SITE AMPLIFICATION EFFECTS BASED ON TELESEISMIC WAVE ANALYSIS: THE CASE OF THE PELLICE VALLEY (PIEDMONT, ITALY)

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Abstract
The investigation of local amplification phenomena by seismic signal analysis is a fundamental step in carefully defining the seismic response of an area. In this study we investigate the use of teleseismic recordings in assessing seismic wave amplification in the Pellice Valley (North-western Alps, Italy). Assuming that teleseismic P-waves are sensitive to the deep structure of a basin, we deal with the computation of horizontal to vertical spectral ratios and with the estimate of teleseismic P-wave arrival time delays and P-wave amplifications with respect to a reference site. The reliability of the H/V results obtained by considering teleseismic signals is confirmed by the agreement with the results coming from both H/V of noise and H/V of S-wave of local events methods. Strong correlation between the P-wave arrival time delays and the relative P-wave amplifications with respect to thickness of the low velocity layers and the geometry of the bedrock is found.

Keywords: Site effects, H/V spectral ratio, teleseismic signals
Introduction

One of the most important problems in microzonation studies is the evaluation of site response. Site effects related to geological and geo-morphological setting actually represent one of the main factors responsible for building damage; in recent years, their evaluation by experimental methods and/or numerical simulations has attracted growing attention.

In regions, characterised by a low rate of seismicity but potentially able to suffer energetic seismic events, it is very difficult to assess site response by experimental methods because of the lack of earthquake occurrence. The problem could be overcome by computing the fundamental frequency of soil by applying the standard HVSR (horizontal to vertical spectral ratio) technique based on ambient seismic noise records (Nakamura, 1989). Nevertheless, assessment of the site amplification effect by means of microtremor measurements, providing only the fundamental resonance frequency of the site, leads to incomplete results, as demonstrated in many studies (Lermo and Chavez-García, 1993; Lachet and Bard, 1994; Bard et al., 1998; Bindi et al., 2000, Parolai et al., 2001, Parolai et al., 2004); therefore, collection of a suitable data set of seismic events is needed to ensure accurate site response estimation.

The main purpose of this work is to test whether site response may be estimated by using teleseismic signals, as recorded by a dense temporary network, only. In particular horizontal to vertical spectral ratio of teleseismic recordings are computed and the results are compared with the same non-reference site technique applied to local earthquakes (Lermo and Chavez-García, 1993) and ambient noise (Nakamura, 1989). Moreover, as suggested by Dolenc et al., 2005, use of teleseismic signals allows correlation between depth of sedimentary coverage and relative P phase arrival time delays and relative P phase amplitude (computed with respect to a reference site), providing further information suitable for site response analysis.

The procedure allows us to check the agreement of the results coming from the H/V spectral ratio technique applied to teleseisms, local earthquakes and noise, as also stated by Riepl et
al., 1998 and Dolenc and Dreger, 2005, and, hence, to confirm that the use of teleseismic recordings only represents a useful alternative to the use of local events for site response estimation in regions seldom experiencing local seismic activity.

In this work, the proposed method has been applied to an alpine valley used as a test site in the framework of the Interreg Sismovalp Project (Seismic Hazard and Response Analysis in Alpine Valleys) in which multidisciplinary subsoil exploration surveys, experimental seismic data analyses and numerical simulations have been carried out with the aim of defining the seismic response of alpine valleys (Cornou et al., 2003; Frischknecht and Wagner, 2004; Frischknecht et al., 2005; Cauzzi et al., 2006; Turino et al., 2006; Lacave and Lemeille, 2006; Barnaba et al., 2006).

Geological and geophysical frameworks and seismic network
The Pellice Valley is an Alpine valley located in the north-west of the Piedmont region (Italy); the area is characterised by a substratum made up of the rocks of the Dora-Maira Massif superimposed by an ancient depositional sequence characterised by lacustrine and/or palustrine sediments; superimposed on the lacustrine deposits are coarse deposits of gravel and pebbly sands characterised by heterogeneity and considerable alteration.

