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Microtremor H/V spectral ratio in two sediment-filled valleys in western Liguria (Italy)

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Abstract - In this paper, the H/V spectral ratio method is applied to ambient noise recordings collected along 4 profiles crossing two alluvial plains located in western Liguria (Northwestern Italy). The results point out that important amplifications occur on both the alluvial plains. In the Argentina plain amplifications affect mainly the 2-5 Hz frequency band, whereas in the Prino plain the highest amplifications occur at nearly 10-11 Hz. Moreover, in the Prino valley, the peaks of spectral ratio appears to be directly related to the alluvial fill thickness whereas in the Argentina valley the amplifications seem to be due to a shallow portion of the Quaternary sediments. Finally, important amplifications are also measured in correspondence of a landslide, having a thikness up to 6 m, located on the western slope in the Prino valley.

1. Introduction

To evaluate site response several techniques have been utilized and compared in recent studies (see, among others, Field and Jacob, 1995; Riepl et al., 1998). One of the most popular techniques, the H/V method (Langston, 1977; Lermo and Chavez-Garcia, 1994), assumes that the vertical component of the ground motion is free of near surface influence. Thus, the site

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effect is evaluated by a division of the amplitude spectrum of the horizontal component with the spectrum of the vertical component of the same event.

The H/V method was also applied to ambient noise recordings in order to detect the dominant period of a sedimentary basin (Nogoshi and Igarashi, 1970, 1971; Nakamura, 1989). In particular, several recent studies (Lachet and Bard, 1994; Lermo and Chavez-Garcia, 1994; Field et al., 1995; Lachet et al. 1996; Konno and Ohmachi, 1998) showed that microtremor analysis (now generally known as Nakamura's method) is capable of recognizing the fundamental resonance frequency of sedimentary deposits even if it generally underestimates the level of amplification.

Moreover, due to its low cost, Nakamura technique has become a very attractive method in microzonation studies covering wide areas. In this study, we apply the microtremor analysis to spectra of noise recordings collected along 4 profiles crossing two alluvial plains located in western Liguria (north-western Italy) (Fig. 1).

This area is generally affected by small size events however, in 1887, an earthquake with epicentral intensity of IX (MCS scale) occurred (Ferrari, 1991). This seismic event destroyed many villages and more than 600 people died. The territorial distribution of the damages presented some anomalies that were ascribed, by the scientists of that time, to the different soil responses. Fig. 1, showing the difference between intensity computed using the Grandori et al. (1987) attenuation relationship, as calibrated by Peruzza (1996) for the western Liguria area, and the observed effect for the 1887 earthquake. Fig. 1 shows some anomalies in the Argentina

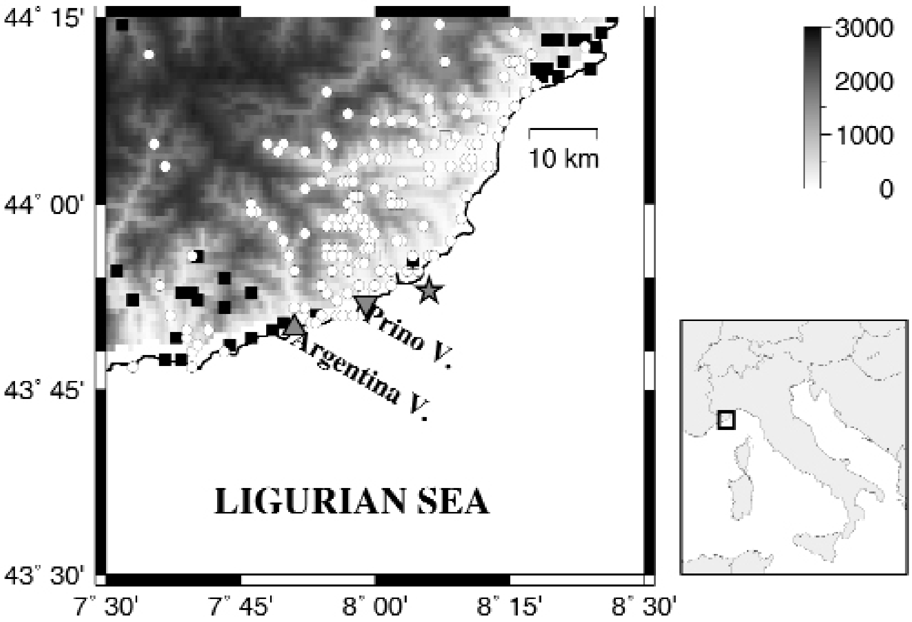

Fig. 1 - Map of the studied area. The star shows the epicentral position adopted for the 1887 earthquake, following the CPTI catalogue (CPTI, 1999). The black filled squares indicate localities with residuals (RES) (i.e. the differences between the values calculated by means of the Grandori et al., 1987, relationship and the observed ones) > 1 degree in the MCS intensity scale; the circles indicate localities with -1 ≤ RES ≤ 1, the empty squares localities with RES < -1. The Argentina torrent Plain and the Prino torrent alluvial Valley are also indicated.

