A comprehensive seismic characterisation via multi-component analysis of active and passive data

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Abstract

A comprehensive seismic survey was conducted with the aim of characterising one of the *Swiss Digital Seismic Network* stations in northern Switzerland. Both active (P- and S-wave refraction tomography, surface-wave analysis, vertical seismic profiling) and passive methodologies (wavelet decomposition, Horizontal-to-Vertical Spectral Ratio, three-component frequency-wavenumber analysis) were jointly considered in order to solve the intrinsic non-uniqueness of the solution and determine a consistent subsurface model free from ambiguities, eventually used for the assessment of the local site amplification.

Introduction

In cooperation with the National Cooperative for the Disposal of Radioactive Waste (Nationale Genossenschaft für die Lagerung radioaktiver Abfälle – Nagra), the Swiss Seismological Service (SED) has recently completed the installation of ten new seismological stations, three of them including a borehole sensor. The ultimate goal of the project is to densify the existing Swiss Digital Seismic Network (SDSNet) in Northern Switzerland, in order to increase the sensitivity to very-low magnitude events and to improve the accuracy of future location solutions. This is strategic for unbiased monitoring of micro-seismicity at the places of proposed nuclear waste repositories.

At each site, to further improve the quality and usability of the recordings, a full seismic characterisation of the area surrounding the seismological station was performed. The investigation consisted of a preliminary geological and geotechnical study, followed by an accurate seismic site response analysis by means of state-of-the-art geophysical techniques. For the borehole stations, in particular, the characterisation was quite accurate and performed by combining different types of active seismic methods (P- and S-wave Seismic Refraction Tomography – SRT, surface wave analysis, Vertical Seismic Profiling – VSP) with passive methodologies based on the analysis of the background microtremor field (wavelet decomposition, Horizontal-to-Vertical Spectral Ratio – HVSR, polarization analysis, three-component frequency-wavenumber analysis). Results converged to the definition of a unique summary velocity profile for the site, later used for the computation of the analytical SH-wave transfer function adopted for the seismic site-amplification assessment.

In this study, we describe the results obtained for the borehole station STIEG (Stiegenhof, Oberembrach – CH) by considering a massive active/passive multi-component dataset. The goal is to improve the reliability of the retrieved subsurface velocity model by decreasing the intrinsic non-uniqueness of the geophysical inverse problem.

The STIEG station consists of a short-period borehole sensor at a depth of about 100 m, and a surface strong motion seismometer, with high-resolution digitisers (24bit @200sps). The surface station sits on top of a gently-sloping hill in the Swiss Molasse basin (Figure 1), on free field conditions. Topography is the result of the action of glaciers during the Pleistocene and is superficially dominated by the occurrence of moraine deposits. The drilling – down to about 140 m – has shown some minor layers of sandstones in a sequence of silt and mudstones with no evidence of water saturation. This can be easily explained by the low permeability of the rocks that dominate the local stratigraphic sequence (the reader should also consider that – especially for these sorts of materials – water has a very minor influence on shear-wave velocities analysed in the present study). A thin weathered till of about 2 m covers the molassic rocks.

With respect to the note presented at EAGE Near Surface 2013 (Dal Moro and Keller, 2013), in this paper we illustrate the analyses performed by following several advanced approaches while considering both active and passive data (Figure 2). We eventually also briefly report the simulation of the local site amplification.

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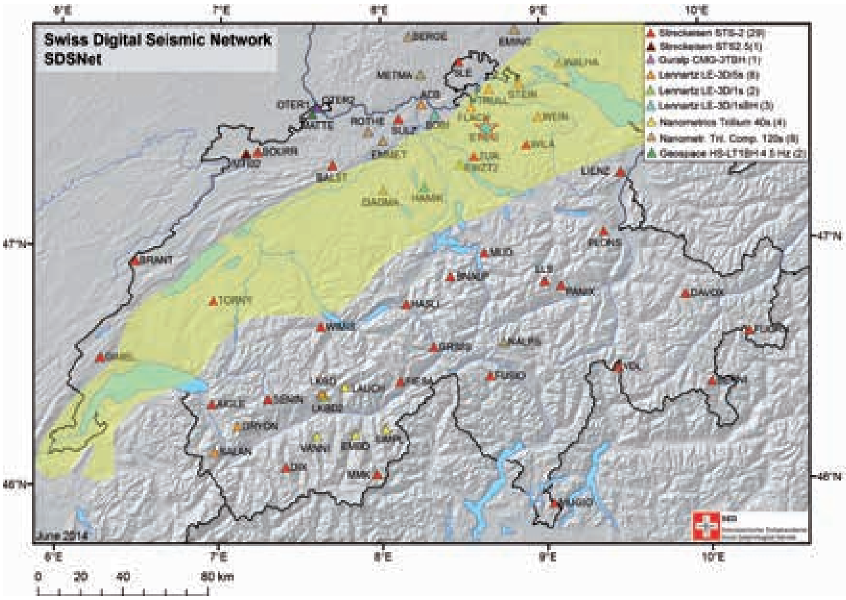

Figure 1 *The STIEG seismological station (red star, north of Zurich) is part of a network of dozens of stations around Switzerland. Around 15 of them are arranged in the Molasse basin (yellow).*

Figure 2 *The survey sketch shows the performed seismic profiles (in red), the borehole used for the VSP, the location of the microtremors stations used for the frequency-wavenumber (f-k) analysis (blue and yellow circles) and the location of the HVSR station.*

