	1.22	1.20	1.34	1.24	1.35	1.13	0.99	0.97	1.20	1.83
n. 2	1.47	1.01	1.41	2.14	1.57	1.68	1.65	1.21	1.13	1.42	1.51	1.59	1.60	1.55	1.11	0.76	0.48	0.50	0.61	1.32	1.54	1.39	1.32	1.64
n. 3	1.78	1.22	2.17	3.51	2.85	7.59	4.04	3.42	3.02	1.43	1.77	1.34	1.18	0.93	0.88	0.91	0.89	1.18	1.53	1.54	1.63	1.90	2.89	11.94
n. 4	1.59	1.22	1.69	1.98	1.34	1.72	1.52	1.22	0.99	1.06	1.01	1.01	1.09	1.40	1.27	1.29	1.15	1.04	1.10	1.00	1.12	1.02	1.21	1.80
n. 5	1.81	1.21	1.71	1.59	1.64	3.89	1.60	1.88	1.23	1.50	1.16	1.24	0.99	0.88	0.66	0.85	0.77	0.74	0.81	1.03	1.24	1.28	1.58	1.74
n. 6	3.41	2.02	3.11	3.56	2.81	3.00	2.33	1.80	1.68	2.06	1.83	1.42	1.25	1.15	1.04	1.58	1.03	1.27	0.92	0.89	1.11	1.36	1.28	0.76
n. 7	1.45	0.99	1.11	1.51	1.03	1.54	0.72	0.60	0.68	0.66	0.73	0.60	0.50	0.43	0.49	0.46	0.51	0.69	0.67	0.71	0.83	1.05	1.07	1.79
n. 8	2.21	1.04	2.42	1.59	1.41	1.33	0.73	1.05	1.03	0.78	0.75	0.78	0.64	0.71	0.92	1.19	1.49	2.04	2.28	1.81	1.33	1.10	1.41	1.34
n. 9	1.17	1.05	1.52	1.54	1.32	1.39	1.12	1.07	0.71	0.64	0.68	0.71	0.82	1.11	1.40	1.18	0.86	0.61	0.71	0.89	1.01	1.13	1.26	1.47
n. 10	3.37	1.19	3.20	3.49	2.07	3.51	2.83	1.22	0.79	0.56	0.68	0.66	0.73	1.23	1.24	1.37	1.38	1.98	1.63	1.84	2.03	3.04	3.16	2.46
n. 11	0.96	1.05	2.03	1.44	1.50	0.98	1.63	1.55	1.64	1.29	0.99	0.72	0.50	0.48	0.54	0.72	0.68	0.80	0.96	1.21	1.27	1.68	1.83	1.72
n. 12	3.70	1.71	3.33	2.93	2.10	1.50	1.29	1.48	1.28	0.86	0.75	0.49	0.33	0.37	0.46	0.55	0.61	0.65	0.69	0.67	0.88	1.06	1.47	1.66
n. 13	4.16	2.06	4.40	3.26	2.27	1.85	1.74	2.11	2.31	1.89	1.12	0.81	0.58	0.49	0.64	0.94	1.29	1.46	1.46	1.45	1.74	2.10	0.93	0.57
n. 14	2.62	1.23	2.66	2.89	1.78	1.51	1.08	1.41	1.11	1.08	1.12	1.19	0.71	0.82	0.85	1.46	1.65	2.56	3.35	3.65	3.02	1.54	1.66	1.87
n. 15	1.53	1.08	1.73	1.98	1.14	1.50	1.54	1.49	1.19	0.95	0.92	0.88	0.68	0.60	0.69	0.78	0.91	0.91	0.95	0.83	0.81	0.96	0.99	0.94
n. 16	2.36	1.30	2.87	2.85	2.49	1.06	1.66	1.89	1.81	1.07	1.05	1.01	0.73	0.68	0.66	0.72	0.81	0.87	0.94	1.03	1.04	1.23	1.07	1.36
n. 17	1.41	1.02	1.42	1.98	1.59	1.68	1.04	0.93	0.95	0.77	0.89	0.77	0.71	0.65	0.66	0.67	0.59	0.62	0.60	0.48	0.51	0.52	0.56	0.58
