



SEISMIC RESPONSE OF ALPINE VALLEYS: THE CASE OF VAL PELLICE, ITALY

Carlo CAUZZI¹, Claudio EVA², Gabriele FERRETTI², Vittorio GIRAUD³ and Roberto PAOLUCCI¹

SUMMARY

In the framework of the EC-funded Sismoalp project, dealing with the evaluation of seismic risk in Alpine valleys, the seismic response of Val Pellice, a fluvial –glacial valley located in North-Western Italy, Piemonte, has been analyzed. A temporary seismic network with several accelerometer and velocimeter stations was installed in the municipal area of Torre Pellice between June 2004 and March 2005, recording a large amount of weak earthquakes and teleseismic events. Local amplification of seismic waves is first investigated through HVSR and RSM techniques. Subsequently, the empirical spectral ratios are compared with the transfer functions of 1D and 2D numerical simulations performed on two different cross-sections of the valley, derived from hybrid seismic profiles, down-hole and SASW tests. We conclude that the seismic response of a relatively narrow and complex valley such as Val Pellice is dominated by 2D effects, posing relevant problems in the interpretation of the experimental amplification functions.

1. INTRODUCTION

We deal here with the evaluation of Val Pellice seismic response, a fluvial –glacial valley located in North-Western Italy, Piemonte. The analysis was carried out in the framework of the EC-funded Sismoalp project and was based, on one side, on the application of spectral techniques on the records of a small temporary network and, on the other side, on the numerical simulation of the seismic response of two transverse cross-sections of the valley, derived from geophysical-geotechnical surveys.

Due to tourism and industrial development, urbanised areas located in Alpine valleys have undergone massive development during recent years. In the last decade, many seismological studies have shown that vibrations due to earthquakes are strongly amplified by alpine-specific soil conditions. Therefore, the alpine fast building expansion may have not been regulated by adequate levels of earthquake resistant design. The main objectives of the Sismoalp project (Seismic Hazard and Alpine Valley Response Analysis) are i) the construction of transnational databases which can be used in the alpine space for seismic hazard studies; ii) the definition of representative alpine valleys shapes and earthquake scenarios; iii) the numerical simulation of the associated earthquake-induced ground motion; iv) the proposition of spectral shapes and accelerograms suitable for the Alpine environment and comparison with the level of protection pursued at a national or European (EC8) scale. The final task of the project is the dissemination of the previous results to civil engineers and local authorities in order to reduce seismic vulnerability in the alpine space.

¹ Department of Structural Engineering – Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133 Milano, Italy
Email : cauzzi@stru.polimi.it; paolucci@stru.polimi.it

² Dip. Te. Ris. – Università di Genova, Viale Benedetto XV, 16132 Genova, Italy
Email : eva@dipteris.unige.it; ferretti@dipteris.unige.it

³ Arpa Piemonte, Via S. Giuseppe 39, 10064 Pinerolo (TO), Italy
Email : Vittorio.Giraud@regione.piemonte.it

Site effects related to geological and geo-morphological setting and topography 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. A joined approach of these two methods could lead to reliable and very accurate determination of the site response as a function of fundamental resonant frequency and of the amplification level of the site. Among methods based on instrumental recordings we mention reference site [Borcherdt, 1970; Bonilla et al., 1997; Parolai et al., 2000] and non-reference site [Lermo and Chavez-Garcia, 1993; Lachet et al., 1996] approaches. The standard HVSR (horizontal to vertical spectral ratio) technique can be applied to ambient seismic noise records [Nakamura, 1989] and/or to earthquake data. Nevertheless, the assessment of site amplification effects by means of microtremor measurements alone often lead to unreliable results as demonstrated in many studies [Lermo and Chavez-Garcia, 1993; Lachet and Bard, 1994; Bard et al., 1998; Bindi et al., 2000; Parolai et al., 2001; Parolai et al., 2004], so that the collection of a suitable data set of seismic events is needed to ensure accurate site response estimation. Reference site methods (RSM) assume that records from the reference site (generally a station installed on outcropping hard rock) contain the same source and propagation effects as records from sedimentary sites and, especially when using the S-wave part of the seismograms, provide a frequency amplification function of the site similar in shape to the HVSR method. However in some cases the level of amplification may differ. In addition, also the generalized inversion technique (GIT) [Castro et al., 1990] can be used to calculate site response separating the contribution of path, source and site by means of an inversion scheme.

2. GEOLOGICAL FRAMEWORK AND SEISMIC NETWORK

Val Pellice is an alpine valley located in the Western part of Piemonte (Italy). The area is characterised by a substratum consisting of rocks of the Dora-Maira Massive superimposed by an ancient depositional sequence characterised by lacustrine and/or palustrine sediments; lacustrine deposits are covered by crude deposits of gravel and pebbly sands characterised by heterogeneity and considerable alteration.

