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From HVSR Results to Site Related Design Parameters

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ABSTRACT

The Nakamura method, which utilizes the Horizontal to Vertical Spectral Ratio (HVSR) analysis, is widely used for seismic microzonation studies. The HVSR is an easy tool for estimation of site response resonances based on recorded ambient noise, however, it gives amplifications at resonant frequencies that are poorly correlated to the actual site amplification during strong ground motion.

Generally, the site response, including resonant effects, depends on the ground motion amplitude and duration. An approach was proposed previously by McGuire[1], in which the transfer function of the soil response was approximated as a Single Degree of Freedom (SDOF) oscillator with one resonant frequency, obtained from the maximum resonance in HVSR. A new approach is developed here, in which the entire HVSR curve is approximated by a manageable set of parallel band-pass resonators, each one defined by three parameters: center frequency, gain, and steepness (Q factor).

The application of the new approach is demonstrated on data recorded by the stations of the Southern Ontario Seismic Network (SOSN/Polaris), which have well studied characteristics and site response [2]. Data collected at each site consists of noise recordings, to obtain the HVSR, as well as earthquakes records.

Keywords: HVSR, Site Response, Ground Amplification, Response Modelling, Earthquake spectra

INTRODUCTION

Current methods of predicting ground motions from future earthquakes are based on an assumed seismological model of the source and the propagation processes. Ground Motion Prediction Equations (GMPEs) as defined by [3] are used to establish expected peak ground velocities (PGV) and peak ground accelerations (PGA) at a site for a given earthquake size and epicentral distance. Commonly, GMPEs are empirically derived from the regression of recorded strong motions. Typical GMPE expression without the error term is given as:

$$lnY = F_M(\boldsymbol{M}) + F_D(R_{JB}\boldsymbol{M}) + \boldsymbol{F_S}(V_{S30}R_{JB}\boldsymbol{M}), \quad (1)$$

where Y is the response variable, $\boldsymbol{M}$ is moment magnitude, R_{JB} is the Joyner-Boore distance, V_{S30} is the average shear-wave velocity to a depth of 30 m. F_M, F_D, and F_S are respectively: the magnitude scaling, distance function, and site amplification function. Site characterization based on V_{S30} has very poor physical background. In general, V_{S30} is not closely related to the spectral amplification of soft sites.

Using GMPEs in design requires knowledge of the source parameters. In general, the far-field earthquake spectra is modelled by the simple Brune [4] model. This model relates the spectrum of the shear radiation to the stress released across an equivalent circular fault surface. The size of the rupture determines the corner frequency. The far-field velocity spectrum is given by:

$$\langle \Omega(\omega) \rangle = \langle \Re \rangle \frac{\sigma\beta}{\mu}\frac{r}{R} F(\epsilon) \frac{\omega}{\omega^2+\alpha^2}, \quad (2)$$

where $\langle \Re \rangle$, is the average of the source radiation, r is the equivalent circular fault radius, R is the distance, β is the shear wave velocity average, σ is the effective stress drop, $F(\epsilon)$ is the stress drop term, $\alpha = 2.21\ \beta/r \sim \omega_c = 2\pi f_c$ where f_c *is* the corner frequency, and μ is the shear modulus.

In order to properly estimate the corner frequency of the source spectrum, it is important to remove the influence of the site response from the horizontal components of the recorded earthquake. This paper proposes a site response model based on HVSR site measurements. The obtained model can be used instead of the site amplification function F_S in Equation (1), or to modify the horizontal ground motion component from an expected earthquake spectrum. Additionally, by reducing the site effect present in seismic records it would be possible to better approximate the Brune model to the earthquake spectra, and therefore obtain the source parameters more accurately.