n. 18	1.02	0.98	2.30	2.63	1.61	1.30	1.40	0.51	0.44	0.47	0.49	0.43	0.34	0.41	0.41	0.64	0.59	0.62	0.76	0.69	0.67	0.83	1.20	2.37
n. 19	2.74	1.34	2.88	3.80	2.52	1.84	2.45	2.25	1.39	0.89	0.91	0.61	0.48	0.42	0.53	0.62	0.66	0.67	0.65	0.61	0.59	0.85	1.25	1.68
n. 20	1.43	1.11	1.31	1.43	1.40	1.06	1.12	0.87	0.85	0.69	0.65	0.44	0.41	0.42	0.45	0.51	0.64	0.67	0.59	0.56	0.59	0.83	1.01	1.54
n. 21	2.34	1.41	3.11	2.52	2.11	1.15	1.33	0.73	0.68	0.60	0.60	0.55	0.43	0.45	0.52	0.80	0.62	0.67	0.79	0.79	0.69	0.80	1.17	1.12
n. 22	5.39	2.26	3.66	5.00	2.79	3.14	1.72	1.16	0.86	0.65	0.73	1.03	0.99	1.14	1.49	2.34	3.65	4.04	2.68	1.46	0.92	1.35	1.48	1.64
n. 23	10.47	3.77	12.08	11.38	9.32	5.19	3.68	4.15	2.19	1.41	1.74	1.59	2.07	2.16	2.38	3.69	4.15	4.06	3.35	2.80	2.17	1.97	1.89	1.76
n. 24	1.89	1.08	2.16	3.16	1.91	3.01	1.89	1.06	0.73	0.77	0.65	0.68	0.58	0.64	0.76	0.85	0.62	0.50	0.59	0.62	0.58	0.62	0.55	0.62
n. 25	1.16	1.06	1.46	2.33	1.22	0.90	0.94	1.04	0.54	0.40	0.44	0.47	0.44	0.43	0.48	0.51	0.66	0.73	0.76	0.84	0.79	0.86	1.04	1.18
n. 26	3.64	1.85	3.38	3.88	2.34	3.14	2.16	1.74	1.56	0.75	0.73	0.97	0.87	1.21	0.99	0.67	0.48	0.53	0.49	0.44	0.41	0.47	0.51	0.59
n. 27	1.33	1.05	1.40	2.18	1.50	1.52	1.14	0.99	0.50	0.42	0.41	0.66	0.54	0.62	0.67	0.78	0.70	0.75	1.07	0.74	1.02	0.84	0.80	0.64
n. 28	3.10	1.37	3.37	4.69	3.56	2.24	1.45	1.61	0.88	0.49	0.72	0.76	0.70	0.69	0.86	0.77	0.77	1.05	1.32	1.20	1.14	0.97	1.14	2.13
n. 29	1.95	1.42	4.23	2.32	1.65	1.30	1.37	1.26	1.44	1.29	0.84	1.02	0.77	0.71	0.96	1.26	1.38	1.38	1.49	1.98	2.07	2.04	1.04	0.72
n. 30	4.84	2.64	5.42	7.43	4.69	2.39	1.67	1.98	1.93	0.98	0.94	0.84	0.81	0.86	0.95	1.54	1.52	1.10	0.70	0.83	0.98	1.30	1.43	1.63
n. 31	2.34	1.46	3.09	3.41	1.97	1.60	1.22	1.21	1.28	0.90	0.68	0.67	0.81	0.97	0.95	1.15	1.04	0.78	0.86	1.27	1.00	1.12	1.03	1.47
n. 32	1.28	1.05	1.30	1.95	1.16	1.26	1.35	1.30	1.26	1.41	1.14	0.81	0.67	0.53	0.59	0.66	0.64	0.60	0.68	0.72	0.66	0.58	0.61	0.69
n. 33	1.96	1.09	1.63	2.93	1.64	1.98	1.81	1.53	1.87	1.74	1.48	1.02	0.91	0.63	0.83	0.92	0.79	0.79	0.78	0.69	0.62	0.70	0.75	0.81
n. 34	1.45	1.04	1.46	2.12	1.24	1.41	1.50	1.19	1.25	1.26	0.82	0.72	0.59	0.74	0.87	0.90	1.06	1.33	1.22	1.38	1.05	1.18	1.64	1.81