Valley which can be ascribed to site effects. No remarkable discrepancies are shown in the Prino Valley, in which, indeed, the macroseismic observations are scarce. In the last fifty years, some areas that in 1887 were utilized for agricultural use, like the two studied valleys, have been urbanized. Today, a seismic event as strong as that occurred in 1887, could cause severe damages and the site effects could have a more significant bearing in the damage distribution than one century ago.

In this paper we relate site response obtained by Nakamura method to the main features (i.e., the thickness of the sedimentary layers and the bedrock topography), determined from geophysical investigations, of the considered basins.

2. Geological setting

2.1 Alluvial plain of the Argentina torrent

The shallow geological structure (Fig. 2a) of the investigated part of the alluvial plain of the Argentina torrent is characterized by the presence of Quaternary alluvial deposits of the Argentina torrent.

The Quaternary sediments (mainly gravel and sand) can be classified, on the basis of the age of the deposits, in three categories (ancient, middle and recent alluvium) corresponding to different terraces. At the points of microtremor measurements (triangles in Fig. 2a and Fig. 2b) the alluvial sediments overlie a bedrock composed by Pliocene conglomerate. In the northern side of the plain the bedrock is characterized by marl and sandstone (Sanremo Flysch).

The morphology of the bedrock, determined by means of Vertical Electrical Soundings (VES) by Peloso et al. (1993), shows the presence of two paleo-riverbeds separated by an emergence of bedrock (Fig. 2b). The thickness of the alluvium is always greater in the eastern paleo-riverbed, and increases towards the Argentina river mouth where it exceeds 70 m.

In particular, the thickness of the alluvium in correspondence of the three profiles (A-A', B-B', C-C'), along which the noise measurements were carried out, is of approximately 70 , 65 and 50 m respectively (Fig. 2b).

The thickness of the alluvial fill beneath the stations not located exactly on the VES profiles was estimated by means of interpolation of the VES profile results. The water table is located inside the alluvial deposits at 5-10 m depth.

2.2 Alluvial plain of the Prino torrent

The alluvial plain of the Prino torrent (Fig. 3a) is characterized by the presence of Quaternary alluvial deposits composed of gravel and sands. These sediments can be classified as recent alluvium and they form the terrace within which the Prino torrent is actually flowing.

The recent alluvium is nearly 15 m thick (Fig. 3b) and the water table is at approximately

