HVSR MEASUREMENTS IN COMPLEX SEDIMENTARY ENVIRONMENT AND HIGHLY STRUCTURED RESONATOR TOPOGRAPHY – COMPARISONS WITH SEISMIC REFLECTION PROFILES AND GEOPHYSICAL BOREHOLE LOGS

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Abstract

Over the last two decades, horizontal-to-vertical spectral ratio (HVSR) measurements from microtremor recordings have gained popularity for seismic microzonation and assessment of earthquake site characteristics such as fundamental frequency (or period). More recently, procedures have been described where empirical relationships are developed between the fundamental frequency and sediment thickness at regional sites where shear wave velocity depth functions are well understood and a simple 2-layer-model is a good approximation of the subsurface structure. In contrast however, in complex glacial stratigraphy, sediment types commonly vary drastically from very soft glaciomarine clay to overconsolidated till. We observe that these changes can lead to strong impedance contrasts and hence, resonating horizons well above bedrock can be resolved. Without a-priori knowledge, sediment thickness could be significantly under-estimated.

We examine the frequency spectra of microtremor recordings in both simple and complex sedimentary settings at locations along high-resolution shear wave seismic reflection profiles and at continuously cored boreholes with shear wave velocity (Vs) profiles. Vs range from 80 – 2000 m/s within the unconsolidated sediment overburden. Our results indicate that resonator topography can have a significant impact on peak shape and amplitude. In relatively simple 2-layer cases, peak frequencies decrease and broaden over dipping resonators and even disappear over very steep resonator slopes, indicating that two- and three-dimensional subsurface resonator topography is highly influential on peak shape. Additionally, we present examples where sharp increases in shear wave velocity within the sediment column form strong resonating horizons, producing a high amplitude peak which does not necessarily correlate with the bedrock surface. Our results suggest that resonator topography and velocity structure need to be well understood by a practitioner before interpreting geological conditions from HVSR data.

Introduction

This paper focuses on observations and findings from two case studies in Southern Ontario, Canada: A) H/V spectral shapes are investigated in a two layer setting with dipping horizons. The topography of the layers has a significant impact on the HVSR responses. B) HVSR results from an environment of complex, glacial sedimentation reveal main amplitude peaks stemming from resonating horizons well above the bedrock.

Case study A: Two layer setting with dipping horizons

In Orleans, a suburb in the east of Ottawa, ON, bedrock depths increase from <10 m to 80 m over a deep bedrock valley (Pugin et al., 2007). The local stratigraphy was simplified into 3 types of material: soft soil (deglacial / postglacial sediments), dense soil (glacial sediments) and bedrock. A strong impedance contrast is expected at the bedrock interface or at the top of the glacial sediments, and a sharp, high amplitude peak from HVSR measurements should be obtained. During the micro-zonation work done in the area (Hunter et al. 2010), it became apparent that the expected high resonance peaks were not observed everywhere. Mallozzi (2017) collected and processed over 300 individual HVSR recordings along high-resolution seismic reflection landstreamer profiles (Top of Figure 1, after Pugin et al., 2007).

As Hunter et al. (2010) have shown, a systematic variation occurs between HVSR measurements and the fundamental site period estimates from shear wave measurements using

$$T_0=4h/Vs_{av} \qquad \text{(Eq.1: Dobry 1976)}$$

For the Ottawa area an empirical equation was found relating the calculated fundamental site period to measured HVSR as

$$T_{passive} = 0.80976 * T^{0.82789}_{site} \qquad \text{(Eq.2: Hunter et al. 2010)}$$

The authors suggested different explanations of the variance (“Dobry effect”); velocity dispersion might be one explanation as seismic reflection measurements are made at 30 to 100 Hz whereas HVSR measurements use a frequency range between 0.1 and 20 Hz.

Effects of this variance can be seen in Figure 1 (top) where HVSR amplitude spectra are shown as green traces on the seismic reflection profile. Red traces show H/V measurements after correction using Eq. 1. A good match between HVSR peak amplitudes and the main seismic reflector is obtained. Peak shapes are asymmetrical and shoulders develop where the reflector/resonator curves. (E. g. compare the measurement sites named CLF-32 (or CLF-26 and CLF-33). Peaks decrease, flatten out and broaden over steep reflector topography (CLF-249 to CLF-251).

