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Site Characterization for ANSN Stations Using the Ellipticity Curve Inversion of Microtremor data

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Abstract

The site-specific shear velocity profile for the top 30 m, V_{S30}, is the most popular geotechnical parameter to characterize local site conditions. Shear velocity measurements are not available for the majority of earthquake-recording stations in the Australian National Seismograph Network (ANSN). Accordingly, the lack of available shear-wave velocity data in Australia makes it difficult to benchmark amplification effects to a reference site condition. One inexpensive and relatively efficient method that can be used to analyse single-station ambient noise data is the Horizontal to Vertical Spectral Ratio (HVSR) method. We used OpenHVSR software for the inversion of the HVSR curves. The S-wave velocity structure and V_{S30} results derived from the inversion process of the HVSR curves are in a good agreement with the previous Spatial Autocorrelation (SPAC) study for the ANSN stations and can be used as a fast and inexpensive technique to measure the V_{S30} for site classification purposes.

Keywords: HVSR inversion; Shear wave Velocity; Site Characterization; Microseism Noise.

1 Introduction

Local site effects due to the characteristics of the near-surface rock or soil are one of the main challenges in the assessment of ground motions. Characterizing the near surface response at seismic stations can help benchmark the recorded data to a reference site condition. This supports the assessment and selection of ground-motion models (GMMs) for use in seismic hazard models. V_{S30}, defined as the average seismic shear-wave velocity from the surface to a depth of 30 meters, has found wide-spread use as a parameter to characterize site response for earthquake resistant design, and is referenced in building codes worldwide. Several proxy methods have recently been proposed to estimate V_{S30} values in Australia. Wald and Allen (2007) correlated V_{S30} to topographic slope using data from the United States, Taiwan, Italy, and Australia. Collins et al. (2006), acquired shear-wave velocity profiles at eighteen permanent and temporary seismograph sites in Western Australia, South Australia, Victoria and New South Wales using the Spectral Analysis of

Shear-Waves (SASW) technique. Later Kayen et al (2014) used the same method to measure the shear-wave velocity profiles at 50 strong motion sites in Australia. In addition, the Spatial Autocorrelation (SPAC) method has been used in Newcastle (Volti, et al, 2014 and Sorensen and Asten, 2005), Perth (Asten, 2003), in the Botany area of Sydney (Asten and Dhu, 2004), Melbourne (Roberts et al., 2004) and in Tasmania (Claprood et al., 2007, 2011). Measurement of the V_S profiles can also be undertaken through geotechnical investigation using downhole or cross-hole borehole methods or during penetration tests. However, these approaches tend not to be useful for evaluation of Australian strong motion sites, as they cannot reach the meaningful depths required for seismic site response analysis without expensive drilling and casing.

One method to estimate site response and soil properties with a single station is Horizontal to Vertical Spectral Ratio (HVSR) proposed by Nakamura in late 1980s (Nakamura, 1989). Methods such as horizontal to vertical spectral ratio of ambient noise only require waveforms at single stations from recordings of ambient noise. The benefit in the use of ambient noise data, besides its low cost, is that the recordings provide direct information on the local amplification characteristics. Since the majority of ANSN stations provide continuous waveforms, these single station based methods can be readily applied to infer site responses. The HVSR method is based on the hypothesis that the ambient noise is composed of Rayleigh waves and the HVSR curve reflects the ellipticity of these waves. However, many researchers have shown that ambient noise is composed of different modes of Rayleigh and Love waves and of body waves (Bonnefoy-Claudet et al. 2008; Albarello and Lunedei 2010, etc.). For this reason, several methods have been proposed for the direct retrieval of Rayleigh waves from noise recordings. A typical example is the HVTFA (H/V using time frequency analysis, Fäh et al. 2009) method, which make use of the phase shift of π/2 between vertical and horizontal components of particle motion that is characteristic of Rayleigh waves.