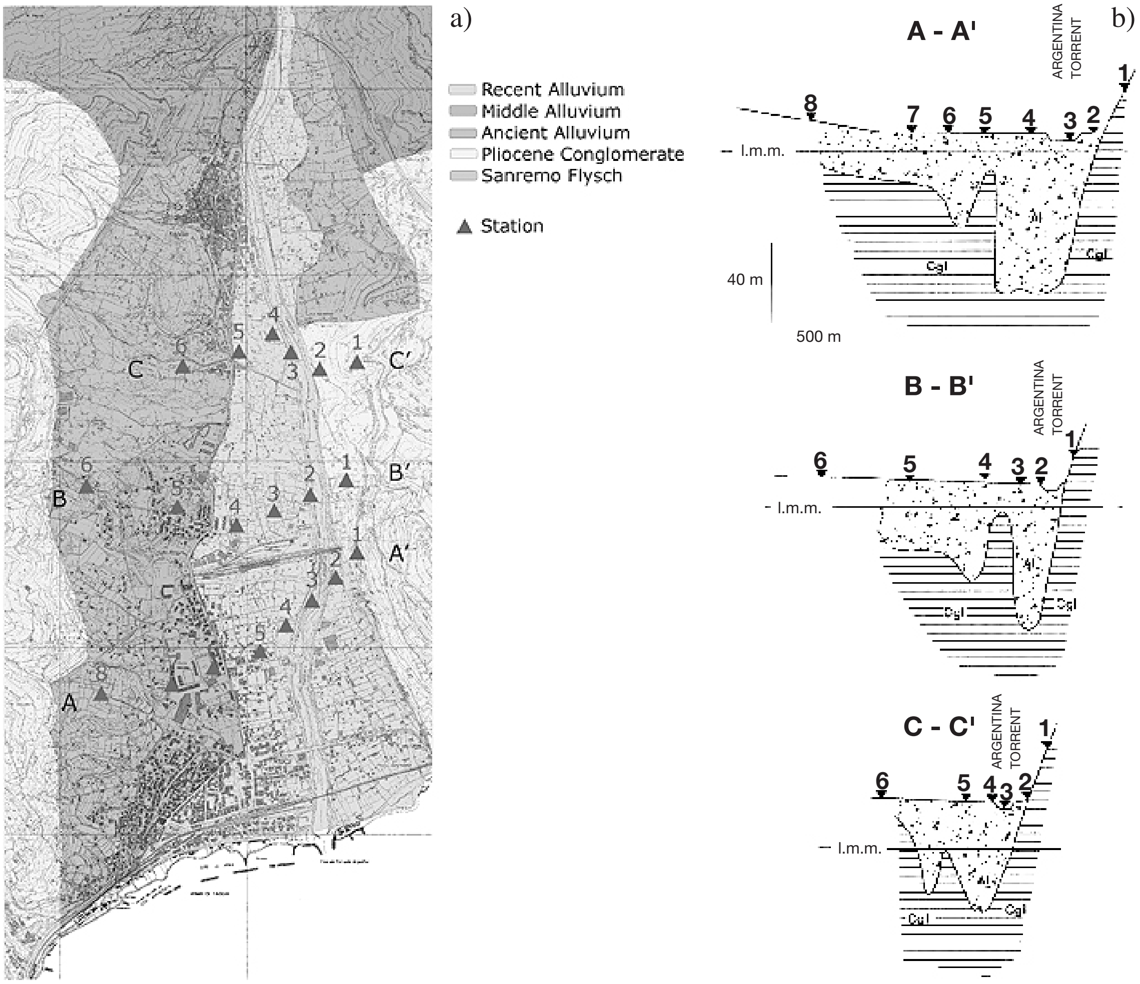

Fig. 2 - (a) Geological sketch of the Argentina plain and (b) sections drawn along the measurement profiles.

5-8 m depth. Outcropping marl and sandstone, belonging to the Sanremo Flysch, surround the alluvial plain. Eluvial and colluvial detritus with varying thickness often covers the slopes bordering the plain.

The bedrock emerges in correspondence of the points of measure on the left riverside. A landslide thicker than 3 m covers it on the right riverside (see station 2 in Fig. 3b).

3. Data acquisition and data analysis

The microtremor data were recorded using a Lennartz Le3D-5s sensor, connected to a Lennartz Marslite digital acquisition system (120 dB of dynamic range). The sensor response in velocity is flat between 0.2 and 40 Hz. At each site, the signal was recorded at 125 Hz sample rate for 15 minutes. The installation was carried out trying to obtain the best coupling between sensor and soil avoiding asphalt. In order to reduce any interference caused by the wind the external wires were fixed.