This study has been concentrated in Torre Pellice, the main municipal area of the valley. The local geology is characterised by four different geological settings, as reported in the simplified geological map of Figure 1:

- 1) the edge of the valley, in which the gneiss formation outcrops (rocks of the Dora-Maira Massive);
- 2) the North-Western part of Torre Pellice, characterised by alluvial fan deposits;
- 3) the town centre, in which ancient fluvial deposits, made up of several orders of terraces, are present;
- 4) the riverbed area, characterised by recent fluvial deposits.

Within the scope of the Sismoalp project, a thorough subsoil exploration was undertaken with the aim of defining the physical-mechanical parameters of the superficial lithotypes as well as providing information about the geometry and the depth of bedrock structures. The investigation survey included: 4 boreholes, 4 seismic down-hole, 4 SASW tests and 2 hybrid seismic profiles (yellow pentagons and white lines in Figure 1).

For optimally designing the temporary seismic network a preliminary noise survey was carried out in Val Pellice. The HVSR technique was applied on microtremor observations, collected using Marslite acquisition units coupled to Lennartz 3D seismometers: the results from 15 measurement points clearly revealed peaks in the frequency response ranging 1.2 - 1.5 Hz along the riverbed and suggested the presence of amplification phenomena between 2 Hz and 3 Hz all over Torre Pellice town alluvial terraces. Then, since June to November 2004, a temporary network composed by six accelerometer stations was installed in the municipal area of Torre Pellice (see Figure 2). K2-Kinematics digital recorders were used, coupled with (external or internal) Episensor FBA ES-T accelerometers. Moreover, a velocimeter (Lennartz 3D-5s/MarsHD) was installed in the town centre in order to detect teleseismic events, useful to better investigate seismic response for frequencies lower than 1 Hz.

As shown in Figure 2, the network was deployed following roughly the two seismic profiles in Torre Pellice, both perpendicular to River Pellice. Two accelerometer stations (PE01-PE07) were installed in the riverbed, three on the alluvial terraces (PE04-PE05-PE06) in Torre Pellice town centre, one on alluvial fan (PE02) and one on outcropping gneiss (PE03). Between November 2004 and December 2004 four velocimeter stations (PE08-PE09-PE10-PE11) were installed in order to better investigate the seismic response of both the lower part of the fluvial fan and the riverbed. During the month of December 2004 all residual receivers were removed and three velocimeter stations were installed at the sites previously adopted for PE03 PE06 and PE07. These stations were removed at the end of March 2005.