METHODOLOGY

Data Selection

The Southern Ontario Seismic Network (SOSN/Polaris) is comprised of three-component broadband seismic stations, located mainly in the Greater Toronto Area and Niagara region of Ontario, Canada [5]. The recorded events from Southern Ontario have magnitudes up to 4.3 m_N. Hypocentral depths are shown to be in the 3–15 km range within the Precambrian Shield. [6]

This study focuses on two of the strongest earthquakes in the area, given in Table 1. These events were chosen based on the magnitude as well as the azimuth toward the SOSN/Polaris stations because both earthquakes are fairly well studied [7], [8]. Analysis was performed using data from all SOSN stations that had records available for the time of the event. This paper shows results from two stations: Bruce (BRCO) and Wesleyville (WLVO). Figure 1 shows the geographic locations of stations and distances to the chosen events. Waveform data was obtained from the GSC database [9].

Table 1: Earthquakes used in the analysis[9]

Event#	Date	Time (UT)	Latitude	Longitude	Depth	Magnitude
1	2005/10/20	21:16:28	44.677	-80.482	11.0g	4.3 m_N
2	2004/08/04	23:55:26	43.677	-78.239	4.0g	3.8 m_N

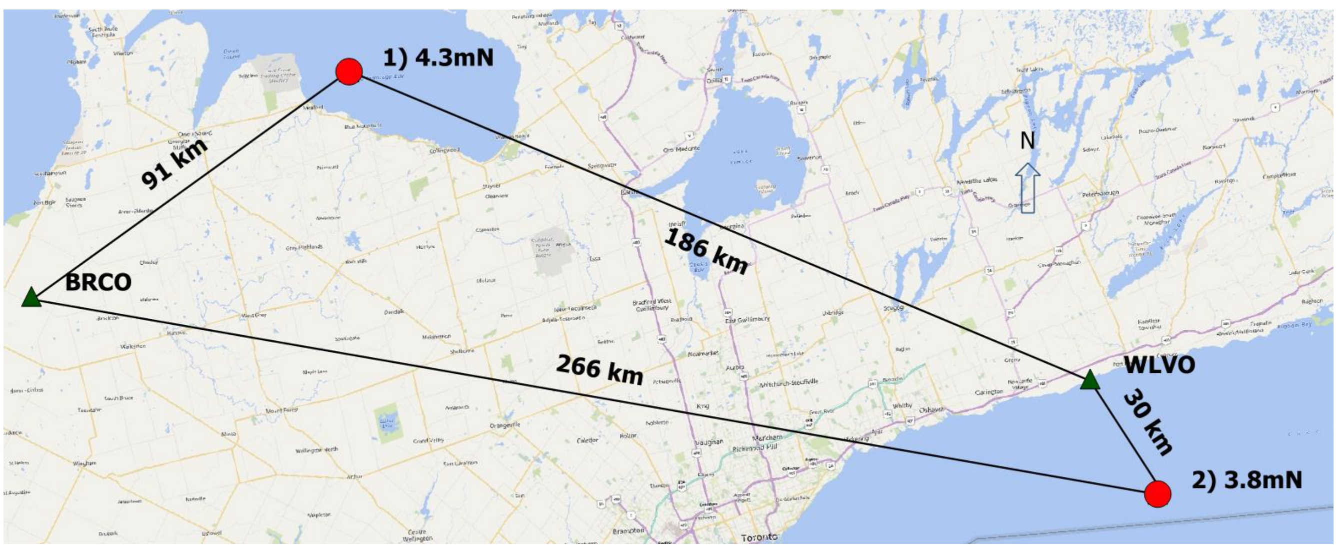


Figure 1: Selected Events and SOSN/Polaris Stations in SW Ontario used for HVSR calculation

Noise recordings used to obtain a site HVSR are often affected by anthropogenic sources, wind noise, and instrument drift. To minimize the influence of the anthropogenic sources on the noise recording, data recorded during night time is used. Wind effects as well as instrument drift are reduced by filtering the waveforms with 2nd order high-pass Butterworth filter above 0.5 Hz.

To further improve the HVSR accuracy, the signal is separated into low-level and high-level noise sections as per Mihaylov et al [10]. For strong motion data, the signal is split into “noise” and “earthquake” sections. Each section of the noise signal is then separated into 40 second windows with 50% overlap, for which the Fast Fourier Transform (FFT) is calculated.