Table II reports the values of amplification function in the frequency range from 0.1 to 20 Hz for all sites. The overall impression emerging from table II is that the lateral variation in this frequency range is very high and thus a much more dense survey is needed to obtain amplification values useful for microzoning purposes. From horizontal to vertical ratio measurements it is possible to note that most of the amplification peaks are at low frequencies.

For all sites, the values of HVSR functions were analyzed by *T*-test to attribute the level of significance at each amplification peak (Albarello, 2001). The values of significance were obtained taking an HVSR value equal to 2 as threshold. Table III shows the values of confidence for the frequency range from 0.1 to 20 Hz, only for values exceeding 0.5: most of the sites have very significant amplification peaks in the frequency range from 0.16 to 0.32 Hz and only 10 sites have reliable amplification peaks at high frequencies (3.16 Hz) too. It is worth nothing that, even though a 1 Hz seismometer was used, the amplifications below 1 Hz are consistent with those observed by other authors using broadband sensors (Azzara *et al.*, 2000).

A look at the value of these spectral ratios distinguishes some common features of spectral ratios (fig. 5). Some interesting amplifications in the high frequency range can be in general attributed to surficial features like sedimentary soils or anthropic debris filling (class A, B and D) while a rather flat response is observed at sites located on thick lava rock (class C).

In order to use the H/V spectral ratios technique to infer the sediment thickness, one must use the relationship between frequency, shear wave velocity and strata depth: for each site we selected among the most significant values in the frequency range 0.1-1 Hz the peak with maximum amplification taken as responsible for the resonance frequency of the layer.

Given V_s the velocity of the shear waves and f the resonance frequency of the layer, under ideal conditions, the thickness d is given by

$$d = V_s/(4 \times f). \qquad (4.1)$$

The stratum thickness below each measurement point was derived from (4.1) using $V_s = 600$ m/s (Catalano *et al.*, 1998) and $f = 0.2$ Hz. We did not apply here the non-linear formula proposed by Ibs-von Seth and Wohlenberg (1999) to take into account a possible velocity increase with depth, since we do not have calibration boreholes exceeding a depth of 50 m (Monaco *et al.*, 2000). The inferred depth of the main reflector, namely the contact with the marly clays forming the substratum, is about 700 m.

5. Discussion and conclusions

Both topographical and local geology conditions such as layer thickness, velocity and density are known to strongly influence the nature of ground motion at a site. In particular, soft-sediment filled basins may cause significant amplification of earthquake motions, due to wave phenomena such as focusing and resonance. Microtremor data can be considered a useful tool to estimate the gross features of soft site response since they may exhibit site-generated spectral shape peaks.

We applied the Nakamura's technique to investigate microtremor characteristics in the urban area of Catania (Sicily) and to relate them to the properties of the shallow geological structure. We made microtremor measurements for 34 sites located on various surface geological conditions in the city of Catania. Both lava flows and sedimentary layers are present at the surface.

The first aim of this study was to investigate the relation between the predominant frequencies detected with the application of the H/V spectral ratio technique and the depth of the main reflector, namely the contact with the marly clays forming the substratum. In this paper we performed our analysis in the frequency range 0.1-1 Hz, where we supposed to find the eigenfrequency of strata deeper than 100 m. The amplification peak is centered around less than 0.2 Hz in most of the microtremor spectral ratios, suggesting that the depth of the main reflector is at about 700 m.

For frequencies higher than 1 Hz we observe some important amplifications (6-8 Hz) at sites

Table III. Values of confidence of the amplification peaks at each site, for the frequency range 0.1-20 Hz.

Freq.	0.1	0.13	0.16	0.2	0.25	0.32	0.4	0.5	0.63	0.79	1	1.26	1.58	2	2.51	3.16	3.98	5.01	6.31	7.94	10	12.6	15.9	20
n. 1			0.64																					
n. 2																								
n. 3			0.61	0.74	0.73	0.84	0.82	0.82	0.82														1	1
n. 4																								
n. 5						0.75																		
n. 6	0.83		0.85	0.87	0.79	0.81	0.66																	
n. 7																								
n. 8	0.75		0.75															0.69	0.93					
n. 9																								
n. 10	0.88		0.85	0.84		0.88	0.83														0.77	0.99	1	1
n. 11																								
n. 12	0.98		0.93	0.96																				
n. 13	0.88		0.99	0.93	0.87			0.67	0.75													0.87		
n. 14	0.87		0.89	0.79														1	1	1	1			
n. 15																								
n. 16	0.74		0.96	0.93	0.89																			
n. 17																								
n. 18			0.75	0.81																				0.99
n. 19	0.77		0.75	0.84	0.68		0.68	0.6																
n. 20																								
n. 21	0.74		0.9	0.9	0.67																			
n. 22	0.8	0.58	0.75	0.82	0.7	0.71										0.85	0.98	0.98	1					
n. 23	0.97	1	0.99	0.98	1	0.96	0.95	0.96	0.71				0.6	0.69	0.91	1	1	0.99	0.99	1	0.93			
n. 24			0.6	0.93		0.8																		
n. 25				0.81																				
n. 26	0.83		0.84	0.92	0.71	0.76	0.59																	
n. 27				0.7																				
n. 28	0.93		0.93	0.99	0.93	0.63																		0.91
n. 29			0.92	0.79																	0.67			
n. 30	0.97	0.84	0.98	0.97	0.98	0.72																		
n. 31	0.71		0.96	0.87																				
n. 32																								
n. 33				0.83																				
n. 34				0.69																				