At the bottom of Figure 1, 4 major types of H/V amplitude spectra in frequency domain are shown: A) symmetrical peak from a deep resonator (CLF-35), B) broad, low amplitude peak from a deep, slightly dipping resonator (CLF-32), C) very broad, low amplitude peak from a steeply dipping resonator (CLF-249), and D) very high amplitude peak from a very shallow (CLF-22) resonator. The height of the triangles is formed by the maximum amplitude. The width of the peak (horizontal lines at the base of the triangles) is calculated at the one half of the peak amplitude. Width and height form the metric of the triangle which depicts the shape of the peak.

The representative metric, depicted by the triangle, for each H/V measurement along the seismic profile are shown in the center of Figure 1. Changes in the shapes of the spectra are more easily observable showing metrics (triangles) compared to the complex traces on top of Figure 1. Clearly, the amplitudes of the peak frequency decrease and broaden as the steepest part of the bedrock incline is reached. The largest amplitudes stem from the shallow resonator. The asymmetry associated with shoulders or double bumps (e.g. CLF-32) seem to be correlated with slightly dipping reflectors. Modelling two-dimensional, sloping and bending interfaces might provide more insight.

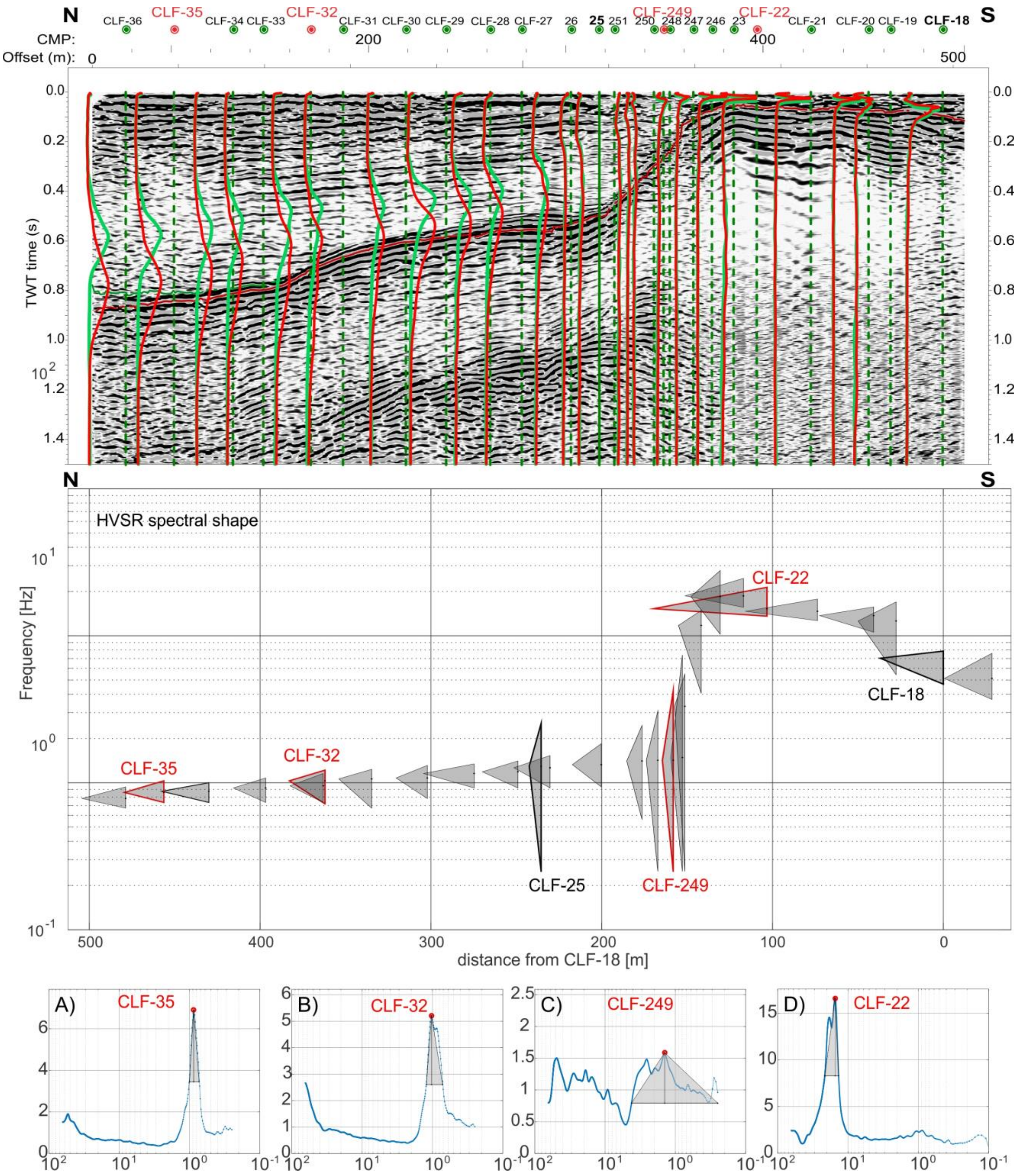


Figure 1: Top: Seismic reflection profile (after Pugin et al. 2007) in time domain (two-way travel time) with HVSR amplitude spectra (corrected = red, uncorrected = green). Green vertical lines indicate the exact location of the measurement sites. Center: Representative metric, depicted by a triangle height and width are shown for each H/V measurement site. Bottom: 4 major types of types of H/V amplitude vs frequency spectra: A) from a deep, flat resonator; B) from a deep, slightly dipping resonator; C) from a deep, steeply dipping resonator; D) shallow resonator.

Case study B: Complex glacial stratigraphy

In fall 2015 and August 2016 about 200 individual HVSR measurements were collected along high-resolution reflection seismic profiles in Southern Ontario. The H/V spectra were transformed into amplitude versus two-way-travel time. Using the time-to-depth relation from seismic velocity analysis, both datasets - all HVSR measurements and the seismic profile - were converted to depth.