The 1D shear-wave structure can be estimated from the direct inversion of the HVSR ellipticity curve using single-station ambient noise records. The aim of this paper is to examine the possibility to use the HVSR curve as an ellipticity curve proxy and invert it to obtain reliable V_{S30} estimates and to perform a comparison between the results obtained from the HVSR curve inversions and V_{S30} estimations from other elaborate methods. For this reason, ambient noise measurements were performed, following the SESAME project guidelines (SESAME 2004), with a Guralp CMG-3T 120sec-50Hz sensor in three ANSN sites, for which the shear-wave 1D profile was known (RIV,SYDH and NTLS) from previous studies. For each site, three hours of continuous record of ambient noise data with a sampling rate of 200sps was used to calculate the HVSR curves in Geopsy software (Wathelet 2005). Moreover, inversion of the HVSR curve has been performed using the OpenHVSR software (Aldahri et al, 2017; Bignardi et al. 2016; Mantovani et al. 2015; Herak 2008; Lunedei and Albarello 2010). Finally, results obtained from the HVSR inversions in each site were compared with the measured SPAC V_{S30} values (Volti et al., 2014). In the present work, we assess if the inversion of HVSR data can be used as a supplementary tool for efficient, large-scale/low-cost V_{S30} estimations, employing a simple data-collection strategy and a minimal amount of data processing.

2 HVSR Curves and Rayleigh Wave Ellipticity

The standard H/V ratio is calculated by using the squared average of the horizontal signal components over the vertical component. However, if the wavefield contains Love or SH waves, they will be present on the horizontal components only and lead to an overestimation of H/V amplitudes. Accordingly, other methods are needed to directly estimate the ellipticity from the signals. The ellipticity is a parameter describing the elliptical motion of Rayleigh waves as a function of frequency and is linked to the soil structure (Fäh et al. 2001; Hobiger et al. 2009, 2013). We utilize the time-frequency analyzing (TFA) 'hvtfa' tool from the open source Geopsy software packages, (http://www.Geopsy.org) and follow the guidelines as described in Network of Research Infrastructures for European Seismology (NERIES-D4 2010) for extraction of Rayleigh wave ellipticity curves in this study.

The HVTFA method (H/V using time frequency analysis, Fäh et al. 2009) was originally proposed by Kristekova (2006) and uses a continuous wavelet transform (CWT) based on modified Morlet wavelets (Lardies and Gouttebroze 2002) to transform the three signal component into the time-frequency domain. It is understood that Rayleigh waves have an energy maximum on the vertical component. Therefore, to extract mostly Rayleigh waves, the absolute value of the CWT for the vertical component is scanned for all maxima (Kristekova 2006). Love or SH waves that contain horizontal energy only are thus effectively excluded from further consideration. For each maximum on the vertical component, the corresponding maximum value on the horizontal components with a phase shift of ±π/2 is identified and used to calculate an ellipticity value. All values derived for a given frequency are analysed statistically via filtering of histograms (Fäh et al. 2009). HVTFA is implemented as a module in the GEOPSY software and requires two input parameters, the Morlet wavelet parameter that controls the wavelet's width in the spectral domain and the number of maxima on the vertical component selected per minute. Based on the study reported by Fäh et al. (2009), we selected a value of 8.0 for the Morlet wavelet parameter and choose five maxima per minute. The ellipticity curve is estimated in this study from the median values and median absolute deviations, which seems to provide a better statistical estimate (NERIES-D4 2010).Figure 1 shows an example of the extracted fundamental mode Rayleigh wave ellipticity (H/V) with median values and median absolute deviations for the RIV station.