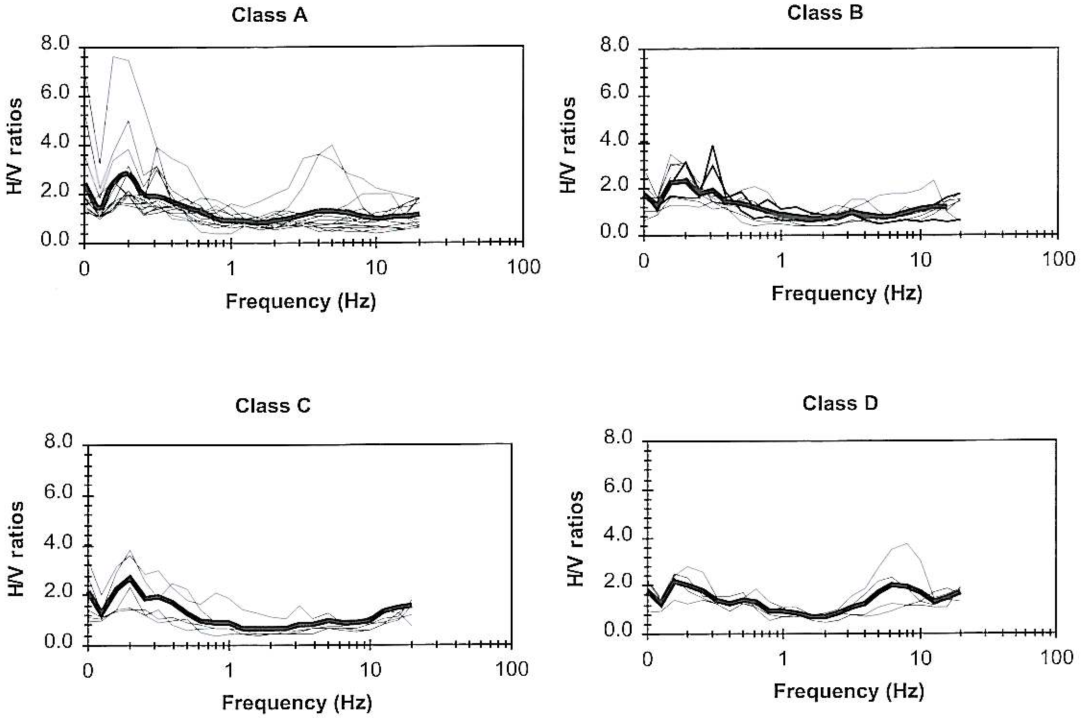

Fig. 5. Spectral ratios and mean value (thick line) for different groups of sites. Class A: sediments and detrita with $h \leq 30$ m (sites: 1, 4, 15, 16, 17, 22, 23, 26, 28, 29, 32, 33, 34); Class B: lava flow with $h < 15$ m and sediments (sites: 2, 3, 5, 9, 12, 13, 18, 24, 30, 31); Class C: lava flow with $h > 20$ m and sediments (sites: 6, 7, 10, 19, 20, 21, 25); Class D: detrita with $h > 2$ m and lava (sites: 8, 11, 14, 27).

located on thick soft sedimentary layers such as clays, sands or anthropic debris filling. Conversely, sites located on thick lava flows do not exhibit significant peaks at specific frequencies. The importance of the subsurface geological conditions in the urban area of Catania has recently been stressed by using strong ground motion simulations (Langer *et al.*, 1999). The main conclusion is that low velocity layers enhance seismic loading, whereas thick lava layers act as «protecting shields» against earthquake shaking.

While a number of systematic results are obtained, in some cases apparently similar geological conditions produce significantly different spectral shapes (fig. 5). The general behavior of the amplitude response with frequency is not stable but shows a high lateral variation. That reflects a very complex subsurface geometry, small-scale heterogeneities and variation in the thickness of the near-surface layers that probably smooth the amplification curves in a such way that the determination of specific resonance modes becomes very difficult. A denser grid of microtremor measurements is thus required for microzoning detailed purposes.

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