The multi-component approach: reducing non-uniqueness of the solution

In most of the studies aimed at site characterisation for geotechnical and seismic-hazard studies, the definition of the one-dimensional vertical shear-wave velocity profile is typically accomplished by the sole use of active or passive techniques (e.g., MASW (Multi-channel Analysis of Surface Waves), SPAC (Spatial Auto Correlation), ESAC (Extended Spatial Auto Correlation) and so forth). Moreover, the ordinary approach consists of analysing a single component (usually the dispersion depicted by the vertical component of Rayleigh waves), whose results are potentially affected by ambiguities related both to the intrinsic non-uniqueness of the solution and to erroneous velocity spectra interpretations (for a wider overview see Dal Moro, 2014).

This can be visually represented with a schematic sketch, such as the one reported in Figure 3. In this scheme, method/dataset#1 (for instance the vertical-component of Rayleigh waves) can be explained by the models A÷F equally well so that it is actually impossible to identify the *true* model. Similarly, the method/dataset#2 (e.g., Love waves) can relate to another (generally different) set of *equivalent* models, with only some of them in common with the method/dataset#1. As a logical consequence, combining the information from two (or more) methods/datasets helps to reduce the ambiguity, eventually ending up with the actual *right* model (in this case the model F).

Actually, these considerations are valid not only to underline that by using the right datasets/methods the obtained solution is necessarily more constrained (thus not

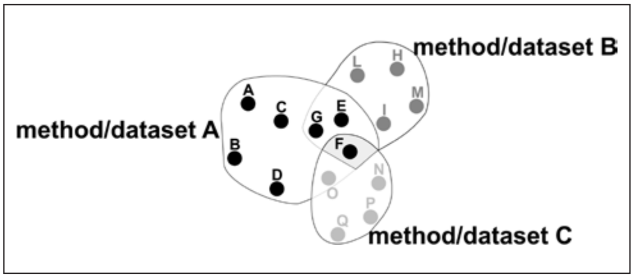

Figure 3 Visual representation of the ambiguity of the solution necessarily present while considering a single method or dataset and its solution by means of a joint analysis capable of fully constraining the solution towards the only model which results in agreement with all the observations.

ambiguous) but also, so-to-speak, in a vertical perspective: while active data are able to properly image only the shallow layers, passive techniques enable us to reach deeper strata.

As previously introduced, the approach we adopt is based on the integration of multiple sources of information, in order to increase the overall confidence on the final subsurface model. To achieve this goal, dispersion obtained from multi-component active and passive data are analysed together with the H/V spectral ratio. Furthermore, the shallow structure is also investigated by means of P- and S-wave seismic refraction tomography.

The V_S profile finally obtained is eventually compared with the one resulting from VSP (Vertical Seismic Profile) analysis and used to accomplish the seismic response analysis performed with the aim of assessing the local seismic hazard.

Acquired datasets

Active data

To characterise the shallow part of the site both in terms of V_P and V_S, a multi-channel and multi-component active seismic survey was performed (Figure 1) by deploying two perpendicular linear arrays (total length approximately 100 m). We used both vertical and horizontal sources and receivers to jointly acquire body (P and S) and surface waves (vertical and radial components of Rayleigh waves and Love waves). Such comprehensive dataset enables the performing of different analyses on different component combinations, such as P/S refraction tomography and surface-wave dispersion. Data were acquired by using low-frequency receivers: 4.5 Hz vertical and 10 Hz horizontal geophones (since this was the first of a series of surveys, 4.5Hz horizontal geophones – then used for all the successive sites – were unfortunately not available).

Rayleigh waves were produced by using a standard vertical-impact sledgehammer, while for the Love waves a simple wooden beam (coupled to the ground by means of a few metal spikes) was transversally hit.

Along one of the lines, we also tested a new active technique that, in spite of the extremely simple and straightforward field procedure (surface waves are recorded by using a single three-component geophone set at a distance which depends on the required penetration depth), potentially allows a well-constrained multi-component Holistic Surface-wave (HS) inversion of all the components describing the Rayleigh-wave dispersion (Table 1). An S- and P-wave VSP completed the dataset.

Passive data

Complementary to the active survey, an array of 14 seismological stations was used for the acquisition of nearly four hours of ambient vibration recordings. Each acquisition point within the array consisted of a three-component seismometer (Lennartz 3C with 5s eigenperiod) and a 24-bit data logger (Quanterra Q330). Synchronisation between stations was assured by standard GPS, while a more accurate differential GPS (Leica Viva system) was used to precisely locate the sensor coordinates with a tolerance of less than 5 cm.