The area investigated in this study is a portion of the valley surrounding the Torre Pellice village and it is characterised by four different geological settings, as shown in the simplified geological map (derived from the Geologic map compiled by A.R.P.A. Piemonte (Regional Agency for Environmental Protection, Piedmont, Italy) scale 1:10000) in figure 1:
1) the area located on the edge of the valley in which the gneiss formation outcrops (rocks of the Dora-Maira Massif);
2) the area located in the north-western part of Torre Pellice village characterised by alluvial fan deposits;
3) the area located in the village centre in which ancient fluvial deposits, made up of several orders of terraces, are present;
4) the riverbed area characterised by recent fluvial deposits.
The area located to the south of the Pellice river (where the reference station PE03 is located) is characterised by a gneiss outcrop.

Under the scope of the Interreg Sismovalp Project, a multidisciplinary subsoil exploration survey was undertaken with the aim of defining the physical-mechanical parameters of the superficial material as well as providing information about the geometry and the depth of the bedrock. The investigation survey, as described in detail in Cauzzi et al, 2006, included: 4 boreholes, 4 down-hole seismic tests and 2 reflection seismic profiles (grey pentagons and white lines in figure 1). The 4 down-hole tests, reaching a maximum depth of 50 m, allow us to define the P- and S-wave velocity of the shallow materials; the reflection profiles, executed by using 10 Hz sensors with an inter-distance of 2m and Vakimpak (50 kg weight dropper) as seismic source, well constrain the stratigraphy of deep sediments and the topography of the bedrock, also defining the P-wave velocity down to more than 200 m.

In order to estimate the seismic site response of the valley, a temporary network composed of three velocimetric stations (equipped with digital acquisition systems with more than 120 dB dynamic range coupled with Lennartz Le-3D/5s enlarged band sensors and recording with a sampling rate of 128 measurements per second) was installed from November 2004 to February 2005 (white circles in figure 1). To better cover the area a further 6 velocimetric stations were installed in November 2004 (grey circles in figure 1).

In order to ensure a complete coverage of the zone, the stations, as shown in figure 1, were installed on the riverbed (Pe07, Pe09 and Pe11), on the ancient alluvial terraces (Pe06 and Pe04), on the alluvial fan (Pe02, Pe08 and Pe10) and on gneiss outcrop (Pe03). More than 50 local events (with magnitude spanning between 2.0 and 3.5 and hypocentral distance between 5 km and 70 km) and 18 teleseisms (table 1) were recorded by the network.

**Method**

Teleseismic events were analysed in order to estimate site response by applying standard H/V spectral ratio method (Bonilla et al., 1997; Parolai et al., 2000; Parolai et al., 2004). The data processing was performed using the following procedure:
STEP 1: a preliminary selection of high quality teleseismic signals was made considering recordings with a signal to noise ratio greater than 15 dB. The S/N ratios, calculated using 20 seconds of pre-event noise and 20 seconds of seismic signal, indicate that, in the range 0.2 Hz (low frequency limit constrained by the flat response of Lennartz LE/3D-5s sensor) - 3 Hz, the level of teleseismic signals is clearly over the noise level (Figure 2);

STEP 2: all seismograms were deconvolved by instrument response and filtered by a low-pass filter at 20 Hz; The Fourier spectra were calculated for windows of 20s including the first and more energetic portion of teleseismic signals; therefore, the signals used for calculation contain different teleseismic phases, such as direct longitudinal waves (P, PKP,...) and, mainly, P or S reflected and/or converted waves (PcP, pP, sP, sPKP,...), according to the wave propagation. Then, Fourier spectra are smoothed, in the frequency domain, using a Hanning window (Press et al., 1994) with 28% relative bandwidth so as to ensure smoothing of numerical instabilities while preserving the major features of the spectra. The Fourier spectra of the NS and EW components were averaged (root mean square) to obtain a horizontal component Fourier spectrum.

STEP 3: the horizontal to vertical spectral ratio was calculated considering the Fourier spectra computed in STEP 2. It is worth noting that the use of different portions of teleseismic recording containing different teleseismic phases leads to stable H/V spectral ratios (figure 3). The average H/V ratio was calculated for all selected teleseismic events for Pe03, Pe06 and Pe07 stations only because of the lack of a significant number (n >3) of high quality teleseismic data for the other stations (acquisition period too short).