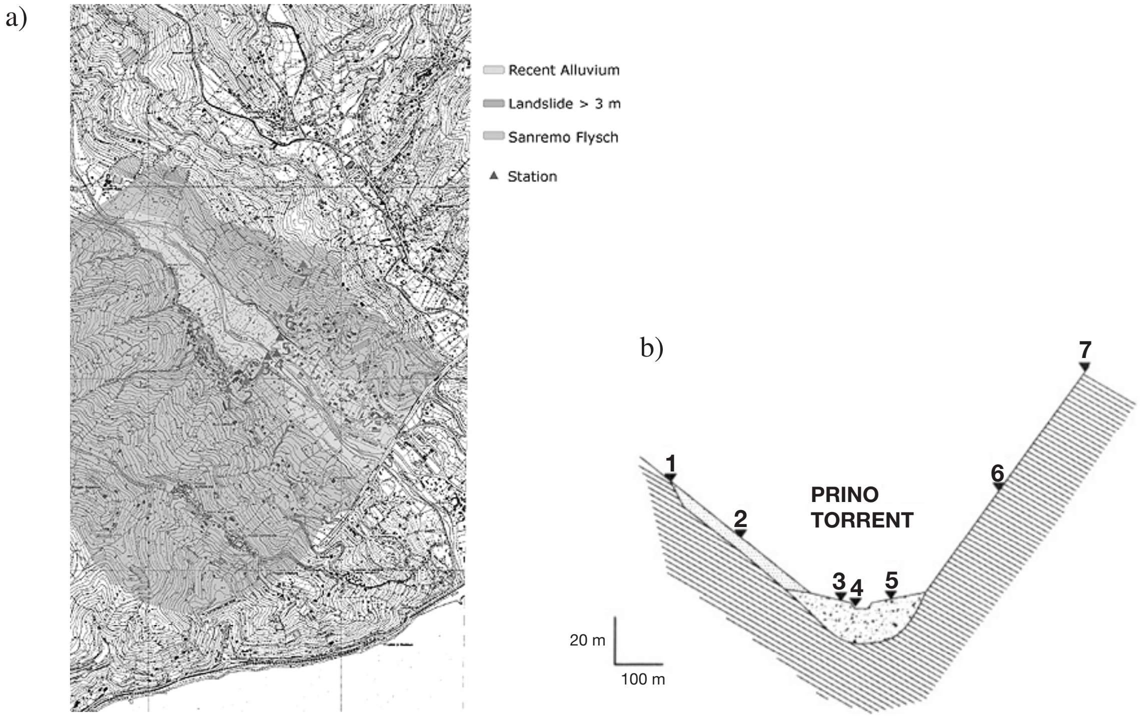

Fig. 3 - (a) Geological sketch of the Prino plain and (b) section drawn along the measurement profile.

Each noise recording was divided into 30 s windows eliminating badly acquired signals. Time series were tapered with a 10% cosine function. The FFT was calculated for each component and spectra were smoothed with an Hanning window of 0.5 Hz half-width. For each selected time window, the spectral ratios between the horizontal components (NS and EW) and the vertical component (Z) were calculated.

Finally, the amplification functions for the two horizontal components were estimated computing the arithmetical mean of all the relevant spectral ratios.

4. Results and discussion

4.1. Alluvial plain of the Argentina torrent

In the upper panel of Fig. 4, the mean NS/Z spectral ratios ±1 standard deviations (grey shaded area) are shown for all the stations placed along the profile A-A'.

Station 1, located on the slope of the valley, does not show any significant amplification. On the contrary, station 2, placed few tens of meters away, shows remarkable mean amplification values (up to five) affecting the 2-5 Hz frequency band. The NS/Z spectral ratios relevant to the station 3 and 4, located in the central part of the valley, present well defined peaks between 2 Hz and 6 Hz. In particular, the highest amplification levels (up to seven) are shown by the NS/Z spectral ratio of the station 4. Secondary peaks are shown by the NS/Z spectral ratios of station 3 at frequencies higher than 10 Hz.

The NS/Z spectral ratios of station 5 appear more complicated since, beside the sharp peaks between 5 and 6 Hz, they also show significant secondary peaks. The behaviour of station 6 shows a well defined peak in the 2-5 Hz frequency range.

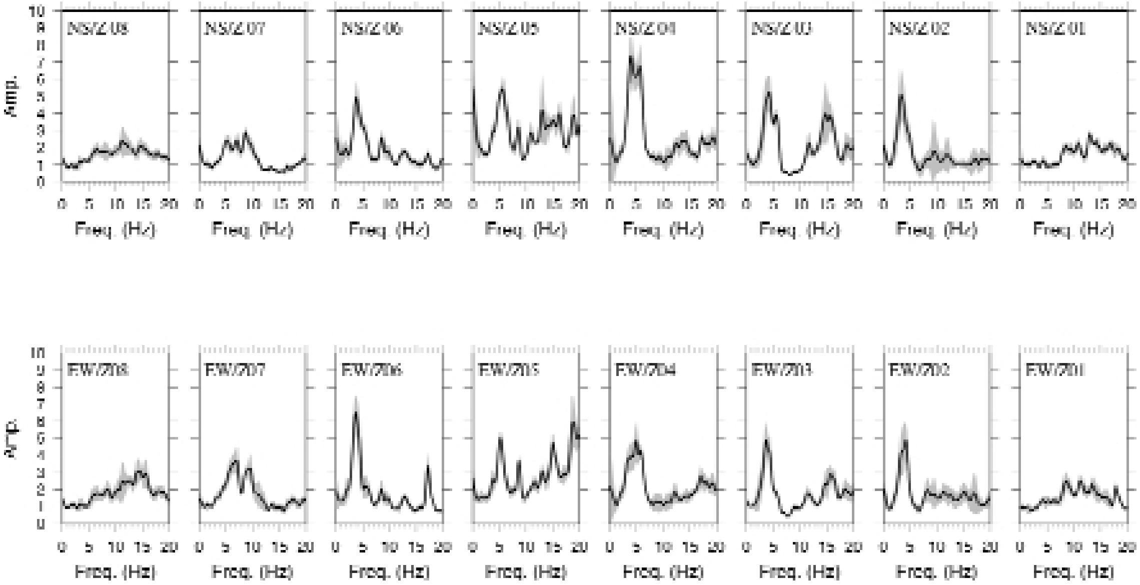

Fig. 4 - Site responses calculated along the A-A' profile of Fig. 2a and Fig. 2b. NS/Z and EW/Z spectral ratios are shown in the upper and lower panels, respectively. Grey shaded area indicate the mean (black thick line) ± 1 standard deviation.

