Site-Amplification Effects Based on Teleseismic Wave Analysis: The Case of the Pellice Valley, Piedmont, Italy

by G. Ferretti, M. Massa, L. Isella, and C. Eva

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 (northwestern 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 (HVSRs) 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 HVSR results obtained by considering teleseismic signals is confirmed by the agreement with the results coming from both the HVSR of noise and HVSR 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.

Introduction

One of the most important problems in microzonation studies is the evaluation of site response. Site effects related to geological and geomorphological 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 characterized 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 horizontal-to-vertical spectral ratio (HVSR) 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-Garcia, 1993; Lachet and Bard, 1994; Bard, 1998; Bindi et al., 2000, Parolai et al., 2001, 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, HVSRs of teleseismic recordings are computed and the results are compared with the same nonreference site technique applied to local earthquakes (Lermo and Chavez-Garcia, 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 $P$-wave arrival time delays and relative $P$-wave 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 HVSR 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; Barnaba et al., 2006; Cauzzi et al., 2006; Lacave and Lemeille, 2006; Turino et al., 2006).

Geological and Geophysical Frameworks and Seismic Network

The Pellice Valley is an alpine valley located in the northwest of the Piedmont region (Italy); the area is char-
characterized by a substratum made up of the rocks of the Dora-Maira Massif superimposed by an ancient depositional sequence characterized by lacustrine and/or palustrine sediments; superimposed on the lacustrine deposits are coarse deposits of gravel and pebbly sands characterized 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 characterized by four different geological settings, as shown in the simplified geological map (derived from the geological map compiled by A.R.P.A. Piemonte [Regional Agency for Environmental Protection, Piedmont, Italy] scale 1:10000) in Figure 1. These settings are (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 northwestern part of Torre Pellice village characterized by alluvial fan deposits; (3) the area located in the village center in which ancient fluvial deposits, made up of several orders of terraces, are present; and (4) the riverbed area characterized by recent fluvial deposits. The area located to the south of the Pellice River (where the reference station Pe03 is located) is characterized by a gneiss outcrop.

Under the scope of the Interreg Sismovalp Project, a multidisciplinary subsoil exploration survey was undertaken to define the physical-mechanical parameters of the superficial material and provide information about the geometry and the depth of the bedrock. The investigation survey, as described in detail in Cauzzi et al. (2006), included four boreholes, four down-hole seismic tests, and two reflection seismic profiles (gray pentagons and white lines in Fig. 1). The four 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 interdistance of 2 m 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.

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 Fig. 1). To better cover the area another six velocimetric stations were installed in November 2004 (gray circles in Fig. 1).

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 the 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 analyzed to estimate site response by applying the standard HVSR method (Bonilla et al., 1997; Parolai et al., 2000, 2004). The data processing was performed by using the following procedure.

**Step 1.** A preliminary selection of high-quality teleseismic signals was made considering recordings with a signal-to-noise (S/N) ratio greater than 15 dB. The S/N ratios, calculated using 20 sec of pre-event noise and 20 sec 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) to 3 Hz, the level of teleseismic signals is clearly over the noise level (Fig. 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 20 sec, 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).