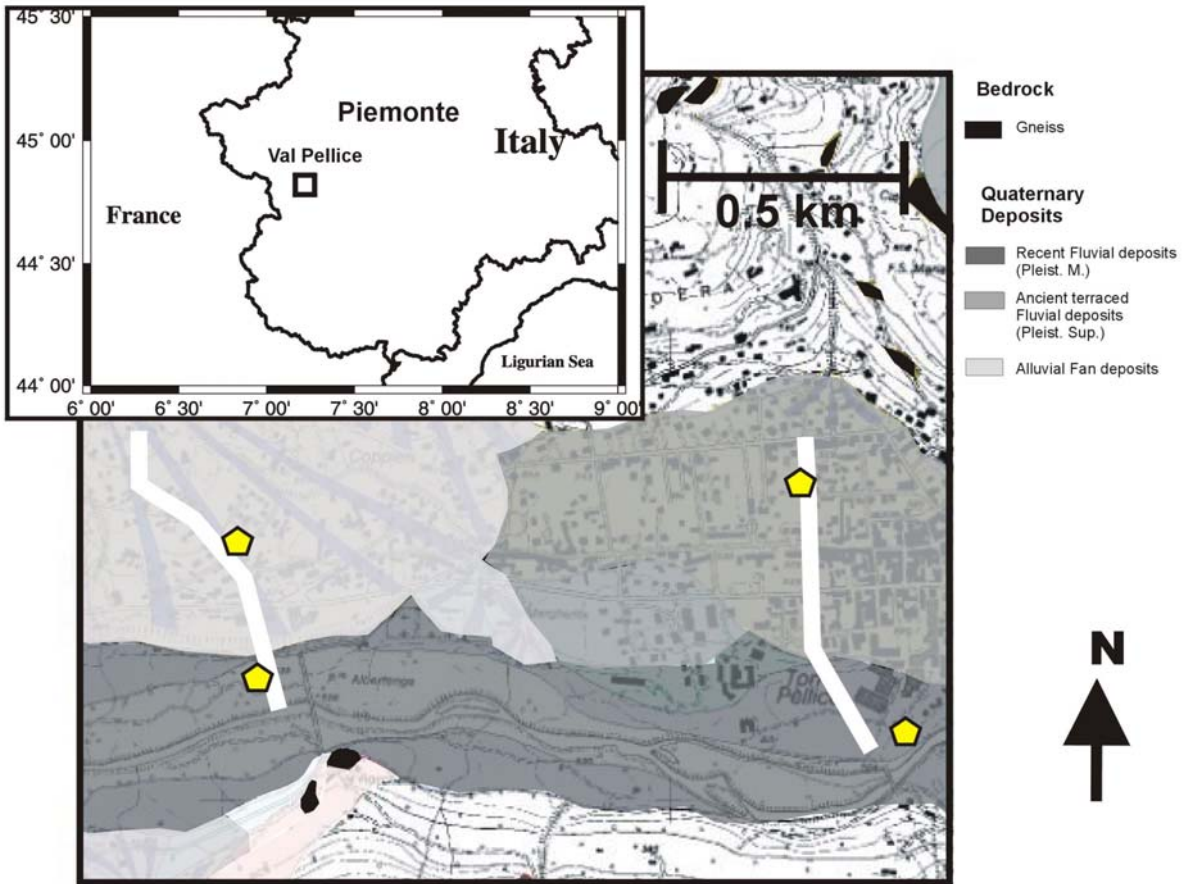


Figure 1: Geological setting of the municipal area of Torre Pellice. The position of down-hole and SASW tests (yellow pentagons) along with seismic profiles (white lines) is reported.

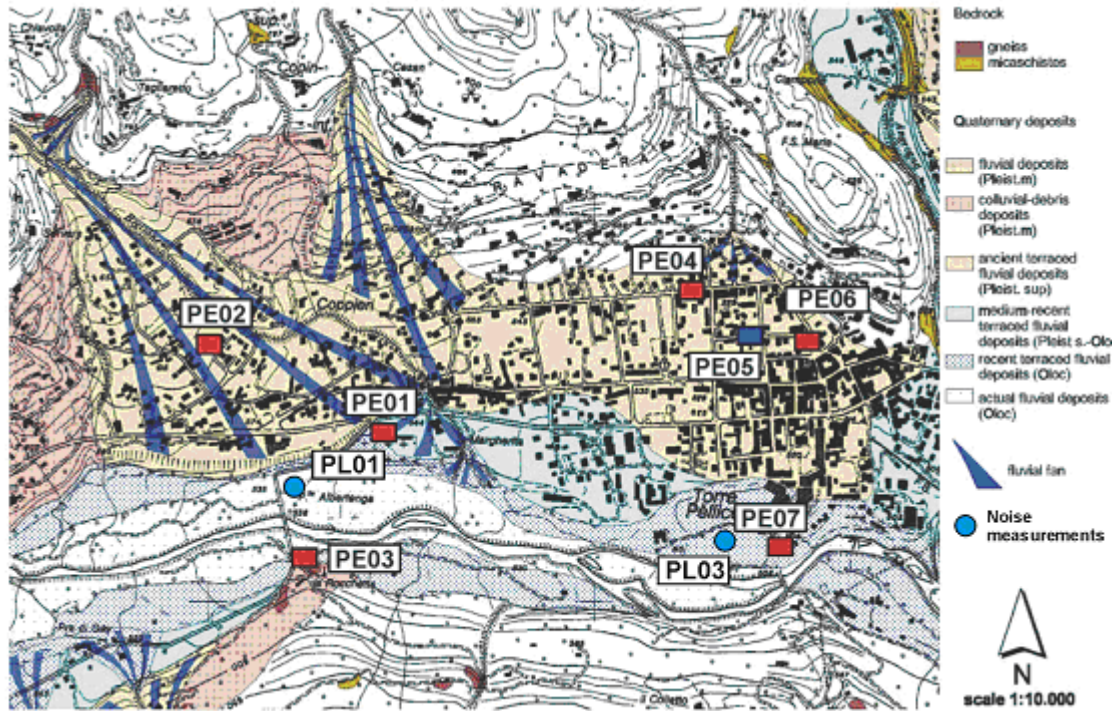


Figure 2: Temporary seismic network working in the period June 2004 – November 2004. Red and blue rectangles indicate accelerometer and velocimeter stations respectively.

3. HVRS AND RSM RESULTS

Since June 2004 to December 2004 more than 170 low energy seismic events ($2 < M_d < 3.5$) and several regional and teleseismic events have been recorded by installed accelerometers and velocimeters. All events were recognized and located by RSNI seismic network (Regional Seismic network of North-western Italy) managed by Dip.Te.Ris., University of Genoa.

Among micro-earthquakes showing an acceptable SNR (signal to noise ratio), records were selected focusing on:

- epicentral distance < 60 Km;
- duration magnitude > 2.5 .

Table 1: List of most relevant local, regional and teleseismic events recorded by the temporary network

Date (Time)	Magnitude	Epicentral area
24/07/2004 (21:03)	3.4	Argentera (Cuneo), Italy
01/09/2004 (17:04)	3.1	Acceglio (Cuneo), Italy
20/11/04 (18:25)	3.2	Faule (Cuneo), Italy
17/12/04 (01:42)	3.4	Northern Adriatic Sea
29/12/04 (22:49)	3.4	Lake Garda, Italy
14/01/05 (07:58)	4.0	Carniche Alps, Italy
13/03/05 (13:01)	3.2	Acceglio (Cuneo), Italy
12/07/04 (13:04)	5.2	Bovec, Slovenia
24/11/04 (23:59)	5.2	Salò (Brescia), Italy
05/12/04 (01:52)	5.1	Freiburg, Germany
26/12/04 (01:09)	9.0	Indonesia
31/01/05 (01:05)	5.8	Greece
22/02/05 (02:30)	6.5	Morocco

Using all events selected at each station, RSM (Reference Site Method) [Borcherdt, 1970; Andrews, 1986; Parolai, 2004] and HVSR techniques were applied. For what concerns RSM method, it is important to underline that a good seismic response estimation is generally obtained if the distance between each station and the reference site is small if compared to epicentral distance of selected events. Moreover, no site effects must be present at the reference site. Being installed on outcropping gneiss, PE03 was used as a reference station.