Regarding the results relevant to station 7 we observe a general diminishing of the mean amplification level with respect to the previous stations. Moreover, at this site, the amplification seems to affect the frequency band between 5 and 10 Hz. The NS/Z spectral ratios of station 8 do not show significant amplifications and resemble the behaviour of station 1.

The EW/Z amplification profiles (lower panel in Fig. 4) show a very similar trend with respect the NS/Z profiles. Furthermore, for each site of measure, the EW/Z and NS/Z spectral ratios are characterized by the same main features, even if the former generally show lower amplification values.

The comparison between Fig. 4 and Fig. 2b points out the correlation between H/V spectral ratios and thickness of the sediments derived by VES. In fact, while the site response functions show no amplification for the station placed on hard rock (station 1 on the slope), the spectral ratios relevant to the stations located on the torrent alluvial plain show significant amplifications.

The complicated shape of the spectral ratios of station 5 could be due to the prominence of the bedrock. Moreover, the abrupt change in the shape of the spectral ratios of station 1 and station 2 could be related to the steep dip of the slope.

In this case, sites placed at small horizontal distances overlie valley fills with very dif-

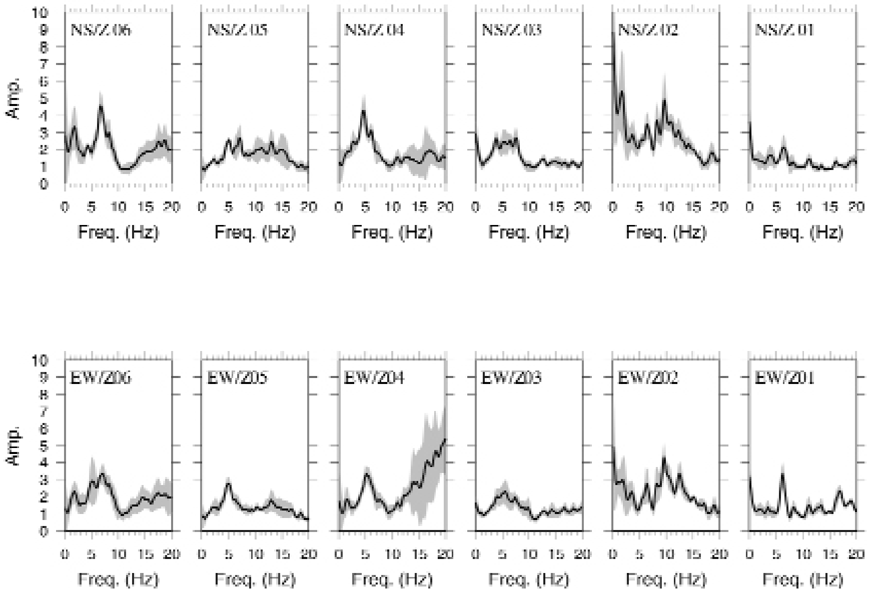

Fig. 5 - Site responses calculated along the B-B' profile of Fig. 2a and Fig. 2b. NS/Z and EW/Z spectral ratios are shown in the upper and lower panels, respectively. Grey shaded area indicate the mean (black thick line) ± 1 standard deviation.

ferent thickness. On the contrary, we observe a gradual reduction of the amplifications from station 6 to station 8. This behaviour seems to be due to the slow decreasing of the sediments thickness. Thus, it appears that variations along the profile correlate with the asymmetry of the valley. In Fig. 5 we show the H/V spectral ratios obtained for the stations of the profile B-B' (Fig. 2b).

The transition from low amplification outside of the valley (station 1) to high amplification in the central part of the valley (stations 2, 3, 4 and 5) is sharp. Moreover, the frequency at which amplification occurs increases from station 2 to station 4 (where the strongest amplification appear at 11 Hz). On the contrary, the fundamental frequency resonance at station 5 can be clearly distinguished in our results by a peak at 5 Hz. More complicated are the results obtained using the station 6 recordings. In fact, we observe both a decrease of the amplification level at frequencies lower than 3 Hz and an increase of the mean amplification values at higher frequencies.