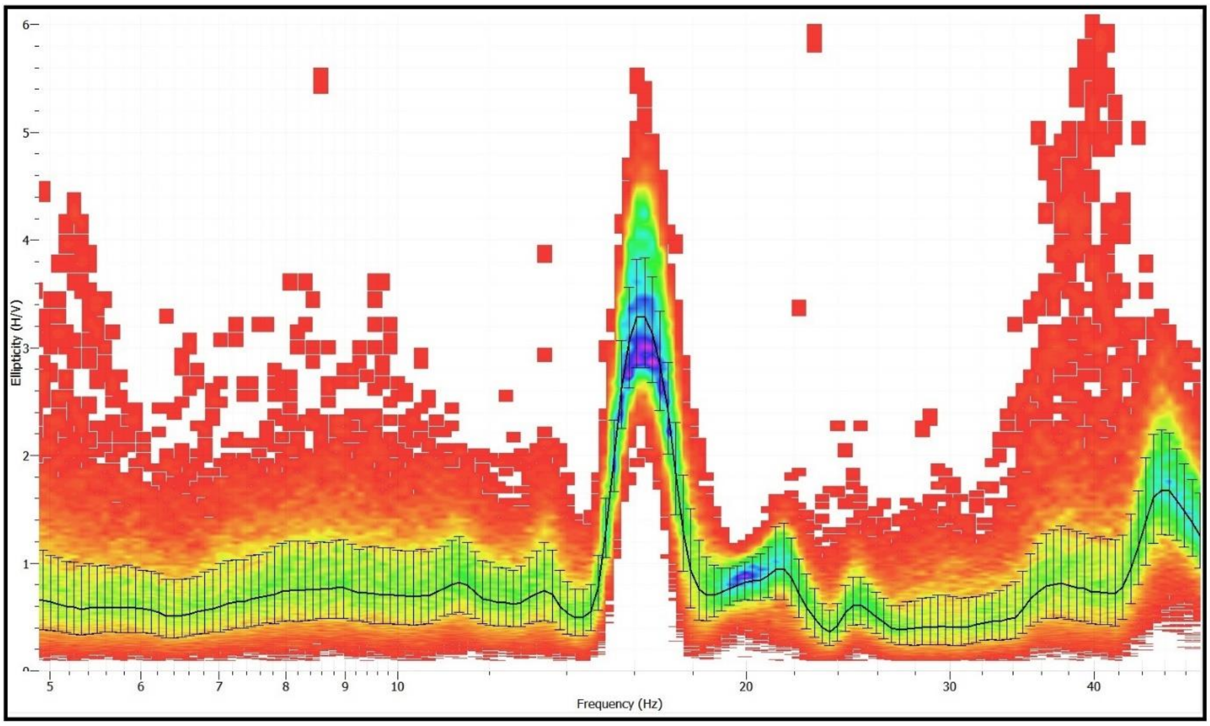

Figure 1. An Example of HVTFA result for station RIV, showing fundamental mode Rayleigh wave ellipticity. The coloured background image is a 2-D histogram of the distribution of ellipticity values calculated at a given frequency, selecting the five largest maxima per minute on the vertical component in the time-frequency decomposition. Error bars are the upper and lower flank of the fundamental mode ellipticity curve selected for this station.

3 Inversion Approach

Nakamura (1989) explained that HVSR curve obtained from microtremors is related to the shear wave velocity of the layers. The basic assumption used in HVSR method is that the H/V value in the bedrock is equal to one because the particle movement in the bedrock is assumed to be the same, horizontally and vertically. Based on this assumption, one can extract information about the impedance contrast beneath the surface by examining the peak location in the HVSR curve. The horizontal tremor is amplified through multi-reflection of S wave, the vertical tremor is amplified through multi-reflection of P wave, while the effect of Rayleigh wave which appear in the vertical tremor has value effect nearly zero when the ratio of H/V is approximately one (Nakamura,1989).

The relative contribution of different seismic phases (P, S, Surface waves, etc.) to the ambient vibration is, indeed, a still a debated topic. The key and controversial aspect is the relative contribution of body and surface waves (Lunedei and Malischewsky 2015). Despite this, it is quite understood that the HVSR curve will, in general, present local maxima at the resonance frequencies of the S waves regardless of the nature of the wavefield (Albarello and Castellaro 2011), such a controversy has led to the development of inversion algorithms based on different assumptions. As Nakamura recently explained (Nakamura 2019), the origin of the peak of the HVSR at its predominant frequency (f_0), can be explained in terms of multiple reflection of SH waves. In the context discussed by Nakamura (2019) contribution to the wavefield from surface waves is included, but the energy of Rayleigh waves is small around the predominant frequency (f_0). Accordingly, Herak (2008) and Herak et al., (2010) proposed a Monte Carlo inversion, based on the modelling algorithm proposed by Tsai and Housner (1970). The latter computes the HVSR curve under the assumption that the peak is generated by sub-vertically propagating P and S waves.

In this study, the HVSR curves have been inverted using the software “OpenHVSR”, an interactive toolbox written in Matlab®, designed for the simultaneous modelling and inversion of large Horizontal-to-Vertical Spectral Ratio datasets (Bignardi et al. 2016). This software comprises the formulations from Tsai and Housner (1970).