RSM and HVSR techniques were also applied to teleseismic events recorded by velocimetric stations in order to better investigate seismic response at low frequencies.

Results from spectral analyses pointed out the presence of relevant site amplification effects involving both Torre Pellice town and the surrounding areas. Starting from information derived using both RSM and HVSR techniques it is possible to recognize four main zones characterized by different seismic response:

- the riverbed zone, showing significant spectral amplifications in the frequency range 1-2 Hz;
- the ancient terraced fluvial deposits zone, characterized by relevant spectral amplifications in the frequency range 2 - 3 Hz;
- the fluvial fan zone, showing a wide band amplification pointed out through the calculation of RSM spectral ratios; in this case no site amplification phenomena have been recognized by using HVSR method;
- the zone located where the gneiss formation outcrops, where no amplification effects have been detected.

Observed amplification effects may depend on the presence of lacustrine deposits, mainly characterized by clay and sand, located in depth between alluvial gravel shallow deposits and altered bedrock formations (till). These deposits present, considering a section orthogonal to the river, both variable thickness and low values of shear waves ($300 \text{ m/s} < V_s < 450 \text{ m/s}$, on the basis of down-hole experiments performed by Politecnico di Torino) with respect to the underlying geological formations (bedrock formations).

The reliability of the analyses performed at different sites is confirmed by the substantial agreement among results coming from both HVSR and RSM techniques, applied for each considered station using noise, local earthquakes, regional and teleseismic events as input signal.

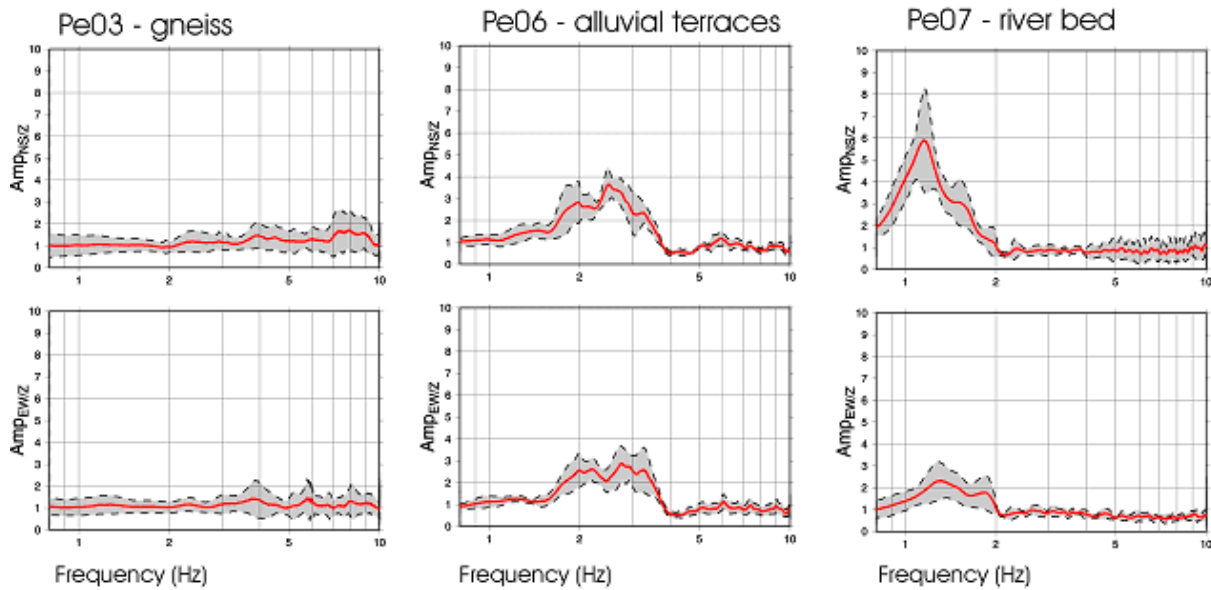


Figure 3: HVSR results; mean value of the HVSR curves (red line) and $\pm 1\sigma$ area (in grey) computed considering the best quality data (local, regional e teleseismic events) for three representative sites