Figure 2 shows a section of a SW-NE trending high-resolution reflection seismic profile south of Georgian Bay, ON. The sediment geology is heavily influenced by the glacial history. Three sequences can be observed as indicated by the green, yellow and petrol layers at the bottom of Figure 2. The reflection with the highest and most coherent amplitude is interpreted as a horizon of major depositional change. Borehole CS-16-01 specifies a change from sand to gravel at about 61 m depth coinciding with this change. The horizon is undulating across the profile closely connected with the peak amplitudes of the H/V measurements, but at slightly shallower depths due to the “Dobry effect”, which was not corrected. But clearly, the main resonating horizon is well above bedrock. The shear wave interval velocity log shows a significant increase which coincides with the amplitude peak. There appears also to be a second amplitude maximum loosely correlated with the shear wave velocity increase at the base of the upper silt layer (interpreted top brown horizon in Figure 2).

Sites WB-24P5A and WB-25A (indicated in red on Figure 2) are roughly 500 m apart with similar stratigraphy - yet large differences in H/V amplitude shapes can be observed (bottom of Figure 3, black). A high amplitude resonance peak at shallow depths (high frequency), and a broad, local maximum in lower frequency exist for WB-25A (right). WB-24P5A has a maximum at depth (lower frequency) and a broad, local maximum at shallow depth (high frequency).

Based on measured Vs and Vp from borehole CS-16-01 a simplified subsurface model was created. Model parameters are shown at top right of Figure 3. These parameters were used to calculate a synthetic H/V response (OpenHVSR, Bignardi 2015). Modelled H/V responses are calculated separately for surface waves and body waves. The modelled surface wave response (green) matches the measured response from WB-25A perfectly, but it is missing completely at WB-24P5A. It appears, based on the modelling, that a deep main resonator (lower frequency) is associated with both body and surface waves. Whereas the high frequency peak (as observed at WB-25A) stems mainly from the surface wave contribution. The seismic profile at WB-25A reveals a thicker layer of low velocity sediments which are very likely responsible for the strong surface wave response.

The broadening and flattening of the secondary peak compared to the main peak of WB-24P5A might be related to the dipping layer beneath WB-25A (compare Figure 2). Additional modelling with topography included might provide further explanation.