	Multi-channel Surface Waves						
Method →	**ZVF (vertical)**	**RVF (radial)**	**THF (transverse)**	**HS**	**pVSP**	**sVSP**	**Microtremors (HVSR and *f-k*)**
Receivers	vertical geophones	horizontal (radial) geophones	horizontal (transversal) geophones	single 2Hz 3-component geophone	probe BGK-5, vertical component	BGK-5, 4 horizontal components	Lennartz 5S
Source	8-Kg sledgehammer	8-Kg sledgehammer	beam and vibro	8-Kg sledgehammer	8-Kg sledgehammer	vibro	ambient
Array	linear 94 m	linear 94 m	linear 94 m	single station	vertical 100 m	vertical 100 m	circular arrays (diameters 100 m & 200 m)
recording time	2 sec	2 sec	2 sec	2 sec	¼ sec	¼ sec	1h 40min 2h 15min

Table 1 Data acquisition parameters for the different surveys. Abbreviations in column header: ZVF Z-receiver, Vertical Force; RVF Radial receiver, Vertical Force; THF Transversal receiver, Horizontal Force (see Dal Moro, 2014); HS – HoliSurface holistic analysis of surface waves; pVSP p-wave vertical seismic profiling; sVSP s-wave vertical seismic profiling. For the sVSP acquisition, the adopted vibro source consisted of a horizontal shaker system (ElViS IIIs) with a linear 10sec sweep (20-180Hz).

The array consisted of two separated measuring configurations (A and B) of different diameters (100 m and 200 m, respectively – Figure 2). The two configurations were planned to partially overlap, by sharing nine common sensors, with the aim of providing a continuous resolution of the frequency range between the two geometries. Configuration A recorded for a total of 1h40min, while configuration B for 2h15min. The differences in the recording length are due to the different resolution characteristics of the two geometries since, as a general rule, larger arrays allow larger penetration depth, but require longer recording time to produce a reasonable statistic of the ambient vibration processing results. H/V spectral ratio was also computed to be jointly used with dispersion data to better constrain the deepest layers.

Joint analysis of dispersion from multi-component surface waves and HVSR

To describe the different components considered, we will adopt the notation widely described in Dal Moro (2014): ZVF – Z-axis receiver and Vertical Force; RVF – Radial receiver and Vertical Force; THF – Transversal receiver and Horizontal Force. Quite clearly, only some of the acquired and analysed data can be presented here both because several lines were actually investigated both because here the aim is just to provide a glimpse of how the joint analysis of the right datasets can actually provide accurate subsurface models. Figure 4 and 5 summarise the result of the joint analysis of the ZVF (i.e., the vertical component of Rayleigh waves once a vertical force is adopted as a source) and THF (i.e., Love waves) jointly with the HVSR curve (Dal Moro, 2010).

Here, the analysis of the phase velocity spectra is accomplished according to the Full Velocity Spectrum (FVS) (Dal Moro, 2014) approach and not by considering the modal dispersion curves.

That means that the observed velocity spectra were not interpreted in terms of dispersion curves but went directly through an inversion/modelling scheme that considered them in their wholeness (for details see provided references).

The background colours in Figure 4b represent the observed field velocity spectrum while the overlaying black contour lines relate to the synthetic spectrum of the identified V_S model reported in Figure 4d.