The resulting spectra are smoothed using Band-Pass Filters (BPF) as will be defined later (Equation 4), resulting in three spectra for the three components (S_{NS}, S_{EW}, S_Z). HVSR curves for each window are then computed using Equation (3), as per Nakamura [11], [12]:

$$HVSR = \frac{\sqrt{S_{NS}^2 + S_{EW}^2}}{S_z} \tag{3}$$

Finally, the site HVSR curve is obtained as the average over all windows. For BRCO station 172 data windows were used, and for WLVO – 233. The resulting HVSR for noise data and for both earthquakes in Table 1 for the same stations are shown in Figure 2. The results confirm the HVSR curves already presented by Murphy and Eaton [2] for seismic noise.

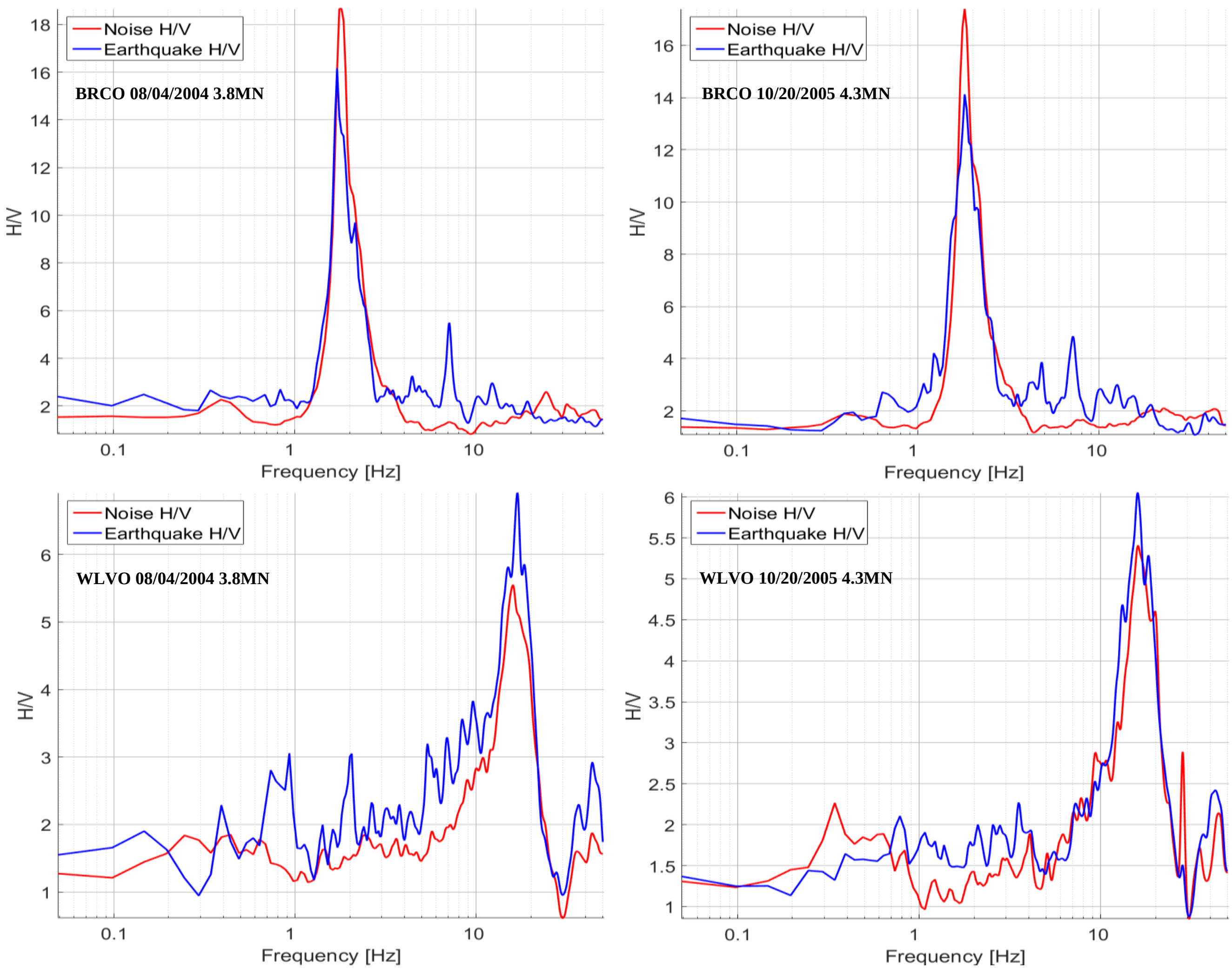


Figure 2: Comparison of HVSR from noise and earthquake data obtained for the two considered earthquakes (Table 2)