The inversion process in OpenHVSR requires the user to provide an initial model, which includes thicknesses and visco-elastic properties of the subsurface layers under the locations at which measurements were performed. The inversion process will then optimize such parameters. The inversion of HVSR curves is highly non-unique and several shear-wave velocity models can satisfy the same HVSR curve. Following Hobiger et al. (2012), the uniqueness of the ellipticity inversion can be severely improved if the shallow 1D velocity profile is known. In our work, we propose a simple and semi-automated method, which employs available shallow V_S information to constrain the solution.

The HVSR method produces the dynamic characteristics of the soil, namely natural frequency and amplification. Here, we use the natural frequency value and amplification factor to get the subsurface profile as an initial model for the inversion. In this approach, we use a single layer model formed by a low-speed layer over a semi-infinite space to define the initial model. The natural frequency (f_0) is influenced by the value of shear wave velocity on the surface layer (V_S) and the thickness of the subsurface sediment (*h*) as expressed by the following equation (Nakamura, 1989):

$$h = V_S/(4f_0) \tag{1}$$

It is assumed that the bottom layer of the model (for which no thickness is required) represents the bedrock. If densities for the bedrock and surface layer are assumed to be the same, then shear wave velocity in the bedrock, V_{SB}, and the velocity in the upper layer, V_S, can be related to the HVSR amplification factor, A_0, as follow (Nakamura, 2000):

$$A_0 = V_{SB}/V_S \tag{2}$$

So that the thickness of the layer, h, can be related to the dominant frequency value, f_0, and the amplification factor, A_0. Considering the shear wave velocity value in the bedrock, V_{SB}, can be assumed, then it can be written by the equation:

$$h = V_{SB}/(4A_0 f_0) \tag{3}$$

By using equation (3) and considering V_{SB}=1500 (m/s) as suggested for hard rocks in NEHRP site classification (BSSC, 2001), we can have an estimation for the depth of the bedrock using the dominant frequency value, f_0, and the amplification factor, A_0, from the HVSR curve. For the layer over the semi-infinite space we can use the available shallow V_S information. The shallow V_S information which are available for all the ANSN stations are the slope based V_{S30} (Wald and Allen, 2007) and geological-proxy-based V_{S30} (ASSCM; McPherson, 2017), we employ slope based V_{S30} information for our initial model for the inversion process.

The inversion process using OpenHVSR also requires model parameters (V_p, V_s, ρ, h, Q_p, Qs) as initial values. Additionally, the algorithm also requires a number of iterations and a standard deviation of random normal for initializing model parameters in the Monte Carlo approach. As mentioned earlier, V_S values are taken from the slope based V_{S30} values for the ANSN stations while *h* is calculated using equation (3). V_p is calculated based on the Castagna (1985) equation as described below:

$$V_P = 1.16V_S + 1.36 \tag{4}$$

The density value is then calculated based on the following equation (Dal Moro et al., 2007):

$$\rho = 0.77log_{10}(V_S) + 0.15 \tag{5}$$

Other model parameters, Qs is determined based on geological conditions while Qp is calculated using Q_p=2Q_s (Giancarlo, 2010). The values of Q_s and Q_p do not significantly affect the resulting model. Table 1 shows an example of initial model used in the inversion process for station RIV. As it can be seen from Figure 1, the natural frequency and amplification factor for this station are f_0 = 16.3 Hz and A_0 = 3.25 and slope based V_{S30} for this station is V_S=526 (m/s) and by using equations (3)-(5) we can have the initial model as it can be seen in Table 1.

Table 1. An example of model parameters used in the inversion process for station RIV.