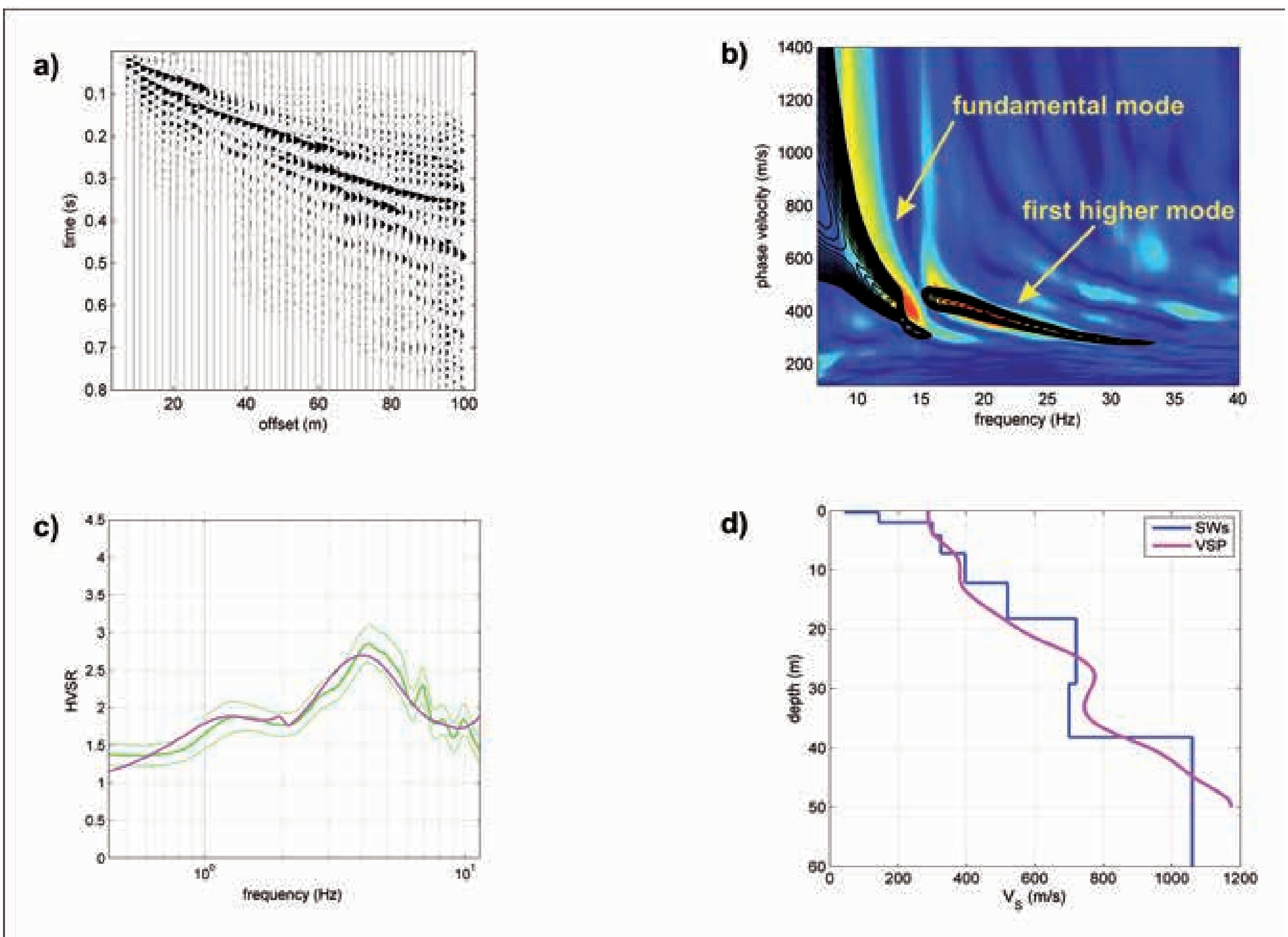

Figure 4 Joint analysis of Rayleigh-wave (vertical component processed according to the FVS approach) and HVSR: a) field seismic traces (ZVF component); b) phase velocity spectra (background colours report the field data while overlaying black contour lines of one of the identified models); c) observed and synthetic H/V spectral ratios; d) V_S model determined via joint analysis of Surface-Wave (SW) dispersion and HVSR and compared with the one obtained from VSP analysis.

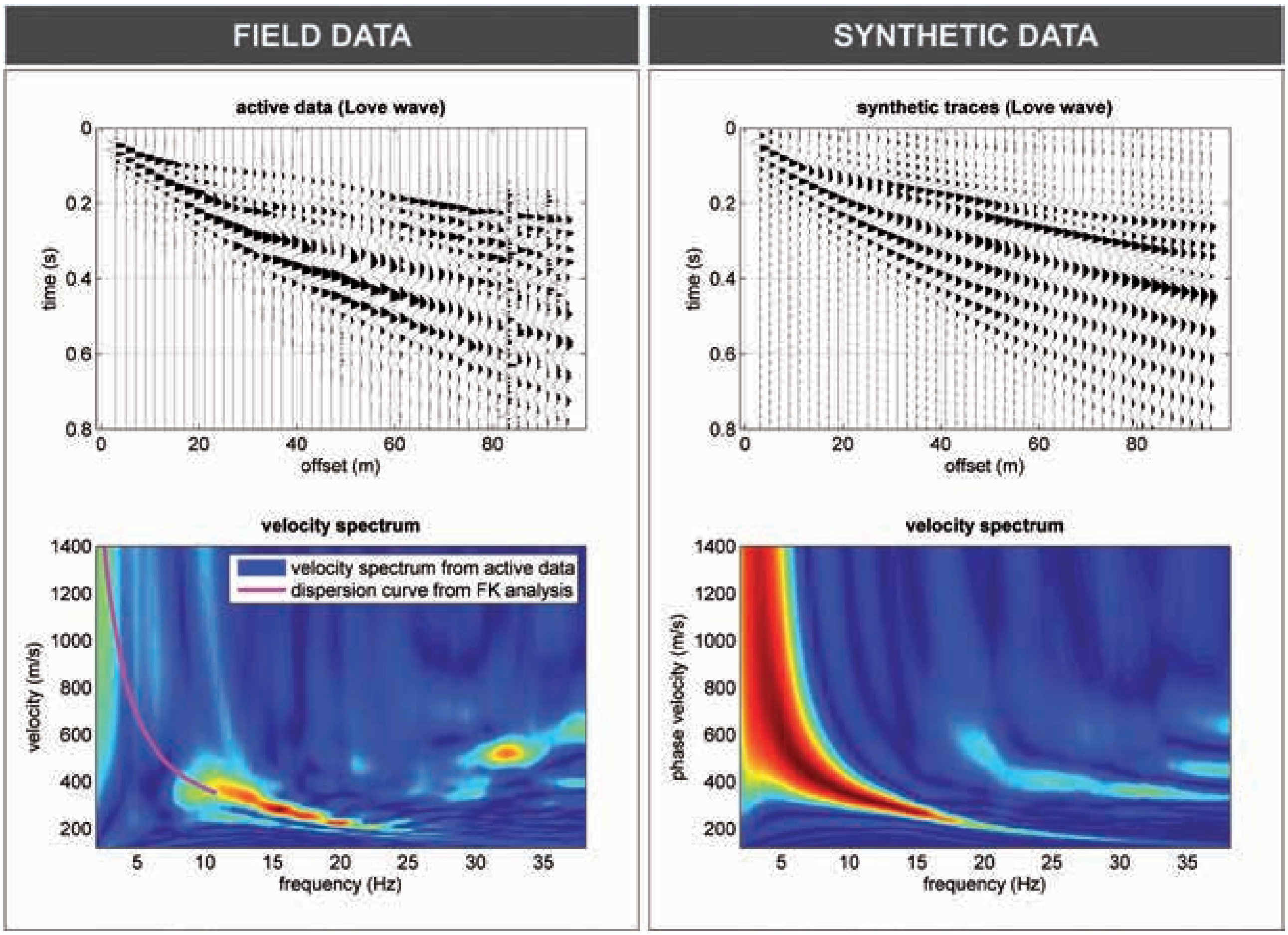

***Figure 5** Love waves: on the left column the field data (field traces and phase velocity spectrum – also reported the Love-wave dispersion curve retrieved from the f-k analysis) and, on the right column, the synthetic data (obtained though modal summation) related to the model reported in Figure 4d.*

It must be clearly underlined that a joint inversion inevitably represents a sort of compromise and the misfits obtained while practising such a compromise are most of the time inevitably slightly larger than while considering a single objective function.