The fundamental resonance frequencies calculated for the stations 2, 3, 4 and 5 appear to be related to the thickness of the alluvial fill. The behaviour of station 6 could be explained by a strong decrease of the alluvial fill thickness. Unfortunately, this site is quite distant from the VES profiles and the bedrock behaviour can not be reliably retrieved.

In Fig. 6 we show the H/V spectral ratios obtained for the stations placed along the profile C-C' (Fig. 2b). Station 1, placed on hard rock on the slope of the valley, does not show important amplifications except for a factor of 3 affecting the frequencies between 6 and 7 Hz.

Moderate amplifications are observed in the center of the valley (station 2, 3, 4 and 5). In contrast to stations 3, 4 and 5, where site-dependent resonance modes are shown by peaks in the

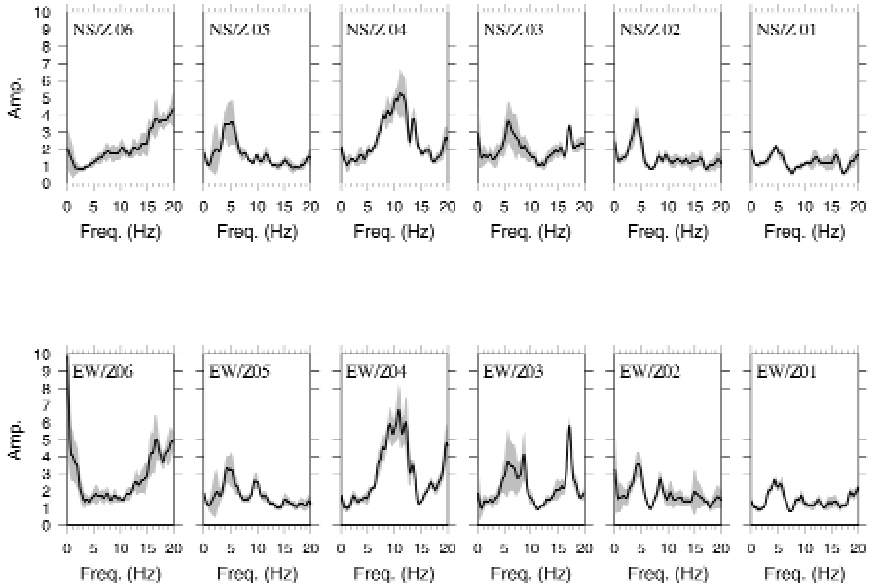

Fig. 6 - Site responses calculated along the C-C' profile of Fig. 2a and Fig. 2b. NS/Z and EW/Z spectral ratios are shown in the upper and lower panels, respectively. Grey shaded area indicate the mean (black thick line) ± 1 standard deviation.

site response functions (between 3 and 7 Hz), no particular resonance frequencies can be clearly distinguished below 10 Hz in our results for station 2. In fact, the amplification is undulating and the most significant peak is around 10 Hz. This effect could be due to the complexity of the near subsurface geometry of the valley.

Furthermore, the mean EW/Z spectral ratio relevant to station 4 shows an increase of the amplification level at high frequency (> 10 Hz). This might be due to the a preferred resonance direction or to azimuthally asymmetric site response for this station. Even for this profile, the amplifications seem to be directly related to the thickness of the alluvial fill. In fact, the changes of amplification levels fit well with the profile derived by VES investigation.

Moreover, the site resonance frequencies seems to be slightly higher than those measured on the A-A' profile where the thickness of the alluvial fills is greater.

Taking into account the computed Nakamura resonance frequencies and the thickness of the sediment at each site, the average shear velocity $<V_s>$ can be derived using the relationship

$$<V_s> = 4\,h\,f, \tag{1}$$

where h is the thickness of the sediments and f is the estimated resonance frequency at the site. Since the peaks of the spectral ratio occur at frequencies > 2 Hz and considering the thickness of the sediments shown in Fig. 2, most of the computed $<V_s>$ (88% about) lie in the stiff soil and rock categories of the Eurocode 8 (CEN, 1994). Fitting an exponential to the whole data set of *h* and $<V_s>$ collected in Argentina Valley, we obtained the following relationship:

$$<V_s> = 60.0\,h^{0.7}. \tag{2}$$

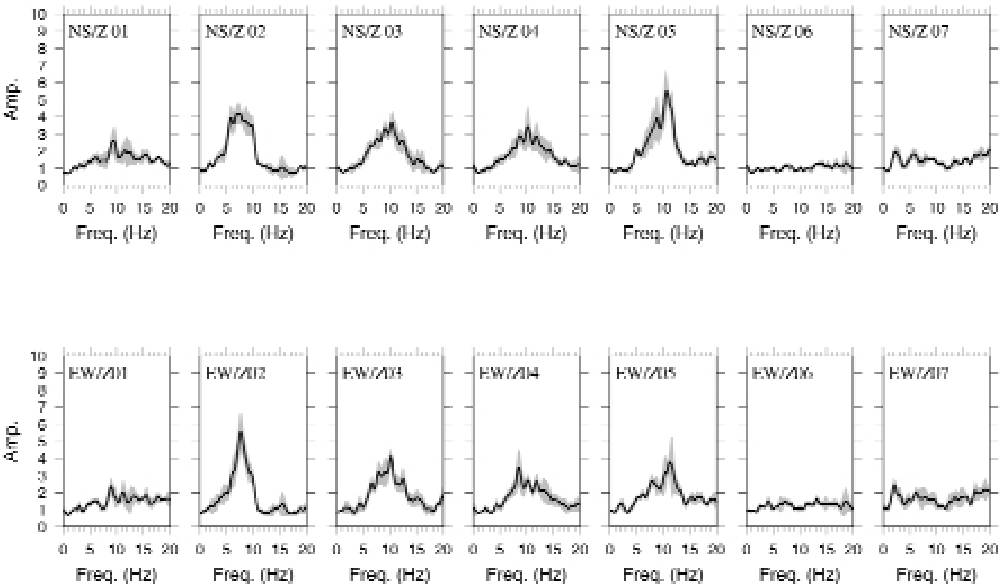

Fig. 7 - Site responses calculated along the C-C' profile of Fig. 3a and Fig. 3b. NS/Z and EW/Z spectral ratios are shown in the upper and lower panels, respectively. Grey shaded area indicate the mean (black thick line) ± 1 standard deviation.

The relationship (2) implies, for example, that the $\langle V_s \rangle$ corresponding to point 4 along the profile A-A' (see Fig. 4) is of the order of 1200 m/s. Therefore, the shear wave velocity V_s in the sediments should be much higher that the expected one for these kind of alluvional fills (gravel and sand). Furthermore, following Konno and Ohmachi (1998), since the Nakamura method should work where the impedance contrast between sediments and bedrock is greater than 2.5, the Pliocene conglomerate should have V_s higher than 3000 m/s, which is too high for fitting the properties of this kind of bedrock. These considerations suggest that the peaks revealed by the Nakamura spectral ratio might be due to a contact between a shallower layer, composed by Quaternary sediments having low average shear wave velocity, and deeper Quaternary layer characterized by more consolidated sediments. If this feature will be confirmed by further geognostic investigations, then the Nakamura method could be unsuitable for retrieving bedrock information in valleys with complex velocity profiles.

4.2 Alluvional plain of the Prino torrent

The mean amplification values across the Prino valley (Fig. 3a and Fig. 3b) are shown in Fig. 7. Important amplifications, by a factor greater than 3, are obtained in the middle of the valley (stations 3, 4, 5), as well as toward the edge where the landslide is relatively thick (station 2). Conversely, the H/V spectral ratios of the stations located both on hard rock sites and at the border of the landslide (stations 1, 6, 7), appear nearly flat. The stations placed on the alluvium show amplifications in the 5-15 Hz frequency band. The strongest amplifications relevant to the stations located on the alluvial plain appear at 10-11 Hz and a value as high as 5.5 is showed by the NS/Z spectral ratio of the station 5.

Considering the thickness of the sediments and the calculated peaked frequencies, the average shear velocity of the alluvial fill ranges between 400 and 600 m/s. These values are compatible with the expected velocities of the Quaternary alluvial deposits in Western Liguria. Therefore, these results seem to confirm that the peaked frequency calculated by means of the Nakamura technique can be directly related to the thickness of the alluvial fill. Particularly interesting is the H/V spectral ratio at station 2 that point out the influence of the landslide in the seismic response of the site.

5. Conclusions

In this paper we calculate site responses applying the H/V technique to noise recordings carried out across two sediment-filled valleys in western Liguria (northwestern Italy). The main results can be summarized as follow:

- strong amplifications of the horizontal microtremor occur at sites on the alluvial plain for both the valleys;
- the accumulations of landslide debris thinner than 6 m can produce strong site amplifications;
- in the Prino valley the peaked frequencies seem to be directly related to the alluvial fill thickness in agreement with previous studies (see, among others, Delgado et al., 2000, Parolai et al., 2001);
- on the contrary, the results obtained in the Argentina valley suggest that usage of the microtremor as a geophysical exploration tool in assessing the bedrock geometry could lead to misleading interpretation in valleys where the impedance contrast is high inside the alluvial fills.