HVSR Model

It is widely accepted to approximate the soil resonances obtained by HVSR as response of a Single Degree of Freedom Oscillator (SDOF). The same approach is used in the determination of the response spectrum by McGuire [1], [13]. This representation assumes that for higher frequencies the response is steeply decaying, and after convolution the high-frequency portion of the signal convolved with the SDOF response will be greatly diminished. In a layered soil model, multiple resonances are often observed in the HVSR curve, leading to the conclusion that multiple resonators should be used to approximate the HVSR curve. Therefore, a set of parallel BPFs, which include also one all-pass filter (used to establish a base level for the HV ratio of 1) is used to approximate a given HVSR curve. Each BPF's response spectrum is defined by the center frequency (f_0), gain (A) and slope steepness (n) as given by Equation (4).

$$BPF(A, f, f_0, n) = A\left[\frac{\left(\frac{f}{f_0}\right)^2}{\left(1-\left(\frac{f}{f_0}\right)^2\right)^2+\left(\frac{f}{f_0}\right)^2}\right]^{n/4} \tag{4}$$

The Q factor of the resulting filter can be obtained from Equation (5), where f_1 and f_2 are -3dB intercept frequencies of filter characteristic, which are the solutions to the above equation when it equals 0.7071(-3dB).

$$Q = \frac{\sqrt{f_1 f_2}}{f_1 - f_2} \tag{5}$$

$$Q = \sqrt{\frac{1}{2^{\frac{2}{n}}-1}} \Leftrightarrow n = \frac{2\log 2}{\log(1+Q^{-2})} \Leftrightarrow slope = f_0\frac{dBPF(f)}{df} = 6n\left({}^{dB}/_{oct}\right) = 10n\left({}^{db}/_{dec}\right) \tag{6}$$

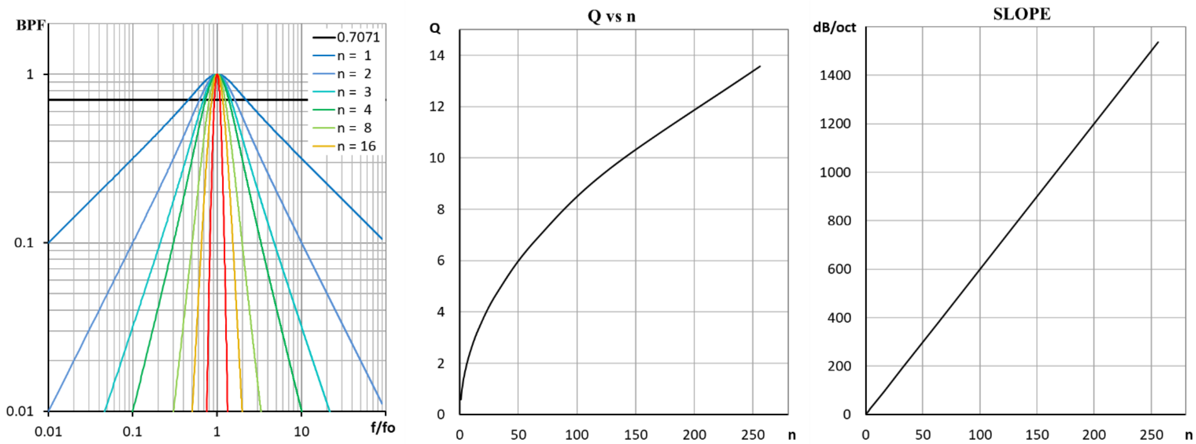


Figure 3: (left) Filter response for normalized f; (middle and right) Quality factor and Slope as a function of slope steepness(n) Equations (4 and 6)