In the present case, the joint use of the H/V spectral ratio (easily well-defined also for very low frequencies) allows for the constraining of the deepest layers otherwise poorly defined by the merely active data.

It must be strongly underlined that the vertical and the radial components of Rayleigh waves are, in general, different in terms of excited modes and neither of them can be universally claimed as the *best* one in terms of clearness of mode identification. While in some cases the radial component appears easier to understand, in others it is the opposite (Dal Moro, 2014).

Figure 5 reports the data pertaining to Love waves (the THF component) and shows a pretty remarkable consistency between the considered active and passive data. While the lack of low frequencies in the active dataset must be ascribed to the 10Hz geophones used for the acquisitions, the dispersion curve obtained though the frequency-wavenumber (*f-k*) analysis (Poggi and Fäh, 2010) was obtained thanks to a set of Lennartz three-component (5s eigenperiod) geophones. Field and synthetic data are reported on the left and right columns, respectively (synthetic data clearly refer to the same model reported in Figure 4d) and the overall consistency is apparent.

While the general agreement between VSP and surface-wave analysis is apparent (Figure 4d), it should be pointed out that due to the well-known difficulties in the identification of the shear-wave first arrivals for the shallowest layers and the consequent erroneous picking, in the first few metres VSP analysis often tends to overestimate the shear-wave velocities while surface-wave dispersion is definitely capable of providing accurate values.

Since not many researchers are currently familiar with the *f-k* methodology here adopted, few words might be probably useful to briefly recall its fundamentals.

The frequency-wavenumber analysis is a spectral technique based on seismic array recordings that allows for the retrieving of the direction and the dispersion characteristics of the surface wavefield (Poggi and Fäh, 2010). Through the analysis of all the three-components of motion, it is possible to retrieve the information about the propagation of the Rayleigh waves (vertical and radial components) as well as

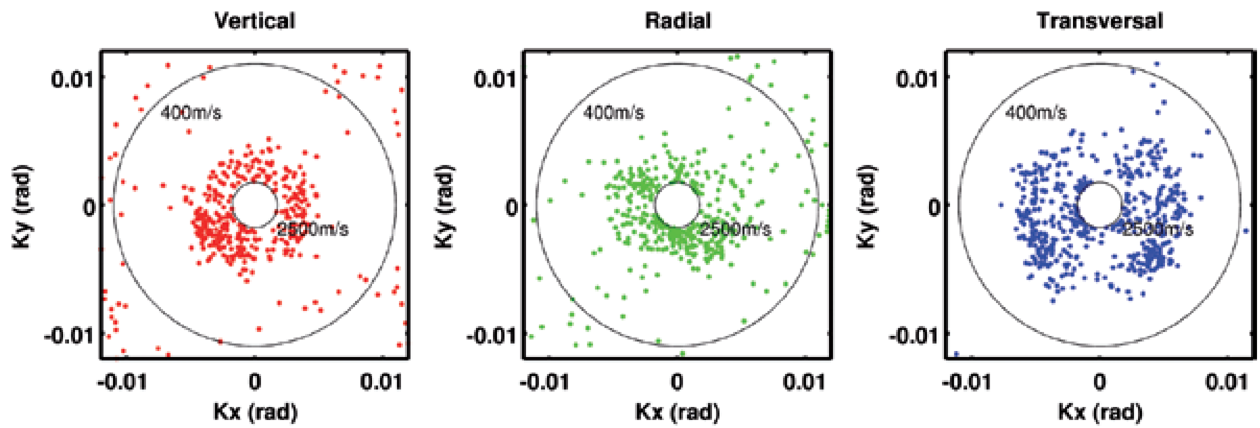

***Figure 6** Example of distribution of microtremor sources at 4.2 Hz (the HVSR peak frequency) over the three components of the f-k analysis. Distribution is homogeneous for the vertical and radial directions, with only some moderate directionality on the transversal direction.*

of the Love waves (transversal component). Using such an approach, the ambient vibration recordings are treated statistically by subdividing the traces in sub-windows. For each consecutive window a separated *f-k* analysis is performed, and the results are then statistically analysed, to calculate the robustness of the final estimation.

A series of quality checks must be applied to assess the fulfilment of those criteria necessary for the use of the three-component frequency-wavenumber analysis. Among these, power spectral density (PSD), directional HVSR and polarisation analysis (Burjanek et al., 2010) were used to map the variability of the subsoil structure along the investigated area, to evaluate the isotropy of wave-field and noise source distribution, and to assess the occurrence of any inconvenient topographic effect.

From the *f-k* analysis it was possible to assess the noise source distribution over a broad range of frequencies for the vertical, the radial and the transversal components (Figure 6), thus eventually being able to properly extract the surface wave dispersion curves (Figure 7).

Being also interested in determining the P-wave values of the uppermost layers, a P- and S-wave tomography survey was also pursued.

