TESTING JOINT APPLICATION OF HVSR AMBIENT VIBRATION MEASUREMENTS AND MASW SEISMIC SURVEY IN THE PUGET LOWLAND AND COASTAL AREA, WASHINGTON

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ABSTRACT

Growing interest surrounds ambient vibration measurements both in the fields of engineering/seismological applications and geologic surveys. In general, a basic drawback of this kind of measurements is the relatively low resolution of subsoil imaging provided by this kind of analyses due to the inherent randomness of the signal, complexity of the relevant inversion procedures and multiplicity of possible subsoil configurations potentially responsible for observations. On the other hand, economy (in terms of costs per unity of explored subsoil volume), relatively large exploration depths, surveying at various locations in short time with less manpower, and negligible soil occupancy make ambient vibration measurements an ideal tool for extensive surveys. In order to evaluate in the field the feasibility of single station ambient vibration measurements (Horizontal to Vertical Spectral Ratio, HVSR, approach) in support of surveys devoted to the seismic and geologic characterization of earthquake recording sites, an integrated approach based on passive (HVSR) and active (MASW) seismic prospecting under geologic control, was carried out in the Puget Lowland and southwest coastal area of Washington state. The HVSR approach proved to be effective in reducing the uncertainties intrinsic in the passive prospecting and extending depth-penetrating capabilities of standard active seismic survey methodologies. The results obtained during this survey are outlined, showing the effectiveness of the proposed approach.

Horizontal-to-Vertical Spectral Ratio (HVSR)

The basic goal of single-station ambient vibration measurements is the detection of seismic impedance contrasts in the subsoil, that are responsible for seismic resonance phenomena (e.g., Kramer, 1996).

$$h \cong \frac{\langle V_s \rangle}{4f_0}$$

Despite of the fact that physical interpretation of the H/V ratios as a function of frequency (hereafter *HVSR* curve) is to some extent controversial (Nakamura, 2000; Fah et al., 2001; Lunedei and Albarello, 2010), the frequency f_0 corresponding to maximum value of the *H/V* function was shown to have a strict correspondence with the local resonance frequency f_r of the sedimentary cover (see, e.g., Bard, 1999; Bonnefoy-Claudet et al., 2006). By exploiting the well known approximate relationships relating the resonant frequency of this cover with its thickness (*h*) and average shear-wave velocity

$$h \cong \left[\frac{V_0(1-x)}{4f_r}+1\right]^{\frac{1}{1-x}}-1$$

bs Von Seht and Wohlemberg, 1999), one can see that f_0 deduced from HVSR measurements allows retrieving important information on the shallow subsoil structure. Furthermore, despite the fact that the relationship between HVSR values and the subsoil structure are rather complex (see, e.g., Albarello and Lunedei , 2010; Lunedei and Albarello, 2010) a nearly monotonic relationship exists between the amplitude of the impedance contrast responsible for the HVSR peak and the amplitude of this peak. This implies that, at least qualitatively, the relative significance of the impedance contrasts can be easily detected by comparing HVSR curves obtained at different sites.

$$\langle V_S \rangle \cong 4f_0 h \cong 4f_0\left\{\left[\frac{V_0(1+x)}{4f_0}+1\right]^{\frac{1}{1-x}}-1\right\}$$

Single station ambient vibration measurements can also be applied to evaluate seismic response of buildings in the range of elastic behaviour (e.g., Mucciarelli *et al.* 2009). In the assumption of a stationary wavefield, ratios of average ambient vibration spectral amplitudes registered at the top of a building and in the nearby free-field (standard spectral ratios or SSR approach) can be used to detect resonance frequency of buildings. Coupling this information with free field f_0 estimates could allow the identification of most critical situations, where double resonance phenomena (coincidence of building and soil resonance frequency) could be responsible for damage enhancement in the case of strong earthquakes.

V_0	x	Soil Material Type
210	0.20	Compact soil
170	0.25	Sand(s)
110	0.40	Reworked or very recent soil (such as landslide)

This method requires at least a rough definition of the free parameters V_0 and x. Specialized values can be provided by a preliminary geological survey or by considering borehole data eventually available (e.g., D'Amico et al., 2004, 2008).

Ibs von Seth and Wohlenberg, 1999; Scherbaum et al., 2003; Delgado et al., 2000 a,b) suggest that:

1) granular soils (sands) present values of *x* near to 0.25,

2) lower values of x should correspond to fine soils (clays and mud), since in these cases the dominant effect is the electrostatic interaction among the particles, which results in a minor effect of the lithostatic load on the form of interaction among them,