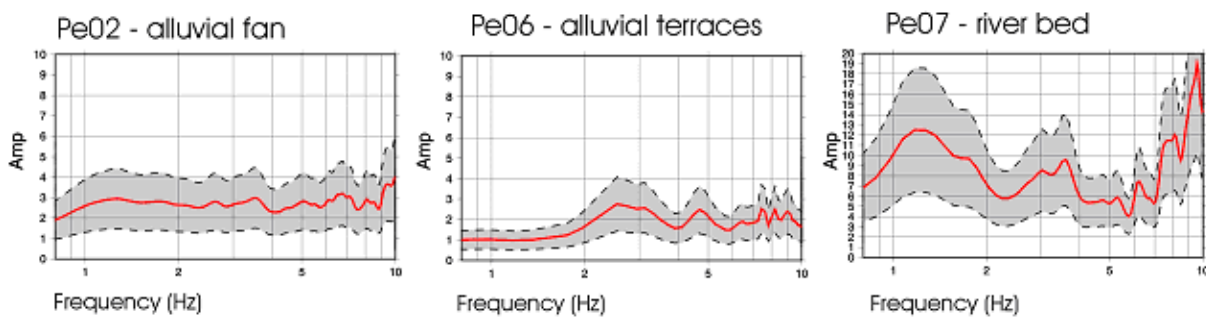


Figure 4: RSM results; mean value of the RSM curves (red line) and $\pm 1\sigma$ area (grey) computed averaging NS and EW component, considering the best quality data (local, regional e teleseismic events) and taking PE03 as reference site

4. NUMERICAL SIMULATIONS

In this chapter the main characteristics and results of 2D and 1D numerical analyses performed on two different cross-section of the valley are presented. Geotechnical models are derived merging data from geophysical and geotechnical tests (hybrid seismic profiles, SASW and down-hole tests) carried out in the municipal area of Torre Pellice between 2004 and 2006. Hybrid seismic lines and location of down-hole and SASW tests are plotted in Figure 1. For what concerns bedrock and till formations in the valley, the hybrid seismic survey revealed a partly unexpected complex geometry. Geotechnical properties are quite well known for shallow units thanks to the down-hole and SASW tests available. Modelling assumptions for deep structure characterisation are presented in the following.

2D numerical simulations are performed using the Spectral Element Method [Faccioli et al., 1997] implemented in the program GeoElse2D [Stupazzini, 2004]. Turning to 1D numerical analysis, the program EERA [Bardet et al., 2000] is used in this study. Non linearity is not taken into account in the analysis.

4.1 2D numerical analyses by SEM

Cross-section A (Figure 4) is related to Eastern seismic profile depicted in Figure 1. The main features of profile A are: (1) the 2D geometry of bedrock and till structures, and (2) the relevant extension of lacustrine deposits, reaching a maximum thickness of about 75 meters in the riverbed zone. Different alluvial units dominate the upper part of the model. Fluvial deposits in the riverbed have a maximum thickness of about 10 m. V_S values for

shallow alluvial deposits are well known from the results of two down-hole and two SASW test. The maximum depth reached with the down-hole test in the riverbed is 30 m, while information down to 50 m are available in the centre of the town. As an average value between the data available in the riverbed zone and in the town centre, V_s value for lacustrine deposits is set to 360 m/s in profile A. Material properties adopted for the different geotechnical units of profile A are listed in Table1.

Table 1: Profile A, material properties adopted for 2D numerical simulations

	V_s (m/s)	V_p (m/s)	Q
Bedrock	500-2400	865-4155	50-240
Till	800-2000	1385-3465	80-200
Lacustrine deposits	360	1700	40
Ancient alluvial deposits	730	1550	70
Ancient terraced alluvial deposits	420	790	40
Riverbed alluvial deposits	250	790	25

Cross-section B is constructed along the Western seismic line in Figure 1. The main features of profile B (see Figure 5) are: (1) the presence of a relatively small fluvial fan, and (2) a steep fluvial terrace. The lacustrine deposits have here a maximum thickness of about 50 meters in the riverbed. Shallow alluvial units substantially differ, in terms of mechanical properties, from the ones in profile A. Fluvial deposits in the riverbed have a maximum thickness of about 10 meters. V_s values for shallow alluvial deposits and the lacustrine unit are well constrained by the results of two down-hole and two SASW test. V_s for lacustrine deposits is set to 415 m/s in profile B. The maximum depth reached with the downhole tests is 40 meters in the riverbed and 26 meters on the alluvial fan. Material properties adopted for the different geotechnical units of profile B are listed in Table 2. For both models, V_s of till formation is assumed to be linearly increasing with depth from 800 m/s to 2000 m/s. V_s in the bedrock increases non uniformly with depth, according to [Faccioli, 1992] and [Cotton et al., 2005], from 500 m/s at the surface to 2400 m/s at a depth of about 200 meters.

Table 2: Profile B, material properties adopted for 2D numerical simulations

	V_s (m/s)	V_p (m/s)	Q
Bedrock	500-2400	865-4155	50-240
Till	800-2000	1385-3465	80-200
Lacustrine Deposits	415	1800	40
Alluvial Deposits	360	790	35
Fluvial Fan	760	1200	75
Riverbed Deposits	440	1200	40
Top Soil and Fill	195	800	20

For each cross-section, a fully unstructured numerical mesh consisting of quadrilateral elements has been constructed. The spatial discretization can accurately propagate frequencies up to 10 Hz. The models are excited by a vertically propagating plane wave, with a time dependence of the Ricker type, with peak frequency at 1.5 Hz and cut-off at 4.5 Hz, to encompass the frequency band between 1 and 3 Hz where the peaks of the experimental frequency response are observed. The mechanical behaviour for all geotechnical units is linear visco-elastic: nonlinearity is not taken into account. Absorbing boundary conditions [Stacey, 1988] are imposed at the bottom and on the lateral edges of the models. Time histories of displacement, stress and strain are obtained as output in the monitored nodes.