The main goal of sSRT analysis was to derive a good estimation of the lateral heterogeneities in the shallowest subsurface due to till deposits and weathering of bedrock. The final 2D section is presented in Figure 8 and, down to about 25 m (its penetration depth is necessarily lower with respect to the other analyses), appear in general agreement with the V_S profile reported in Figure 4d as well as with the VSP data.

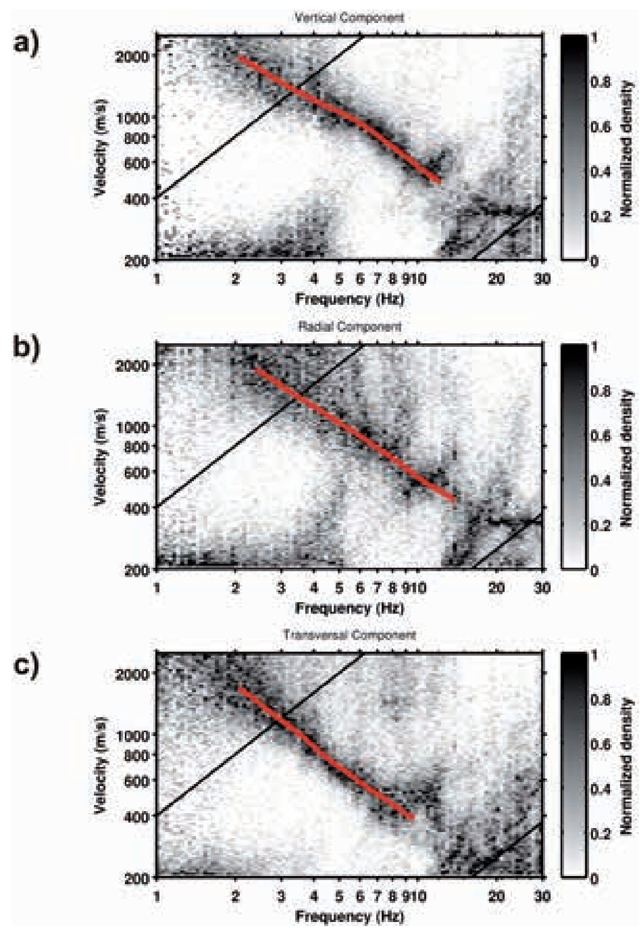

***Figure 7** Density distribution of all the surface wave components obtained from the larger array configuration by means of the f-k analysis: a) Rayleigh – vertical; b) Rayleigh – radial; c) Love – transversal. The phase-velocity dispersion curves are highlighted in red.*

An unconventional approach to the holistic analysis of Rayleigh waves

A novel, patented methodology potentially capable of robustly constraining the inversion process in spite of the extremely simple field procedures, was also tested. Such a methodology and some related case studies are presented in Dal Moro (2014) and Dal Moro et al. (2015). The acquisition procedure (quite trivial indeed – see Figure 9) is performed while considering a single two-component calibrated geophone set at a certain offset with respect to the source.

Of course, it is also possible to use a three-component geophone (the same used for acquiring the passive data used for the computation of the H/V spectral ratio) because several

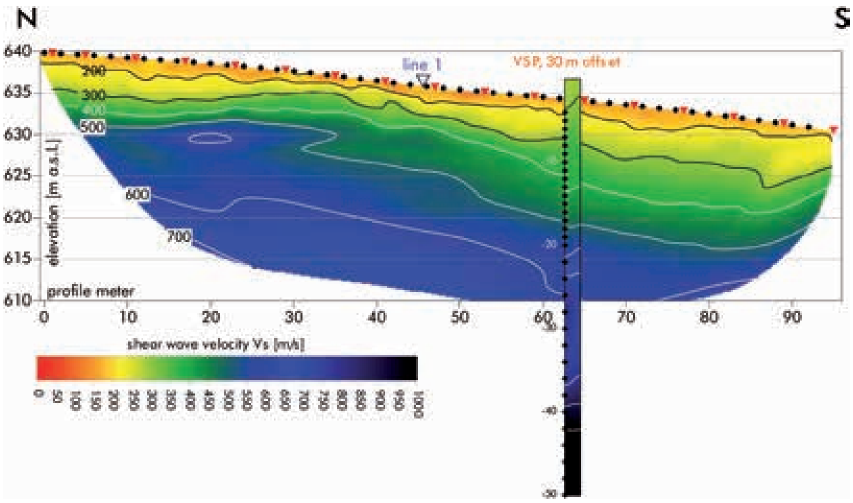

Figure 8 *Shear-wave refraction tomography (also shown the VSP profile).*

improved implementations are possible, but in its simplest and purest implementation, it is a merely-active methodology based just on Rayleigh waves and therefore requires only one vertical and one horizontal (radial) calibrated geophone.

The offset will obviously determine the maximum investigation depth which, according to a series of performed tests, can be roughly estimated in two thirds of the adopted offset, even if a more conservative and cautious rule of thumb could suggest half of it.

As a matter of fact, this methodology can be considered as an improved version of the classical MFA (Multiple Filter Analysis) technique and the fundamental point is schematically presented in Figure 9.

By considering just two geophones and a simple vertical-impact source capable of generating Rayleigh waves, it is in fact possible to define three objective functions to use in a multi-objective inversion scheme (Dal Moro, 2014): the group-velocity spectra of the vertical and radial components and the corresponding Radial-to-Vertical Spectral Ratio (RVSR).