---

### Table 1

<table>
<thead>
<tr>
<th>Date (yy/mm/dd hh:mm)</th>
<th>Latitude (°)</th>
<th>Longitude (°)</th>
<th>Depth (km)</th>
<th>Magnitude</th>
<th>Δ (°)</th>
<th>Azimuth (°)</th>
<th>Event No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>04/11/11 21:40</td>
<td>8.15 S</td>
<td>124.87 E</td>
<td>10.0</td>
<td>7.5</td>
<td>115</td>
<td>76</td>
<td>1</td>
</tr>
<tr>
<td>04/11/15 09:18</td>
<td>4.70 N</td>
<td>77.51 W</td>
<td>15.0</td>
<td>7.2</td>
<td>83</td>
<td>270</td>
<td>2</td>
</tr>
<tr>
<td>04/11/17 21:26</td>
<td>20.07 S</td>
<td>178.71 W</td>
<td>622.0</td>
<td>6.6</td>
<td>185</td>
<td>13</td>
<td>3</td>
</tr>
<tr>
<td>04/11/22 20:45</td>
<td>46.68 S</td>
<td>164.72 E</td>
<td>10.0</td>
<td>7.1</td>
<td>164</td>
<td>105</td>
<td>4</td>
</tr>
<tr>
<td>04/11/26 02:39</td>
<td>3.61 S</td>
<td>135.40 E</td>
<td>10.0</td>
<td>7.2</td>
<td>119</td>
<td>64</td>
<td>5</td>
</tr>
<tr>
<td>04/11/28 18:43</td>
<td>43.01 N</td>
<td>145.12 E</td>
<td>39.0</td>
<td>7.0</td>
<td>85</td>
<td>30</td>
<td>6</td>
</tr>
<tr>
<td>04/12/13 15:35</td>
<td>13.39 N</td>
<td>89.37 W</td>
<td>62.0</td>
<td>6.0</td>
<td>85</td>
<td>284</td>
<td>7</td>
</tr>
<tr>
<td>04/12/14 23:28</td>
<td>4.77 S</td>
<td>152.46 E</td>
<td>97.0</td>
<td>4.3</td>
<td>130</td>
<td>48</td>
<td>8</td>
</tr>
<tr>
<td>04/12/14 23:31</td>
<td>18.96 N</td>
<td>81.41 W</td>
<td>10.0</td>
<td>6.8</td>
<td>76</td>
<td>283</td>
<td>9</td>
</tr>
<tr>
<td>04/12/18 06:57</td>
<td>48.84 S</td>
<td>156.31 E</td>
<td>11.0</td>
<td>6.2</td>
<td>83</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>04/12/22 21:22</td>
<td>55.94 S</td>
<td>125.00 W</td>
<td>10.0</td>
<td>6.1</td>
<td>148</td>
<td>232</td>
<td>11</td>
</tr>
<tr>
<td>04/12/26 01:10</td>
<td>3.30 N</td>
<td>95.98 E</td>
<td>30.0</td>
<td>9.0</td>
<td>87</td>
<td>89</td>
<td>12</td>
</tr>
<tr>
<td>04/12/26 04:32</td>
<td>6.91 N</td>
<td>92.96 E</td>
<td>39.0</td>
<td>7.5</td>
<td>82</td>
<td>88</td>
<td>13</td>
</tr>
<tr>
<td>05/01/09 22:24</td>
<td>4.93 N</td>
<td>95.11 E</td>
<td>40.0</td>
<td>6.1</td>
<td>85</td>
<td>88</td>
<td>14</td>
</tr>
<tr>
<td>05/01/12 08:48</td>
<td>0.88 S</td>
<td>21.19 W</td>
<td>10.0</td>
<td>6.8</td>
<td>52</td>
<td>217</td>
<td>15</td>
</tr>
<tr>
<td>05/01/31 01:07</td>
<td>37.53 N</td>
<td>20.16 E</td>
<td>31.0</td>
<td>5.8</td>
<td>12</td>
<td>122</td>
<td>16</td>
</tr>
<tr>
<td>05/02/08 15:05</td>
<td>14.25 S</td>
<td>167.26 E</td>
<td>206.0</td>
<td>6.8</td>
<td>145</td>
<td>35</td>
<td>17</td>
</tr>
<tr>
<td>05/02/22 02:32</td>
<td>30.74 N</td>
<td>56.83 E</td>
<td>14.0</td>
<td>6.5</td>
<td>41</td>
<td>93</td>
<td>18</td>
</tr>
</tbody>
</table>
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 north–south and east–west components were averaged (root-mean-square) to obtain a horizontal component Fourier spectrum.

Step 3. The HVSR was calculated considering the Fourier spectra computed in Step 2. Note that the use of different portions of teleseismic recording containing different teleseismic phases leads to stable HVSRs (Fig. 3). The average HVSR 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 with 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 bandpass filtered between 0.2 and 1 Hz, according to S/N analysis (same as in Step 1 but considering shorter window lengths 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.