STEP 4: the computation of P wave arrival time delays and relative amplitudes of the initial P waves was carried out with respect to the Pe03 station. If the hypocentral distance of the events is large compared to the array aperture, the seismic wave field could be considered uniform as it arrives beneath the investigated area and we may assume that the differences in the observed teleseismic waveforms are correlated to differences in local superficial structure (Dolenc et al., 2005). The unprocessed recordings were first band-pass filtered between 0.2 and 1 Hz, according to S/N analysis (same in STEP1 but considering shorter
window lengths in order to account for P-waves only), and, then, the P wave time delays were carefully determined by cross-correlating the first quarter-cycle of initial P waveform of each station with respect to Pe03 station recordings. Finally, the amplitude ratios of the first P wave arrivals were determined with respect to Pe03 station.

In figure 4, as an example, the seismograms of teleseisms no. 17 (table 1) recorded by Pe03 (bedrock), Pe06 (alluvial terraces) and Pe07 (riverbed) stations are plotted, clearly showing the differences in shape and amplitude among the recordings.

**Results**

In the top panels of figures 5, 6 and 7 (A panels) the H/V ratio curves computed considering teleseismic events for the stations Pe03 (figure 5), Pe06 (figure 6) and Pe07 (figure 7) are shown. The Pe03 site is a reference rock site with no amplification effects (flat H/V curve). The Pe06 station, installed on ancient terraced fluvial deposits, shows a broad peak between 2 and 3.5 Hz confirming the existence of a sedimentary layer superimposed on a bedrock shallower than in the riverbed area. The Pe07 station, installed on actual fluvial deposits in the riverbed, indicates the presence of an amplification peak at about 1.3 Hz, in agreement with the depth of the bedrock as suggested by the available geological information. It is worth noting that the H/V of teleseisms are reliable in the frequency range between 0.2 and 3 Hz only, according to S/N analysis (STEP1). The results obtained processing teleseismic data are compared with H/V ratios of ambient noise (B panels of figures 5, 6 and 7) and of local earthquakes (C panels of figures 5, 6 and 7). The microtremor recordings were processed with the Nakamura technique (Nakamura, 1989) taking into account 40-minute-long signals recorded for each site in different noise conditions (both night and day) and dividing each recording, filtered between 0.2 – 20 Hz, into 40-s-long windows. The Fourier spectra of NS and EW component were smoothed (Hanning window) and averaged to obtain the horizontal component Fourier spectrum and the mean and standard deviation (± 1σ) of all H/V ratios were computed for each site. Local earthquake data (Ml < 3.5), collected during the campaign, were processed (1) filtering the signals between 0.2 and 20 Hz, (2) computing
smoothed (Hanning window) Fourier spectra for windows that include the S-phase arrival as well as the majority of phase energy, (3) merging the two horizontal components and (4) computing the mean and standard deviation ($\pm 1\sigma$) of all H/V ratios, as suggested in Parolai et al., 2004.

The H/V curves and the frequency peaks derived from processing teleseismic data converge on the results of H/V ratios from noise and local earthquakes and the agreement between the results is confirmed for each site condition analysed in this test. It is worth noting that, between 0.2 and 3 Hz, the differences in resonance frequency peak and amplification level between the H/V of teleseisms and the H/V of local events for all stations are absolutely negligible. On the contrary, the H/V of noise results show lower amplification level mainly for the Pe07 station.

The use of teleseismic data allows the computation and interpretation of P wave arrival time delays and relative P wave amplification with respect to reference stations. Figure 8 illustrates the strong correlation between arrival time delays of teleseismic P waves with respect to the thickness of sedimentary coverage of the valley. The geological sections reported in figure 8 are coincident with the two seismic profiles indicated in figure 1 (white lines) and are based on the available geophysical-geotechnical investigation results (2 reflection profiles and 4 down-hole tests). The absolute values of arrival delay residuals, calculated with respect to the Pe03 reference station, vary between 0.02 and 0.16s and are correlated with the thickness of the low velocity superficial layers (alluvial sediments and clays) and to the geometry of the bedrock topography. The delay time residuals reach the highest values for the stations located in the river bed (Pe07, Pe09), where the low velocity layers go down to more than 60m in depth, and decrease toward the alluvial terrace zone (Pe04, Pe06) where the high velocity layers (till and bedrock) are more shallow (figure 8a). It is worth noting that low time delays are observed at stations located in correspondence with high velocity superficial materials and upwelling of the bedrock (alluvial fan deposits, figure 8b).
The relative amplitude (figures 8a and 8b, bottom-right panels), that is the amplitude ratio of the initial P waves with respect to the reference site located on rock (Pe03), also correlate well with the thickness of the near surface low velocity layers. P-wave amplitudes indicate a mean amplification factor of about 3 - 4 for stations located on ancient terraces, of about 2 - 3 for alluvial fan deposits and of about 5 - 6 for riverbed recent and thick sediments.