The sum of the BPF responses is subtracted from the original HVSR and the Sequential quadratic programming (SQP) constrained optimization [14] is used to estimate the parameter set that minimizes the RMS error. The iterative SQP optimization adjusts the gain and steepness parameters, while the center frequencies are pre-defined and kept constant. Automatic detection is used to establish the most prominent peaks in the HVSR curve. This set of peaks is used to set the frequency parameters for the BPFs. Additional manual adjustments of the fit are possible by also picking the inflection points. Constraints are placed that limit the parameter values to $n \geq 0, A < HVSR(f_i)$ BPF gain is limited to the HVSR value at each selected peak frequency. The HVSR model is obtained as a sum of the optimized BPFs (Figure 4).

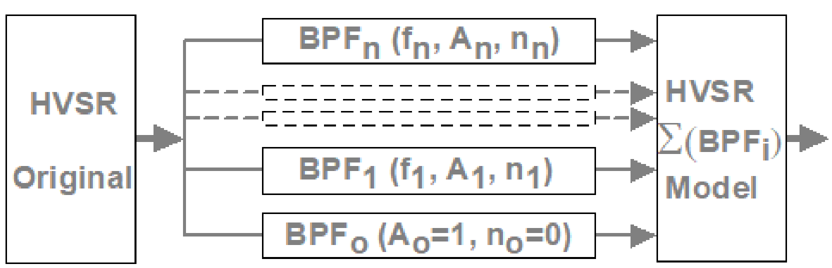
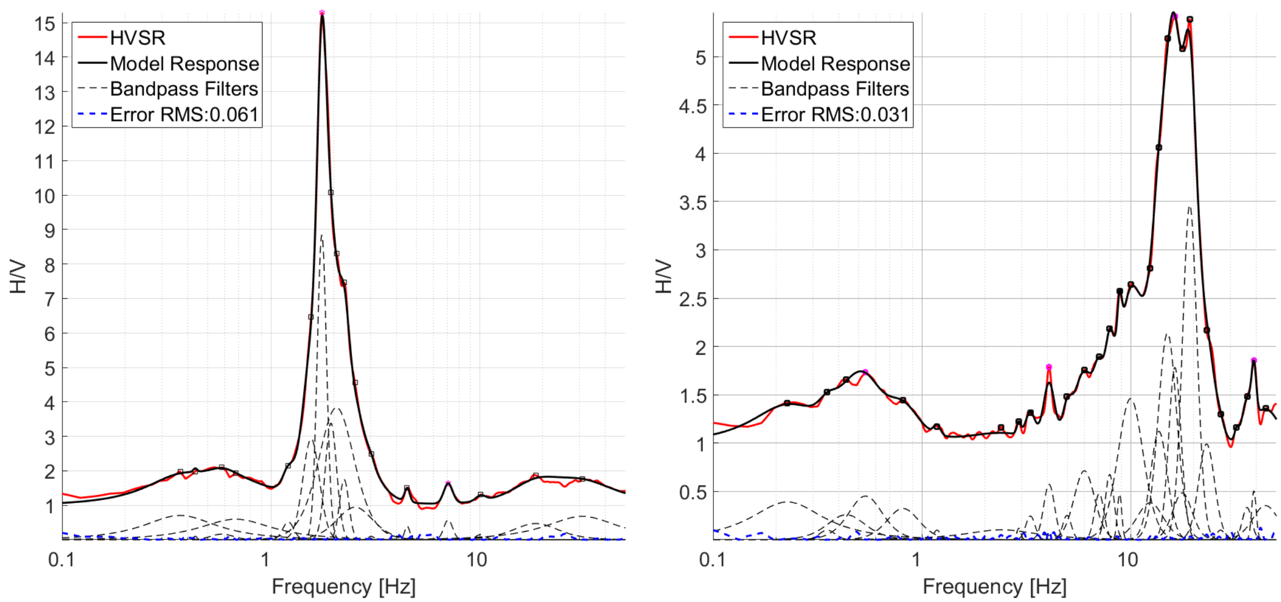


Figure 4: Simplified procedure for estimating a parametric HVSR spectral model

HVSR curves for all considered stations were obtained using night-time noise. BPF models were developed to approximate these HVSR curves. These approximations were limited to a minimum HV ratio of 1, to maintain the assumption that the vertical motion is not affected by the soil response. Examples for stations BRCO and WLVO are shown on Figure 5.