For the present case, we considered an offset equal to 70 m (maximum penetration depth can then be estimated in about 40-50 m) and the results of the adopted three-objective inversion scheme are reported in Figure 10 where, on the left side are shown the field and synthetic group-velocity spectra of the vertical and radial components together with the RVSR, while on the right side the obtained V_S profile is reported along with the one from the VSP analysis.

It is apparent how, in spite of the light field procedures and necessary equipment, the overall agreement is quite good.

Needless to say, the simplest way to increment the investigation depth is represented by the joint acquisition of the H/V spectral ratio as well (Dal Moro, 2010; 2014).

Site response analysis

H/V spectral ratio represents a simple and inexpensive approach to retrieve valuable information about the seismic response of a site. In soft sediment sites, with significant contrast of seismic impedance between the sediments and the underlying bedrock, the H/V peak can be assumed as a proxy for the fundamental frequency of resonance of the SH-waves, where the largest amplification is generally expected. However, it has been shown (Haghshenas et al., 2008) that such an H/V peak is in general not representative of the actual amplification level. In practice, the amplification estimated merely from the H/V curve, very often results in an underestimation of the actual ground motion.

The reason can be found in the nature and composition of the ambient vibration wave-field. Seismic noise is in fact fundamentally dominated by the surface waves, with just a minor contribution from body waves. The relative contribution of Rayleigh and Love waves is site and time dependent, but in many cases Rayleigh waves tend to dominate. Therefore, when computing the H/V spectral ratio from the analysis of the background microtremor field, we fundamentally get a snapshot of the surface-wave ellipticity.

Because of the geometrical interaction of the Rayleigh wave-field with the medium, ellipticity function develops a singularity (maxima) in the vicinity of SH-wave resonance frequency. Amplitude of the singularity is, however, controlled by different phenomena and cannot be used directly as proxy for site amplification. For this reason an indirect computation of analytical amplification function is needed. This can be obtained from the soil velocity profile, which in turn can be obtained from the joint analysis of surface-wave dispersion (depicted through active and passive methodologies) and H/V spectral ratio (see previous paragraphs).

In the present case, site amplification functions were computed using two different numerical approaches (Figure 11): the SH-wave transfer function for vertical propagation and the quarter-wavelength approximation (Joyner et al., 1981; Poggi et al., 2012). The first method is based on the computation of the actual impulse response function of the vertical soil column (the soil transfer function), whose absolute value is the site amplification function. On the other side, in the second (simplified) approach, the approximated site ampli-

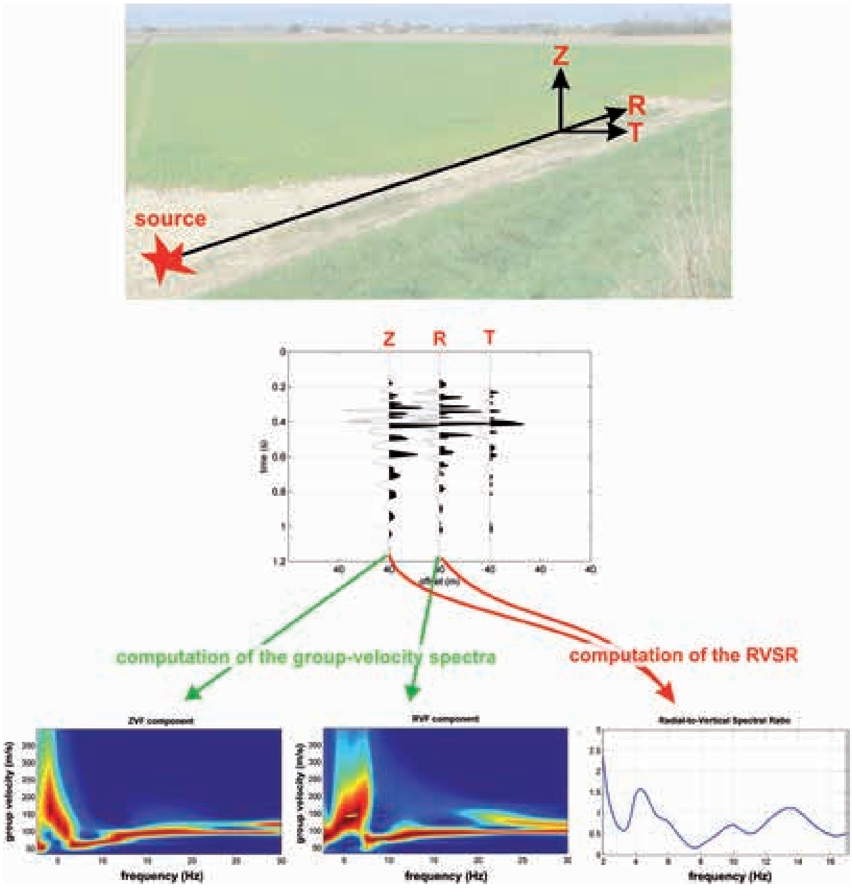

Figure 9 Data acquisition for the holistic analysis of Rayleigh-wave propagation by means of a single (at least) two-component geophone recording the vertical (Z) and radial (R) components then used to determine the two group velocity spectra and the Radial-to-Vertical Spectral Ratio (RVSR). The transversal (T) component is not considered here.