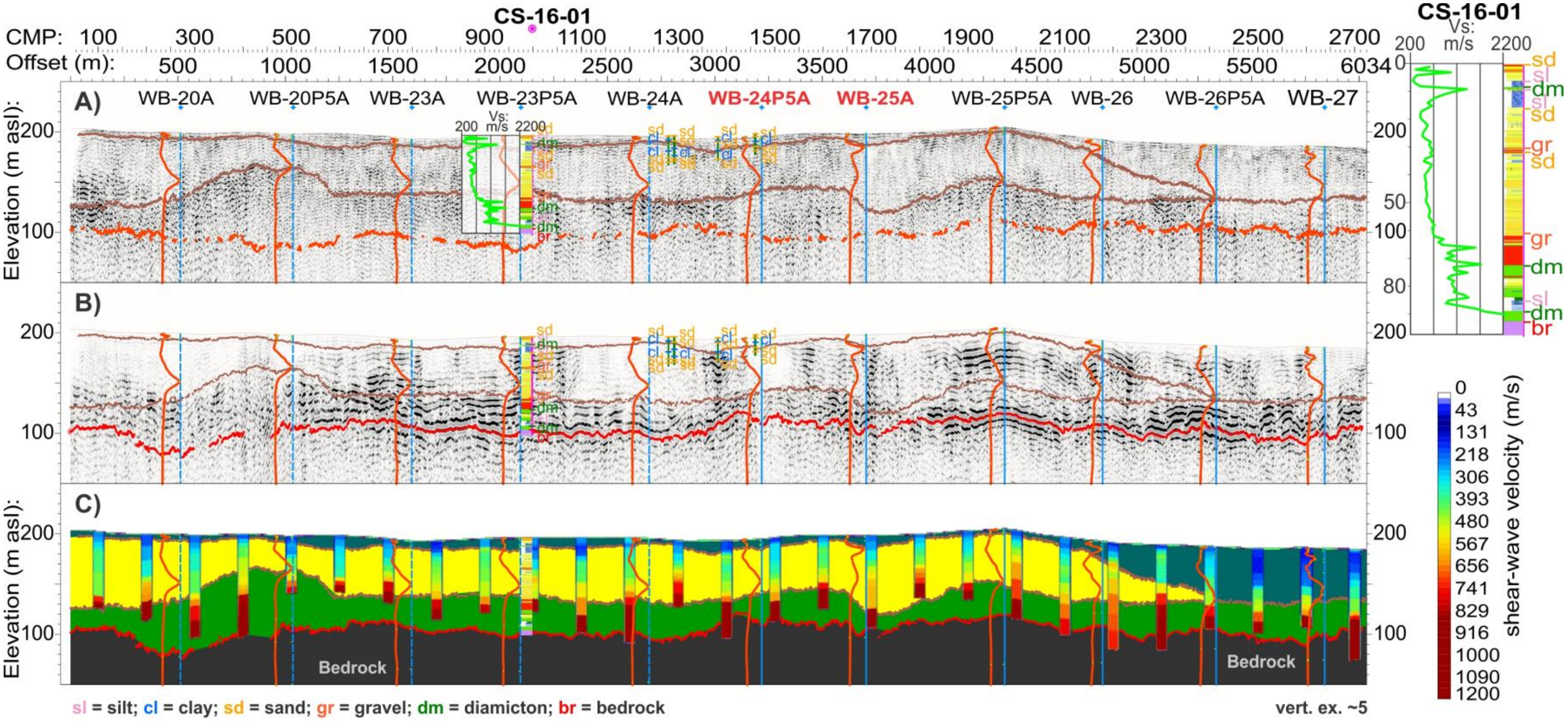
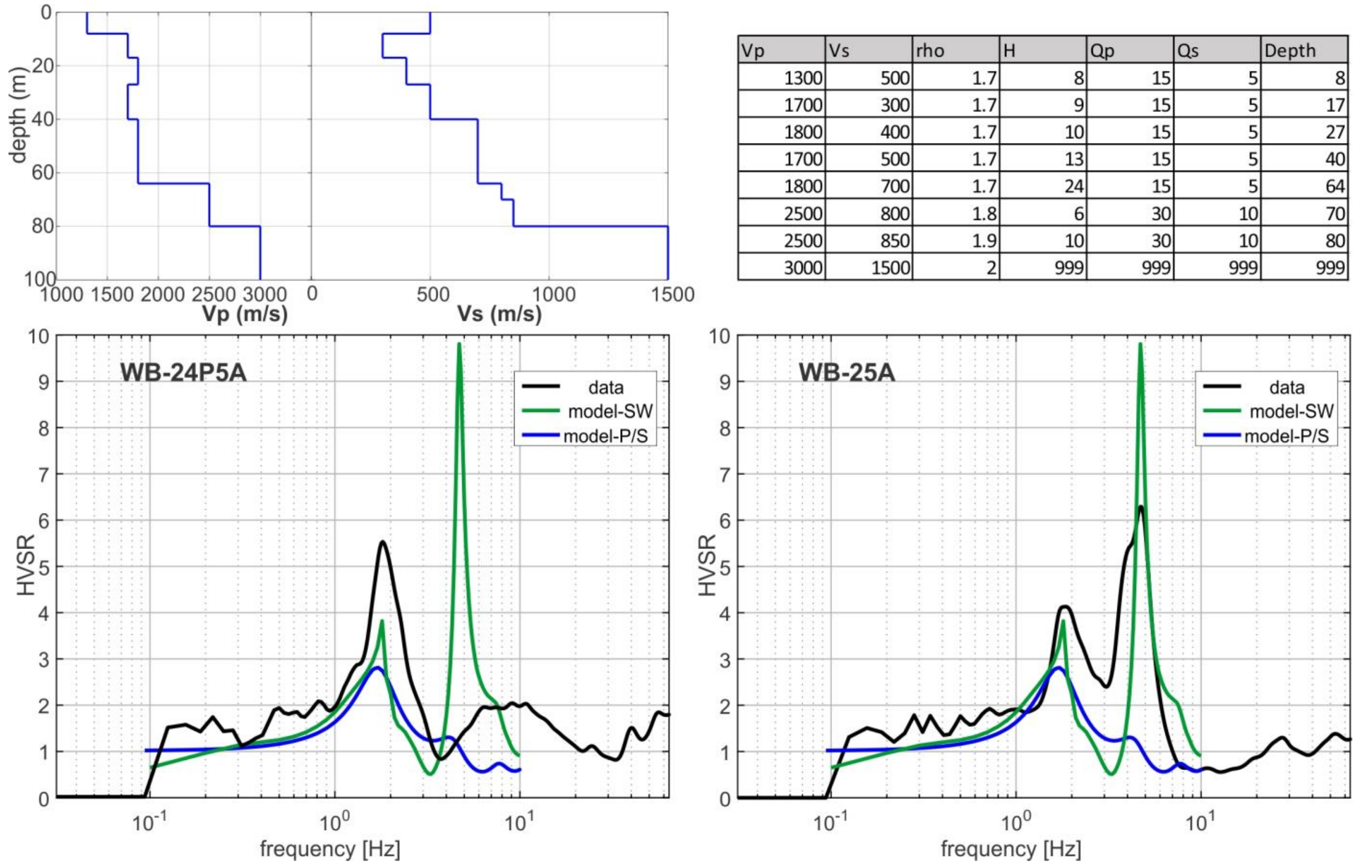