BRCO *WLVO*

Figure 5:HVSR Models obtained from night time noise at the Bruce Peninsula (BRCO) and Wesleyville (WLVO) SOSN/Polaris stations. The points on the curves indicate the locations of the BPF center frequencies chosen for the approximation of the HVSR spectra

APPLICATION AND RESULTS

The BPF models for stations BRCO and WLVO were used to reduce the site effects present in the earthquake records of the two events in Table 1. For this purpose, the original non-smoothed spectra of each component are divided by the model response. The modified spectra keep their original phases. After performing an inverse Fourier Transform, the resulting waveforms show reduced site effects.

Additionally, the HVSRs (using the same method as above) were calculated for the earthquake records, where the signal is separated into high and low level sections: noise and earthquake). Window size of 20 seconds overlapped by 50% were used to establish the mean values presented in Figure 2. Comparing the two HVSR curves, shows that for these cases there is good agreement between the HVSRs from noise before the earthquake and from the earthquake. Noise HVSR's dominant peak overestimates the earthquake HVSR dominant peak by 17% for BRCO station and underestimates it by a factor of 10% for the WLVO station. Higher frequency content present in the BRCO earthquake HVSR is underrepresented in the BRCO noise model. Site effect removal is applicable for these two cases, as the HVSR curves for both noise and earthquake have close similarity (see Figure 2).

For either station, the rotated horizontal components and vertical components are overlapped by waveforms corrected for the site response using their corresponding models (Figures 6 and 7). In both cases, PGV and energy are reduced after correction. In the case of seismic station WLVO the reduction of horizontal amplitudes after correction is readily apparent.

If the Nakamura philosophy is correct, the corrected waveform could be as recorded over the bedrock. The similarity between corrected horizontal and original vertical spectra for both stations agrees with the assumption that only the horizontal components of motion are affected by the site effect. In this case the surface amplification (~2) is not considered.

The original and modified horizontal and vertical spectra are also shown in **Error! Reference source not found.**6 and 7. Both horizontal spectra (Transversal and Radial) show significant changes at the HVSR dominant frequencies for both earthquakes. In the case of WLVO, the dominant peak is at 2 Hz and the estimated corner frequency is at 5 Hz. The reduction in horizontal PGV is significantly larger than the PGV at the vertical component. For the BRCO station the dominant peak is at 15 Hz, however, the estimated corner frequency is 3 Hz, and the effect over PGV is much less pronounced.

The application of the HVSR model provides better results, in some cases, if the original NS-EW waveforms are rotated to radial and transversal components. This can provide better separation between SH and P-SV seismic waves. Unfortunately, wave-separation depends not only on the back azimuth to the source but on source orientation and existing vertical geological structures.