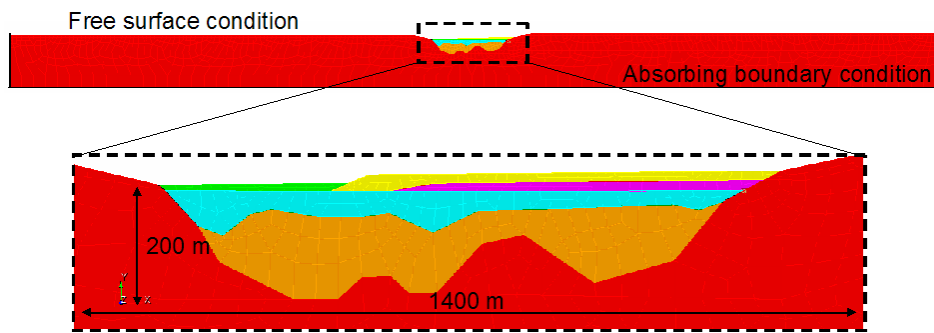


Figure 4: profile A, the whole model (top) and the area of interest (bottom). Geotechnical units are plotted with different colours: bedrock (red), till (brown), lacustrine deposits (blue), ancient alluvial deposits (purple), riverbed deposits (green), ancient terraced alluvial deposits (yellow)

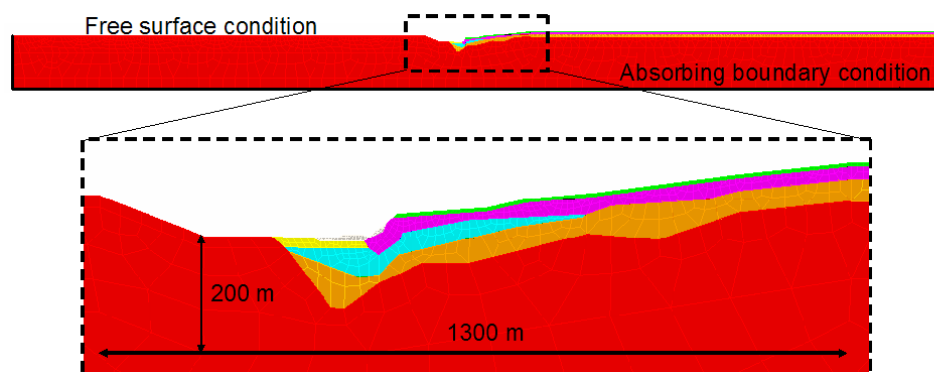


Figure 5: profile B, the whole model (top) and the area of interest (bottom). Geotechnical units are plotted with different colours: bedrock (red), till (brown), lacustrine deposits (blue), fluvial fan (purple), riverbed deposits (yellow), alluvial deposits (green), top soil and fill (light grey)

4.2 1D numerical simulations

1D simulations corresponding to down - hole and SASW tests locations are also performed to check whether significant differences exist between 1D and 2D seismic response of the valley . Results will be compared with the ones obtained by 2D analyses in the following. Material properties used in 1D simulation are listed in Table 1 and Table 2. Models in this case are represented by plane parallel layer systems, down to the underlying bedrock with $V_s = 2400$ m/s.

4.3 Results and comparison with experimental data

A summary of the numerical results, in terms of amplitude of the computed transfer functions, is reported in Figure 6 for both profiles A (top) and B (bottom). The comparison with the observed RSM (from local events only) and HVSR amplification functions is provided for the sites along the two cross-sections for which accelerometer stations are available, namely, PE07 and PE06 along profile A and PE02 along profile B.

Considering first profile A, the 2D spectral element simulations at point 2, within the riverbed, reveal a dominant amplification peak at about 2 Hz, while 1D analysis shows a fundamental resonance frequency at 1.05 Hz; this highlights that the seismic response is strongly influenced by the shape of the contact between lacustrine deposits and till in the riverbed, and 2D effects are prominent. Note that the 2D results are at variance with the HVSR amplification function (blue line in Fig. 6), which shows a significant spectral peak between 1 and 1.5 Hz, in better agreement with 1D simulations, while they are in closer agreement with the RSM function based on local events (red line in Fig. 6) suggesting amplification effects ranging in a relatively large band between 1.5 Hz and 2.5 Hz. This discrepancy with the HVSR may be likely attributed to the strongly 2D geometry of the site, for which the application of a non-reference technique such as the HVSR is questionable.