![Figure 4. Shape of the waveforms of teleseisms no. 17 (Table 1) as recorded by Pe03 (bedrock), Pe06 (alluvial terraces), and Pe07 (riverbed) 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 20-sec-long windows used to compute the HVSR.](image-url)
Results

In the top panels of Figures 5, 6, and 7 the HVSR curves computed considering teleseismic events for the stations Pe03 (Fig. 5a), Pe06 (Fig. 6a), and Pe07 (Figure 7a) 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. Note that the HVSR of teleseisms are reliable in the frequency range between 0.2 and 3 Hz only, according to S/N analysis (Step 1). The results obtained processing teleseismic data are compared with HVSRs of ambient noise (Figs. 5b, 6b, and 7b) and of local earthquakes (Figs. 5c, 6c, and 7c). The microtremor recordings were processed with the Nakamura technique (Nakamura, 1989) taking into account 40-min-long signals recorded for each site in different noise conditions (both night and day) and dividing each recording, filtered between 0.2 and 20 Hz, into 40-sec-long windows. The Fourier spectra of the north–south and east–

Figure 5. Averaged HVSRs ± one standard deviation of teleseismic (a), noise (b), and local events (c) for the Pe03 station. The shaded area in the top panel (a) indicates the frequency band in which the S/N is small and the HVSR result could be significantly biased by the noise.

Figure 6. Same as in Figure 5 but for the Pe06 station.

Figure 7. Same as in Figure 5 but for the Pe07 station.
west components were smoothed (Hanning window) and averaged to obtain the horizontal component Fourier spectrum and the mean and standard deviation (±1σ) of all HVSRs were computed for each site. Local earthquake data (M1 <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 (±1σ) of all HVSRs, 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 HVSRs from noise and local earthquakes and the agreement between the results is confirmed for each site condition analyzed in this test. Note that, between 0.2 and 3 Hz, the differences in resonance-frequency peak and amplification level between the HVSRs of teleseisms and of local events for all stations are negligible. On the contrary, the HVSR of noise results shows a 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 (two reflection profiles and four down-hole tests). The absolute values of arrival-delay residuals, calculated with respect to the Pe03 reference station, vary between 0.02 and 0.16 sec 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 60 m, and decrease toward the alluvial terrace zone (Pe04, Pe06) where the high-velocity layers (till and bedrock) are more shallow (Fig. 8a). Note that low time delays are observed at stations located in correspondence with high-velocity superficial materials and upwelling of the bedrock (alluvial fan deposits; Fig. 8b).

The relative amplitude (Fig. 8a and b, 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 article we verify the potentiality of a procedure to analyze 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 HVSR technique to different types of seismic signals, considering different local geological conditions. The HVSR 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 HVSR of noise gives lower levels of amplification with respect to the HVSR of teleseisms and local earthquakes.

Finally, 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 analyzing 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 characterized by a low-seismicity rate, a spectral analysis based on teleseismic signals could be an important tool to reliably define the main geological structure of the valley.

Acknowledgments

The investigation 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).

References

Frischknecht, C., F. Rosset, and J. J. Wagner (2005). Toward seismic mi-
Figure 8. (a, top) Geological section coincident with the eastern seismic profile in Figure 1; the material types and $V_p$ and $V_s$ values (as derived from the reflection profiles and down-hole tests) of soils and the probable geometry of the bedrock are shown. (a, bottom) $P$-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. (b, top) Geological section coincident with the western seismic profile in Figure 1; the material types and $V_p$ and $V_s$ values (as derived from the reflection profiles and down-hole tests) of soils and the probable geometry of the bedrock are shown. (b, bottom) $P$-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.


Parolai, S., P. Bornmann, and C. Milkereit (2001). Assessment of the natural frequency of the sedimentary cover in the Cologne area (Germany) using noise measurements, *J. Earthquake Eng.* 5, no. 4, 541–564.