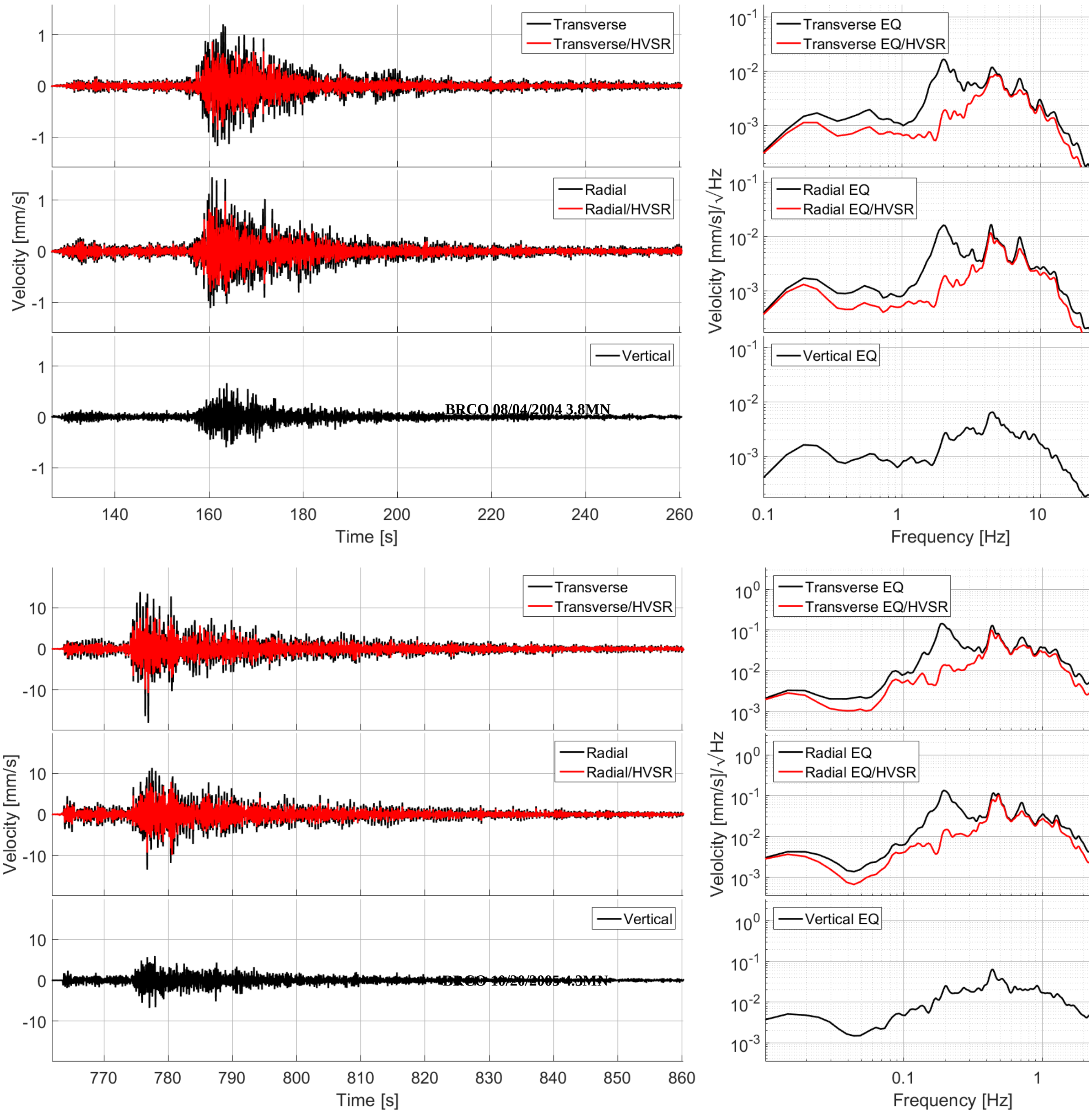


Figure 6: BRCO earthquake record (left) and spectra (right) for both considered earthquakes. (Black) original earthquake waveform and spectra, (Red) Waveforms and spectra of horizontal components corrected by HVSR model