Finally, these results point out that the ground motion can vary sharply over very short distances in the studied valleys. Since in the last decades new buildings were built over many of the sites showing the highest levels of amplifications (for instance stations 4, 5, 6 on the profile A-A' and station 5 in the Prino valley profile), we feel that an earthquake similar to that which occurred in 1887 could cause significant damages. In order to verify this hypothesis, a further and more detailed study, has to be carried out to measure the buildings vulnerability.

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References

CEN; 1994: *Eurocode n. 8.*

CPTI; 1999: *Catalogo parametrico dei terremoti italiani,* ING, GNDT, SGA, SSN; Editrice Compositori, Bologna, 92 pp; http://emidius.itim.mi.cnr.it/CPTI/home.html

Delgado J., Lopez Casado C., Giner J., Estevez A., Cuenca A. and Molina S.; 2000: *Microtremors as a geophysical exploration tool: applications and limitations*. Pure Appl. Geophys., **157**, 1445-1462.

Ferrari G.; 1991: *The 1887 Ligurian earthquake: a detailed study from contemporary scientific observations*. Tectonophysics, **193**, 131-139.

Field E.H., Clement A.C., Jacob K.H., Aharonian V., Hough S.E., Friberg P.A., Babaian T.O., Karapetian S.S., Hovanessian S.M. and Abramian H.A.; 1995: *Earthquake site-response study in Giumri (formerly Leninakan), Armenia, using ambient noise observations*. Bull. Seism. Soc. Am., **85**, 349-353.

Field E.H. and Jacob K.H.; 1995: *A comparison and test of various site-response estimation techniques, including three that are not reference-site dependent*. Bull. Seism. Soc. Am., **85**, 1127-1143.

Grandori G., Perotti F. and Tagliani A.; 1987: *On the attenuation of macroseismic intensity with epicentral distance*. In: Cakmak A.S. (ed), Ground motion and engineering seismology, Elsevier, Amsterdam, pp. 581-594.

Konno K. and Ohmachi T.; 1998: *Ground motion characteristics estimated from spectral ratio between horizontal and vertical components of microtremor*. Bull. Seism. Soc. Am., **88**, 228-241.

Langston C.A.; 1977: *Corvallis, Oregon, crustal and upper mantle receiver structure from teleseismic P and S waves*. Bull. Seism. Soc. Am., **67**, 713-724.

Lachet C., and Bard P.-Y.; 1994: *Numerical and theoretical investigations on the possibilities and limitations of Nakamura's technique*. J. Phys. Earth, **42**, 377-397.

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

Lermo J. and Chavez-Garcia F. J.; 1994: *Are microtremors useful in site response evaluation?*. Bull. Seism. Soc. Am., **84**, 1350-1364.

Nakamura Y.; 1989: *A method for dynamic characteristics estimations of subsurface using microtremors on the ground surface*. Quart. Rep. Railway Tech. Res. Inst. (RTRI), **30**, 25-33.

Nogoshi M. and Igarashi T.; 1970: *On the propagation characteristics estimation of subsurface using microtremors on the ground surface*. J. Seism. Soc. Japan, **23**, 264-280 (in Japanese with English abstract) .

Nogoshi M. and Igarashi T.; 1971: *On the amplitude characteristics of microtremor (Part 2)*. J. Seism. Soc. Japan, **24**, 26-40 (in Japanese with English abstract) .

Parolai S., Bormann P. and Milkereit C.; 2001: *Assessment of the natural frequency of the sedimentary cover in the Cologne Area (Germany) using noise measurements*. J. Earthq. Engineering, **5**, 541-564.

Peruzza L.; 1996: *Attenuating intensities*. Ann. Geofis., **39**, 1079 - 1093.

Peloso G. F., Boni P., Cotta Ramusino S.; 1993: *Studio delle risorse idriche di sub alveo del Torrente Argentina,* Internal Report, Dip. Sc. della Terra, Univ. Pavia (in Italian with English abstract).

Riepl J., Bard P. Y., Hatzfeld D., Papaioannou C. and Nechtschein S.; 1998: *Detailed evaluation of site-response estimation methods across and along the sedimentary valley of Volvi* (EURO-SEISTEST). Bull. Seism. Soc. Am, **88**, 488-502.