Vp (ms^{-1})	**Vs (ms^{-1})**	**ρ (g.cm-3)**	**h(m)**	**Q_P**	**Q_S**
611.52	526.0	2.24	7.0	30	15
1741.36	1500.0	2.59	999.0	999.0	999.0

In the inversion, the HVSR curve is assumed to be a reconstruction from body waves. The algorithm for the inversion of HVSR curves calculates the amplification spectrum of P- and S-waves under the assumption of vertically incident body waves on layered media to approximate the HVSR curve as follow:

$$HVSR(f) = \frac{AMP_s(f)}{AMP_p(f)} \tag{1}$$

where AMP_P(f) and AMP_S(f) are the theoretical amplification spectra of P- and S-waves, respectively. The inversion strategy is based on the guided Monte Carlo method, where at every iteration a randomly perturbed version of the best fitting model (i.e., the model which best re-produces the data) is produced and used to compute a set of simulated curves to be compared with the experimental HVSR curves. The generation of many trial models allows for exploring the parameter-space while looking for a new and better fitting model. In the guided search method, the perturbations are done around the best set of parameters found so far. The guided search converges more quickly, but there is always a possibility that it will miss the global minimum of misfit and end up in a local one. Therefore, there is also an option to choose what proportion of perturbations will be done around the best solution so far, with the rest of the perturbations being centred around the initial model parameters. The progress of iterations can be monitored in a GUI, and all evaluated models are stored along with the corresponding misfit. In the inversion process, the values of Vp, Vs, ρ, and h always change to arrive at the best model (lower misfit or equal to the previous iteration), while the values of Qp and Qs are fixed. The final result of the inversion process is a 1-D graphic of the relationship between Vs and depth. The best model found is displayed at the end with the option to accept it as a new starting model for a new perturbation series.

In this study, we divided the inversion process into three steps. In the first step, we allow 25% perturbation for 5000 iterations under the initial model for the HVSR curve. Successively, we add more layers in order to account for the possible contribution of H/V amplification from a deeper layer and to increase the degree of freedom in the inversion process and we allow 5% perturbation for 10,000 iterations to finalize the 1D local inversions. For the last step, we performed 15,000 laterally constrained iterations which allows 20% perturbation with respect to the best-fitting model. Figure 2 shows the final results of the inversion process using OpenHVSR software for station RIV. As it can be seen from Figure 2 the final result for the inversion of HVSR curve is so close and comparable to SPAC measurement in station RIV.

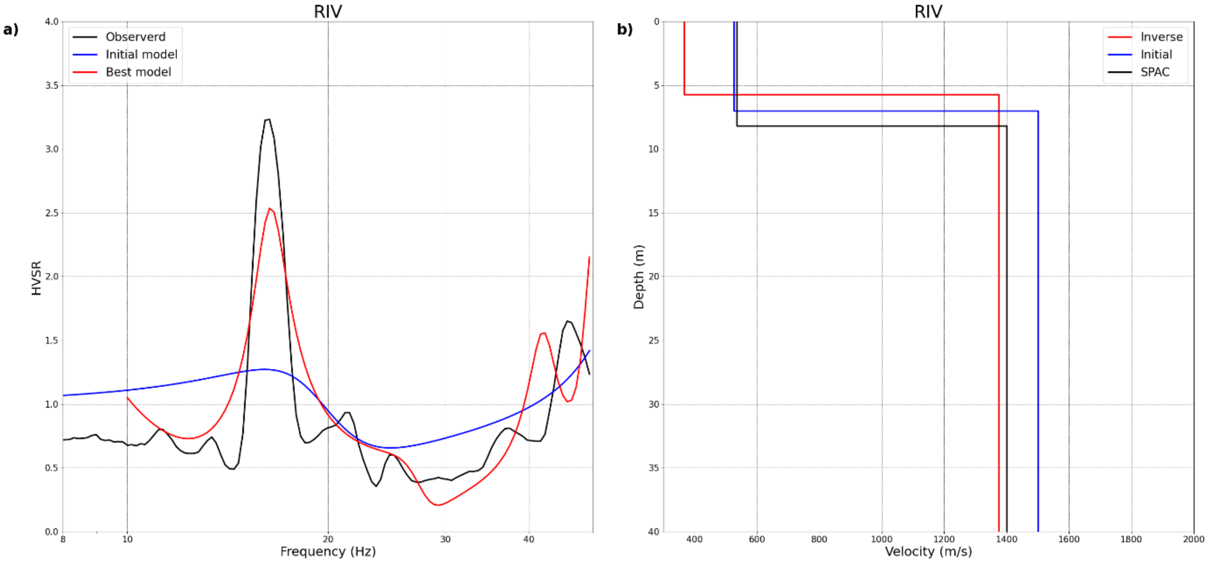

Figure 2. Result of the inversion process using OpenHVSR software for station RIV. a) shows the observed HVSR curve (black line) compared with initial HVSR curve (blue line) and final best fitted model from the Inversion (red line). b) Shear wave velocity structure obtained from inversion of HVSR curve (red line) compared with initial model (blue line) and SPAC survey results (black line).