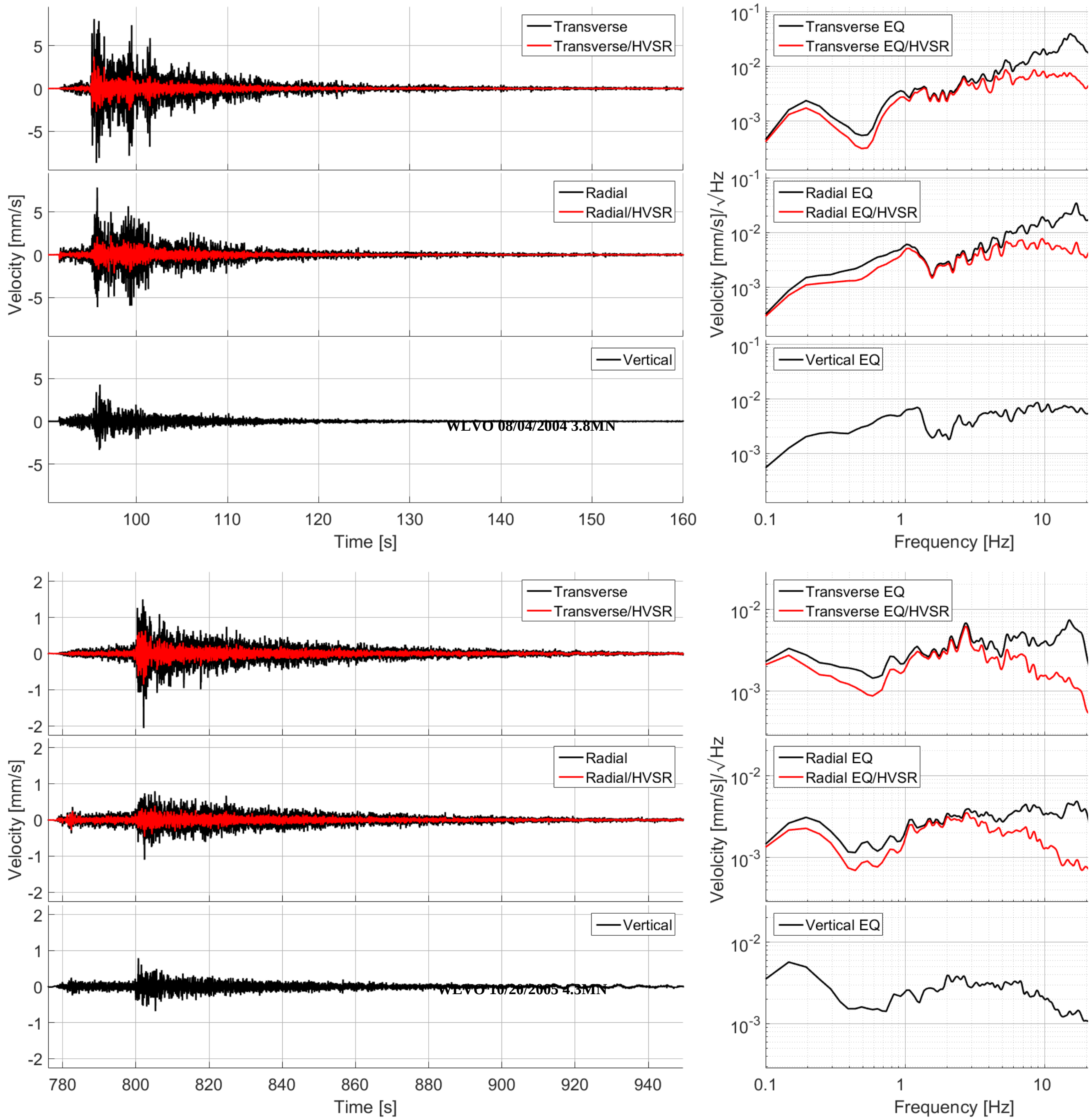


Figure 7: WLVO earthquake record (left) and spectra (right) for both considered earthquakes. (Black) original earthquake waveform and spectra, (Red) Waveforms and spectra of horizontal components corrected by HVSR model

CONCLUSIONS

This paper demonstrated the design and application of a procedure for automatic HVSR approximation using a parallel set of BPF. This proposed modeling tool can be useful to estimate the influence of the site response over earthquake waveforms and spectra. It is applicable if the site response is taken over the same soil layers which will be used for the foundation of a structure. If this foundation needs to be deeper, the HVSR should be acquired at the lowest proposed foundation level, before completion. The possible influence of foundation embedment should be considered during the analysis.

Estimation of the expected Brune source model, especially the corner frequency, for each site can be performed after removing the site response influences on the earthquake spectra using the proposed model. Changes in the corner frequency could significantly alter the expected source parameters. Based on Equation 2, a change to the corner frequency of the assumed Brune spectra will require a change in either the stress drop parameter or the rupture radius of fault.

This model is applicable for elastic soil behavior. If a strong earthquake causes significant strain in soil layers, the reduction in shear strength and Q factor should be considered accordingly [15].

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