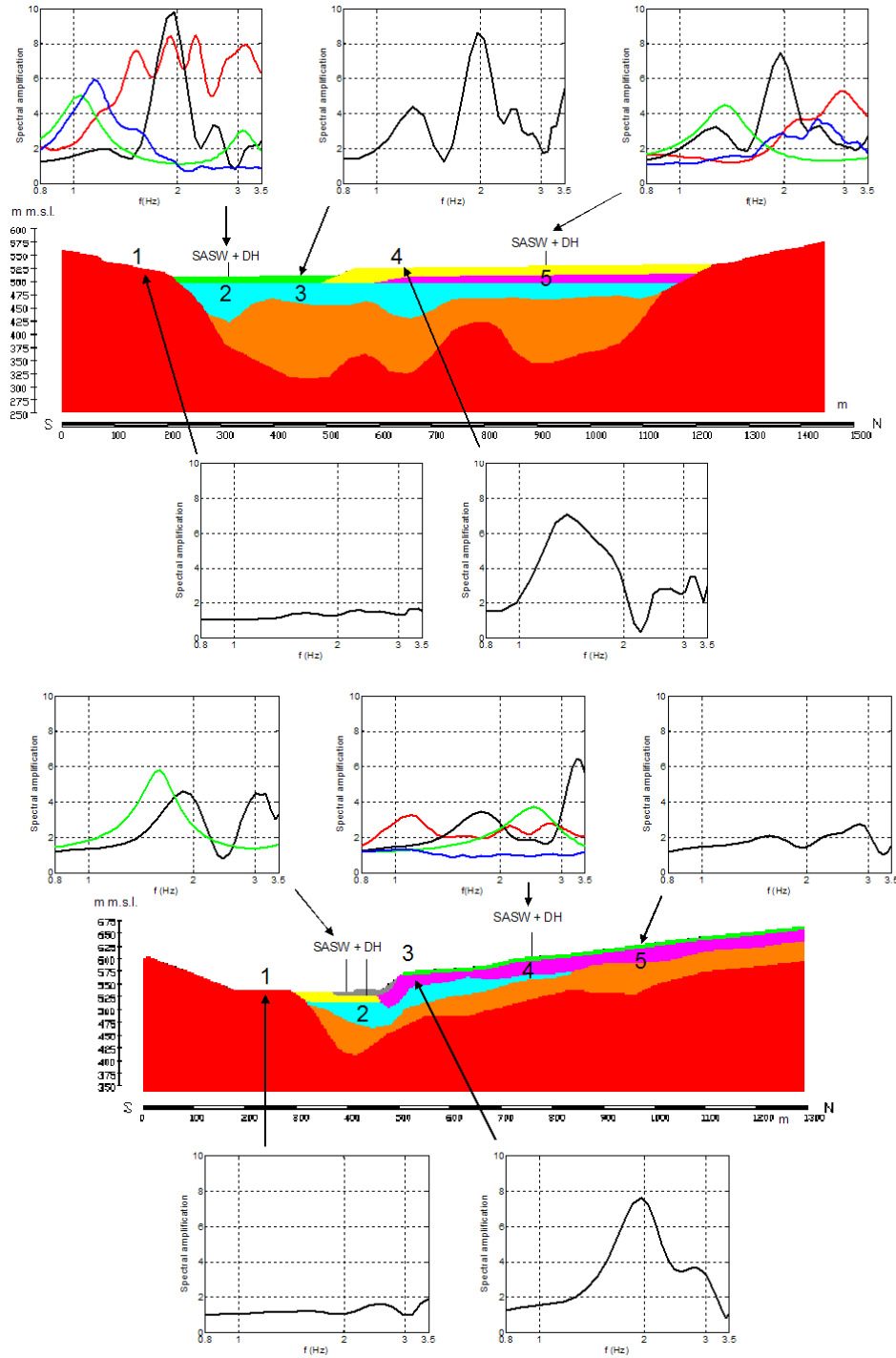


Figure 6: numerical transfer functions and experimental data for profile A (top) and B (bottom). Numerical transfer functions obtained by SEM (black lines) are compared with RSM results (red lines, average spectral amplification from local events only, N-S direction), HVSr (blue lines) and 1D transfer functions (green lines)

A similar disagreement of 2D and 1D results may be also noticed at point 5 on profile A (station PE06), where the seismic response turns out to be strongly influenced by the lateral contact between bedrock and till. In this case, both HVSr and RSM amplification functions suggest frequency peaks above 2 Hz, not far from the 2D transfer function, while the 1D response peaks at 1.35 Hz.

Referring now to profile B, we note that we have just a single accelerometer station available for comparison (PE02), while station PE01, installed in the riverbed zone at the beginning of the temporary seismic survey, was unfortunately soon removed due to technical problems. Experimental data at PE02 are compared with numerical

transfer functions at point 4, suggesting that the relatively wide band amplification observed at the fluvial fan can be predicted by our simulations. We note that, as for profile A, the resonance peaks from 1D and 2D are significantly different suggesting again that in a complex geological configuration like the one considered in this study, the 1D approximation may lead to inaccurate results. As a further support to this comment, we remark that at point 3, at the upper edge of the alluvial fan, the combined effect of topography and stratigraphy results in a relevant amplification effect at about 2 Hz.