4 Discussions and Conclusions

The technique of the inversion of the single station HVSR curves has been applied on ambient noise data to estimate the velocity structure and characterising the subsoil for three selected ANSN stations. The available shallow shear wave velocity information and the dynamic characteristics of the soil, namely natural frequency and amplification was used to define the starting model for the inversion. The HVSR curves have been inverted by using a guided Monte Carlo approach in OpenHVSR software. Figure 3 shows the inversion results of the HVSR ellipticity curve for two other selected ANSN stations SYDH (3a and 3b) and NTLS (3c and 3d). Spatial Autocorrelation (SPAC) results from Volti et al. (2014) was used to compare the inversion results (Figure 3b and 3d). The average shear wave velocity for the topmost 30 m depth, V_{S30}, for different stations are shown in Table 2.

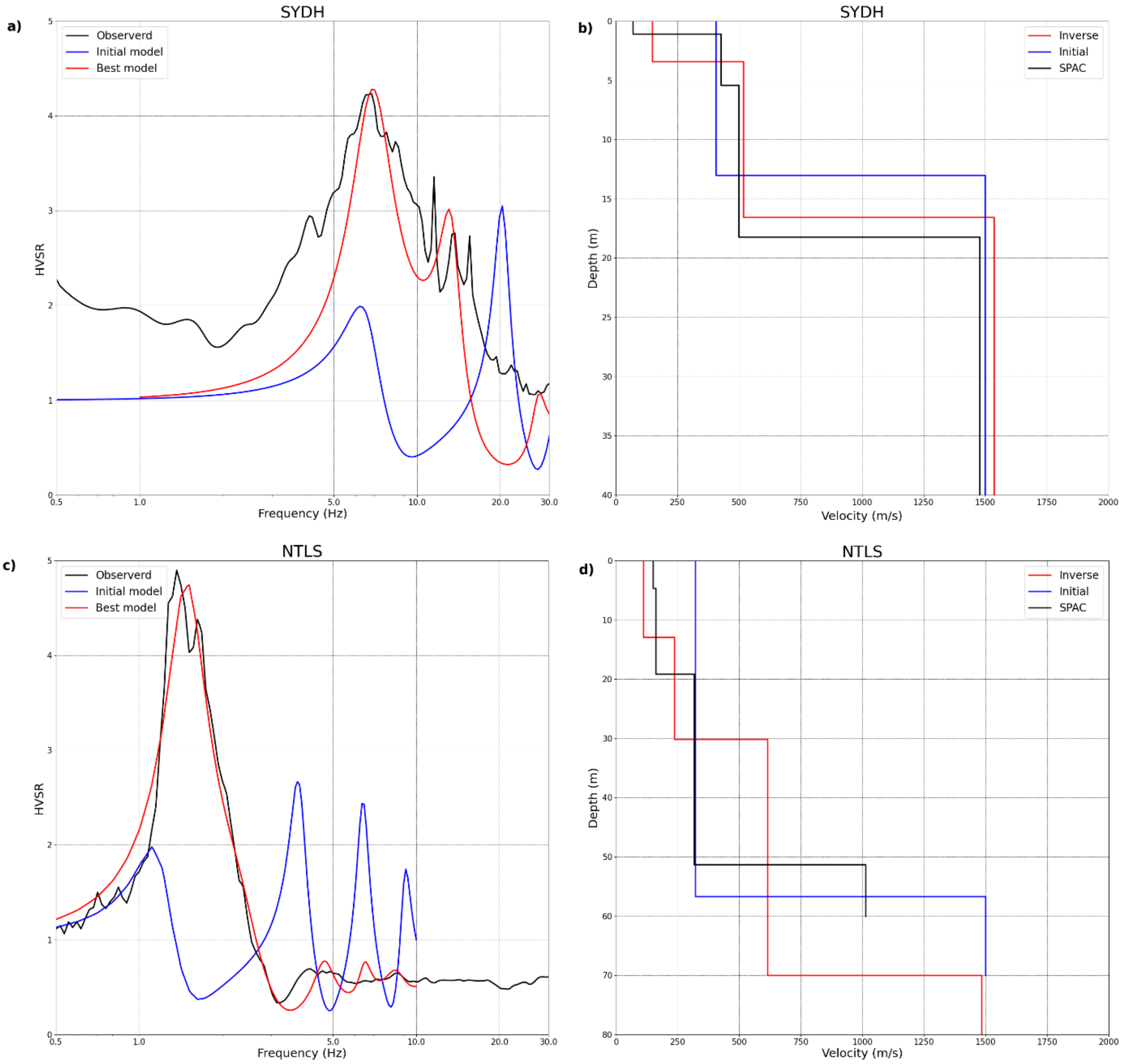

Figure 3. Result of the inversion process using OpenHVSR software for two selected ANSN stations SYDH (a and b) and NTLS (c and d). (Left) Observed HVSR curve (black line) compared with initial HVSR curve (blue line) and final best fitted model from the Inversion (red line). (Right) Shear wave velocity structure obtained from inversion of HVSR curve (red line) compared with initial model (blue line) and SPAC survey results (black line).

Table 2. Results showing natural frequency, amplification and V_{S30} values derived from inversion of HVSR curves, SPAC (Volti, et.al. 2014), slope-based (Wald and Allen, 2007) and geological-proxy-based (ASSCM; McPherson, 2017) methods for three selected ANSN stations.

Station	V_{S30} (m/s) (SPAC)	HVSR Amplitude	f_0 (HZ)	V_{S30} (m/s) (Slope)	V_{S30} (m/s) (ASSCM)	V_{S30} (m/s) (HVSR inversion)
RIV	971	3.25	16.3	526	1100	902
SYDH	590	4.22	6.69	406	1100	525
NTLS	172	4.82	1.38	321	180	159