Figure 2: A) Seismic shear wave reflection profile in depth domain. B) shows the P-wave seismic section, and C) an interpretation of major stratigraphical units and seismic Vs are shown. Two main sedimentary horizons (brown) are interpreted as well as the bedrock surface (red). H/V spectra are shown as red traces. H/V measurement locations are indicated with blue vertical lines such that peak amplitudes coincide with exact locations in depth. Lithology (Mulligan 2016) and Vs for well CS-16-01 are shown on the right.



Vp	Vs	rho	H	Qp	Qs	Depth
1300	500	1.7	8	15	5	8
1700	300	1.7	9	15	5	17
1800	400	1.7	10	15	5	27
1700	500	1.7	13	15	5	40
1800	700	1.7	24	15	5	64
2500	800	1.8	6	30	10	70
2500	850	1.9	10	30	10	80
3000	1500	2	999	999	999	999

Figure 3: Simplified Vp (top, left) and Vs profiles (top center) and input values (top right) for modelling body waves and surface waves. Measured H/V responses from WB-24P5A (bottom left, black) and WB-25 (bottom right, black) are compared to modelled body (p- and s-waves, blue) and surface waves (green) H/V.

Conclusions

Many factors are contributing the shape of H/V amplitude spectra, e.g. the depth of the resonating horizon, the steepness of the dip and the whole structure of the sediment overburden. It is speculated that a shallow resonating layer produces a stronger surface wave contribution to the spectral shape at higher frequencies. It is also more likely to exhibit a secondary peak at lower frequencies produced by a lower layer from body and surface wave contributions.

The impact of these factors to the spectral shape are not yet fully understood. More statistical analyses are needed with larger sample sizes. More modelling preferably in two- and three-dimensions is needed to account for dipping layers. It is important that the full waveforms are included in the modelling as many interactions possibly play a major role in the definition of the H/V amplitude shape. Considering all factors and their not yet fully understood contribution to HVSR shapes, it is very difficult to use H/V amplitude shapes without other prior information for subsurface mapping in complex sedimentary environments.

Acknowledgement

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