5. CONCLUSIONS

Relevant amplification effects were highlighted through spectral analyses on local, regional and teleseismic events recorded in Val Pellice between 2004 and 2005 by a temporary seismic network installed within the framework of the European project Sismoalp. Four different zones can be recognized in Torre Pellice area: 1) the riverbed zone, showing significant spectral amplifications in the frequency range 1-2 Hz; 2) the ancient terraced fluvial deposits zone, characterized by relevant spectral amplifications in the frequency range 2 - 3 Hz; 3) the fluvial fan zone, showing a wide band amplification pointed out through the calculation of RSM spectral ratios (in this case no site amplification phenomena have been recognized by using HVSR method); 4) the gneiss formation outcrops, where no amplification effects have been detected.

Both 1D and 2D numerical simulations of seismic response were carried out, the latter ones based on the best interpretation of the geophysical and geotechnical investigations available. Both profiles show prominent 2D effects, with significant differences with respect to 1D results. The comparison with the observed amplification functions shows a reasonable agreement with the RSM results, considering the local events alone, but a significant discrepancy with the HVSR, especially in the locations where 2D effects dominate site response. The observed differences between experiments and modelling seem to be more related to geometric features of the models than to assumed mechanical properties of the different units.

Although further numerical analyses are foreseen to clarify the reasons of the observed discrepancy among the numerical and experimental site amplification functions, namely by investigating the influence of different modelling assumptions, especially the geometry and the dynamic properties of the geological units at depth, we can conclude that the seismic response of a relatively narrow and complex valley such as Val Pellice is dominated by 2D effects, posing relevant problems in the interpretation of the experimental amplification functions.

6. ACKNOWLEDGEMENTS

The contribution of Luana Isella, Luca Labaa, Marco Massa, Davide Villa, Enzo Zunino, and all other students, researchers and technicians who gave significant collaboration to the management of the seismic network, data analyses and simulations is gratefully acknowledged.

7. REFERENCES

- Bard, P.Y. (1998), Microtremor measurement: a tool for site effect estimation?, *Second International Symposium on the effects of the surface geology on the seismic motion, ESG98-Japan*.
- Bardet, J. P., Ichii, K. and Lin, C. H. (2000), EERA: a computer program for equivalent-linear earthquake site response analysis of layered soil deposits, *University of Southern California, Department of Civil Engineering*.
- Bindi, D., Parolai, S., Spallarossa, D. and Cattaneo, M. (2000), Site effects by H/V ratio: comparison of two different procedures, *Journal of Earth. Eng.*, 4, n° 1, 97-113.
- Bonilla, L. F., Steidl, J. H., Lindley, G. T., Tumarkin, A. G. and Archuleta, R. J. (1997): Site amplification in the San Fernando valley, California: variability of site effect estimation using S-wave, coda, and H/V method, *Bull. Seism. Soc. Am.*, 87, n°3, 710-730.
- Borcherdt, R. D. (1970), Effects of local geology on ground motion near San Francisco Bay, *Bull. Seism. Soc. Am.*, 60, 29-61.
- Cotton, F., Scherbaum, F., Bommer, J. J., and Bungum, H. (2005), Criteria for selecting and adjusting ground motion models for specific target regions: Application to Central Europe and rock sites, *Journal of Seismology* (accepted for publication).
- Faccioli, E., Maggio R., Paolucci R. and Quarteroni, A. (1997), 2D and 3D wave propagation by a pseudo-spectral domain decomposition method, *Journal of Seismology*, 1, 237-251.

- Faccioli, E., (1992), Selected aspects of the characterization of seismic site effects, including some recent European contribution, *International Symposium on the effects of surface geology on seismic motion, ESG92-Japan*
- Lachet, C. and Bard, P. Y. (1994), Numerical and theoretical investigations on the possibilities and limitations of Nakamura's technique, *Journals of Physics of the Earth*, 42, 377-397
- Lermo, J. and Chàvez-García, F.J. (1993), Site effects evaluation using spectral ratios with only one station, *Bull. Seism. Soc. Am.*, 83, n° 5, 1574-1594
- Nakamura, Y. (1989), A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface, *Rep. Railway Tech. Res. Inst., Jpn*, 30, n°1, 25-33
- Paolucci, R. (1999), Shear resonance frequencies of alluvial valleys by Rayleigh's method, *Earthquake Spectra*, 15, 503-521
- Parolai, S., Bindi, D. and Augliera, P. (2000), Application of the generalized inversion technique (GIT) to a microzonation study: numerical simulations and comparison with different site estimation techniques, *Bull. Seism. Soc. Am.*, 90, n° 2, 286-297
- 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, *Journal of Earth. Eng.*, 5, n° 4, 541-564
- Parolai, S., Richwalski, S. M., Milkereit, C. and 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.
- Riepl, L., 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, n° 2, 488-502
- Stacey, R. (1988), Improved transparent boundary formulations for the elastic wave equations, *Bull. Seism. Soc. Am.*, 78, 2089-2097
- Stupazzini, M. (2004), A spectral element approach for 3D dynamic soil-structure interaction problems (PhD Thesis), *Politecnico di Milano*