As it can be seen from Figure 3, while the HVSR inversion attempts to optimise the spectral ratio at all the investigated frequencies, the frequency range that is actually best fitted is around the fundamental peak. In other words, the average velocity of the full sedimentary part is usually correctly retrieved. The shallow part of the model, mostly (but not only) impacts higher frequencies, for which unfortunately, having the best fit is typically difficult (Figure 2a and Figure 3a). The well-known rule f_0 = Vs/4H suggest that the V_{S30} from HVSR could be expected to be reliable for shallow bedrock sites, where the V_{S30} and the average velocity of the sedimentary stack are not very different (Bignardi, 2017). Consequently, we expect the bedrock depth and V_{S30} to be retrieved correctly when the bedrock is sufficiently shallow (Figure 2b and Figure 3b). According to this investigation, we found that for deeper bedrock, where the inversion is much less sensitive to shallow velocities, the location of the deepest bedrock was overestimated, however, the V_{S30} was approximately correctly estimated (Figure 3c-d). Another aspect to take into account is that only 2–3 layers contributed to the computation of the Vs obtained from microtremors, which may be an oversimplification for the Vs and bedrock depth evaluation purposes.

In this paper, analysis and processing of microtremor data were divided into two steps; the first one was to measure the HVSR curve and pick the predominant frequency and its amplitude for each site. The second step was to measure the average shear wave velocity in the upper 30 m (V_{S30}) of subsoil using inversion of HVSR technique. Table 2 compares the shear velocities of the shallow 30 m, obtained from inversion of HVSR, with the analogous result from SPAC survey (Volti, et.al., 2014), slope based V_{S30} (Wald and Allen, 2007) and geologically-based V_{S30} (McPherson, 2017). The agreement between the outcomes of the HVSR and measured SPAC results (Table 2) is showing that inversion of the single station HVSR curve can be a valuable method for the estimation of the site amplification effects. This method will be used for characterizing the near surface response for the majority of the ANSN seismic stations. The method used in this study is a fast and inexpensive technique to measure the V_{S30}, based on the single station HVSR of microtremor and could be applied for many other areas.

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