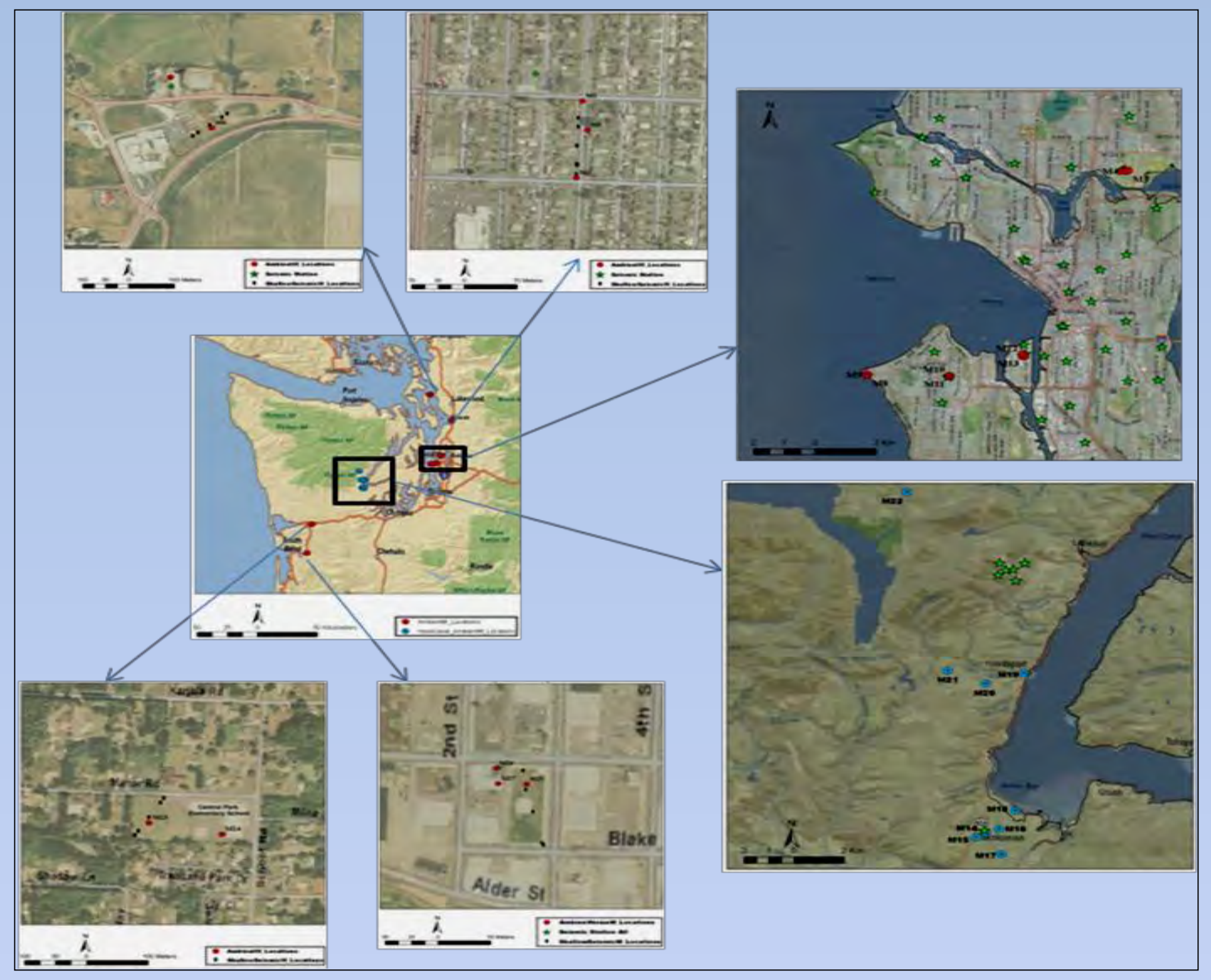
3) greater values of x can be expected in reworked soils (landslides) or in fan zones with big non-cemented clasts,

4) fluids under pressure can reduce the effect of the lithostatic load, decreasing the exponent *x* also in granular soils.