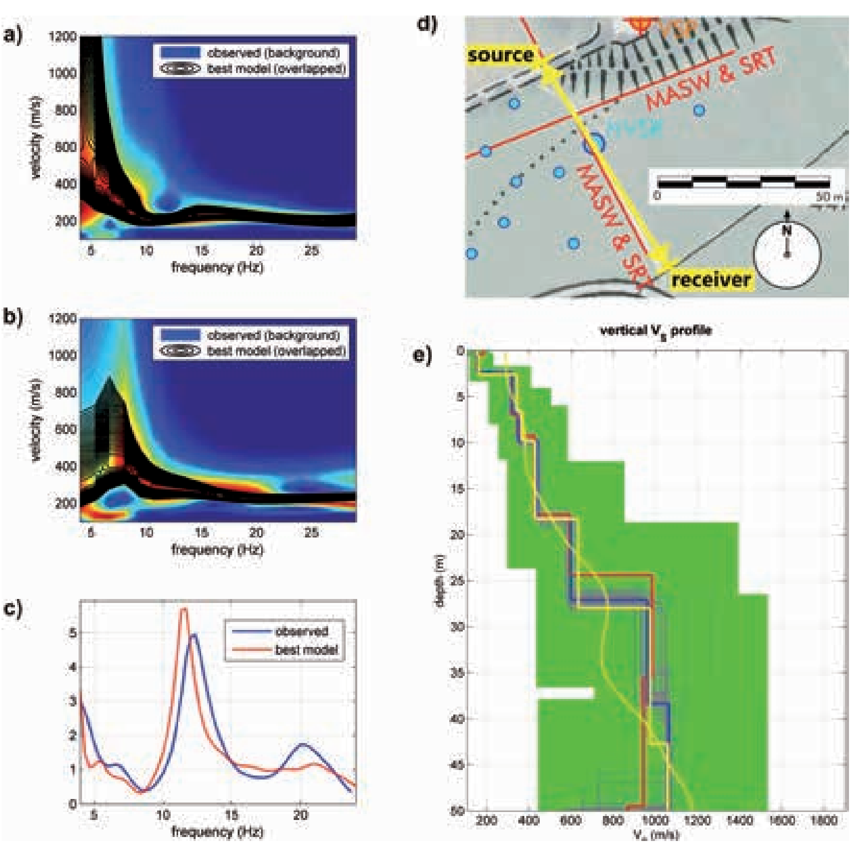

Figure 10 Holistic analysis of the vertical and radial-component group-velocity spectra jointly with the Radial-to-Vertical Spectral Ratio (RVSR): a) and b) the observed velocity spectra (background colours) and, overlaying (black contour lines), the synthetic ones; c) observed and computed RVSRs; d) map reporting the position of the source (in this case a simple vertical-impact sledgehammer) and receiver (a single three-component calibrated geophone – offset 70 m); e) the retrieved V_S profile and the one obtained by means of VSP analysis.

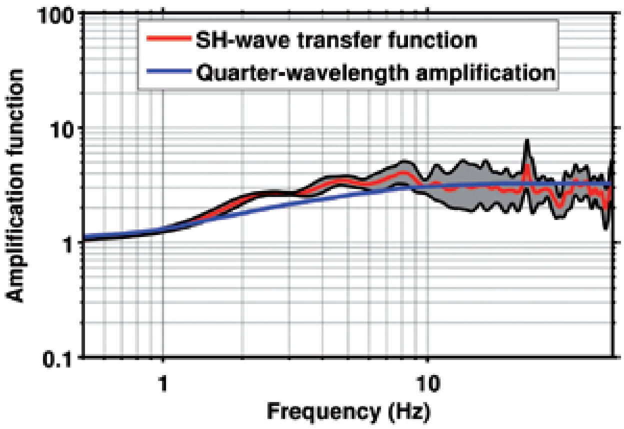

Figure 11 Modelled amplification functions using SH-wave transfer function formalism (in red, with standard deviation in grey) and the simplified quarter-wavelength approximation (in blue).

fication is directly computed from the seismic impedance contrast between the bedrock and uppermost sediments. To make the evaluation frequency dependent, however, a travel-time averaging of the soil properties (velocity and density) is performed at progressively increasing depths, corresponding to ¼ of the wavelength of interest.

Actually, a relevant issue to address in engineering seismology regards the need to compare earthquake signals recorded at sites where different geological/stratigraphic conditions are present. To solve this problem, the modelled amplification function can be used to remove the effect of the uppermost geology from observed earthquake recordings, which are then normalised for the so-called standard rock reference conditions. In this study, computed amplification functions have then been corrected for the Swiss rock-reference velocity profile as defined in Poggi et al. (2011).

Conclusions

With the aim of obtaining a robust subsurface model to use in the assessment of the site response analysis, a multi-component joint analysis of surface waves acquired according to both active and passive methodologies was accomplished via advanced procedures capable of providing an accurate subsurface model without the need for costly and punctual VSP analysis.

The pursued approach can be described as a holistic attempt to consider surface waves in all their aspects: the propagation velocities defined by the velocity spectra of all the components (Love waves and radial and vertical components of Rayleigh waves acquired both according to active and passive methodologies) jointly with the relative amplitudes represented by the HVSR (while considering passive acquisitions) and the RVSR (while considering active data).

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