**Conclusion**

In this paper we verify the potentiality of a procedure to analyse site response by applying teleseismic data only. In particular this work deals with the comparison of the results coming from the application of a standard spectral ratio technique (H/V) to different types of seismic signals, considering different local geological conditions. The H/V analysis was performed using microtremors, local and teleseismic events separately and the results converge on the same value of fundamental resonance frequency. On the contrary, the H/V of noise gives lower levels of amplification with respect to H/V of teleseisms and local earthquakes.

Finally, an accurate processing of the available teleseismic seismograms allows us to point out the correlation between both P-phase arrival time delays and P-wave relative amplitude with respect to the bedrock topography and alluvial deposit thickness. This result confirms that by analysing teleseismic data it might be possible to estimate local amplification effects and preliminarily map the 2D geometry of a valley or a basin. The case of the Pellice Valley shows that, in a region characterised by a low seismicity rate, a spectral analysis based on teleseismic signals could be an important tool to reliably define the site response and the main geological structure of the valley.

**References**

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Parolai S., Richwalski S. M., Milkereit C., Bormann P., 2004: Assessment of the stability of H/V spectral ratios from ambient noise and comparison with earthquake data in the Cologne area (Germany), Tectonophysics, 390, 57-73 pp.


Captions

Table 1: teleseisms recorded by the temporary network between November 2004 and February 2005

Figure 1: Geological setting of the Pellice Valley near Torre Pellice village (simplified map). The position of the velocimetric stations (white and grey circles), the down-hole tests (grey pentagons) and seismic profiles (white lines) is shown.

Figure 2: Signal (grey line) to Noise (black line) ratio for stations Pe03, Pe06 and Pe07.

Figure 3: H/V spectral ratios computed for Pe07 considering 20-s-long window including PKP phase (top panel) and sPKP phase (bottom panel).
Figure 4: shape of the waveforms of teleseism no. 17 (table 1) as recorded by Pe03, Pe06 and Pe07 stations. Note the same amplitude scales (the recordings are deconvolved by instrument response and filtered by a low-pass filter at 20 Hz). The shaded areas indicate the 20s-long windows used to compute the H/V ratio.

Figure 5: Averaged H/V spectral ratios ± one standard deviation of teleseisms (A), noise (B) and local events (C) for the Pe03 station. The shaded area in the A panel indicates the frequency band in which the S/N is small and the H/V result could be significantly biased by the noise.

Figure 6: Same as figure 5 but for the Pe06 station.

Figure 7: Same as figure 5 but for Pe07 station.

Figure 8a: Top panel: geological section coincident with the eastern seismic profile in figure 1; the material types and Vp and Vs values (as derived from the reflection profiles and down-hole tests) of soils and the probable geometry of the bedrock are shown. Bottom panels: P wave arrival time delays and relative amplitudes of P waves computed with respect to the Pe03 station. In the arrival time delay plot (bottom-left panel) the black crosses indicate the theoretical delay times derived considering vertical propagation through the 1D velocity structure below each station.

Figure 8b: Top panel: geological section coincident with the western seismic profile in figure 1; the material types and Vp and Vs values (as derived from the reflection profiles and down-hole tests) of soils and the probable geometry of the bedrock are shown. Bottom panels: P wave arrival time delays and relative amplitudes of P waves computed with respect to the Pe03 station. In the arrival time delay plot (bottom-left panel) the black crosses indicate the
theoretical delay times derived considering vertical propagation through the 1D velocity structure below each station.

Acknowledgement

The investigation campaign was made with the collaboration of A.R.P.A Piemonte, University of Turin, Politecnico di Milano and Geo-Expert S.r.l. in the framework of the Sismovalp Project (Seismic Hazard and Response Analysis in Alpine Valleys).
Figure 1
Figure 2
Figure 3
Figure 4
Figure 5
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Figure 8
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**Table 1**