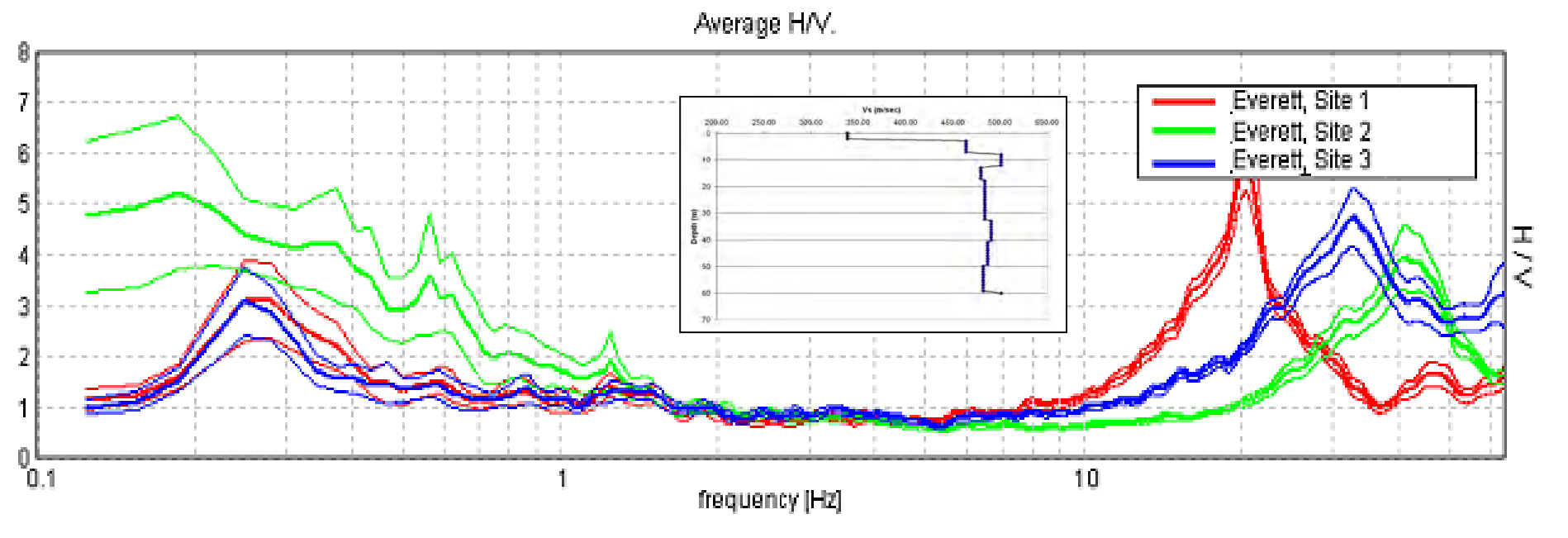
fr (Hz)	h (m)	Vs30 (m/s)	V ave (m/s)
0.1	2185	315	874
0.2	870	315	696
0.3	509	315	610
0.4	348	315	556
0.5	259	315	518
0.6	204	315	489
0.7	166	315	466
0.8	140	315	447
0.9	120	315	431
1.0	104	315	417
1.5	62	315	369
2.0	42	315	340
2.5	32	315	319
3.0	25	336	304
3.5	21	362	292
4.0	18	385	282
4.5	15	405	274
5.0	13	424	267
6.0	11	456	256
7.0	9	483	247
8.0	8	505	240
9.0	7	525	235
10.0	6	542	230
20.0	3	641	205
30.0	2	685	195
40.0	1	710	190

Table. Relationship between resonance frequency fr and thickness of the resonant layer (h) in the assumption that relationship [3] holds with parameters $V_0 \approx 170$ m/s and x ≈ 0.25. V_{ave} represents the estimate of the average Vs velocity in the resonant layer (eq.[4]). V_s30 represents the estimate of the average V_s up to a depth of 30m

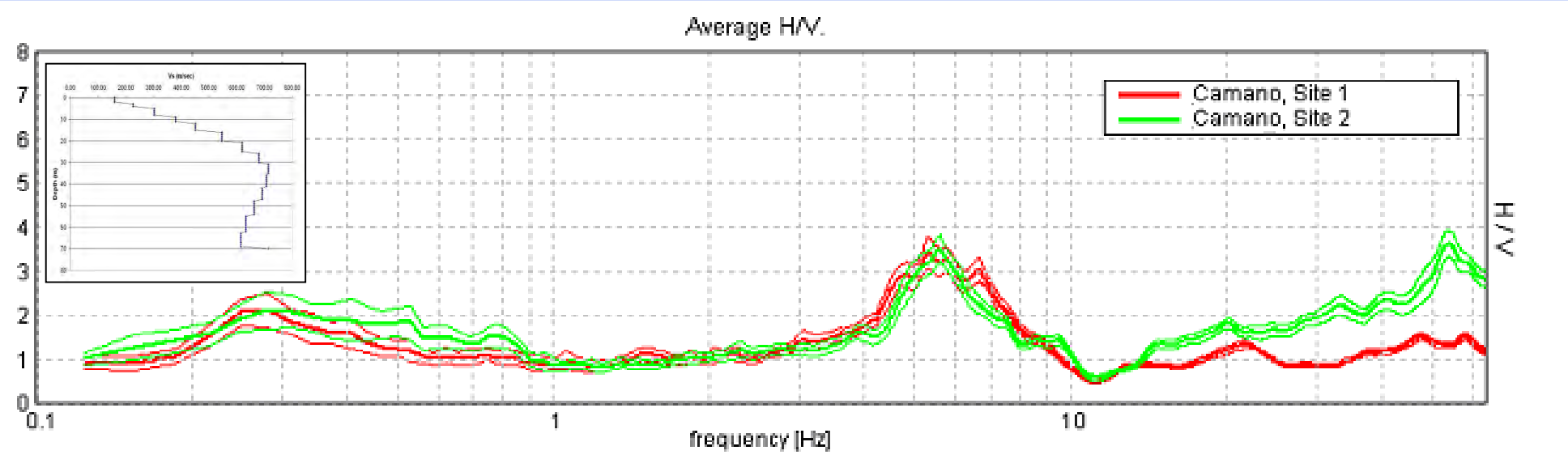
HVSR Measurements in Washington State



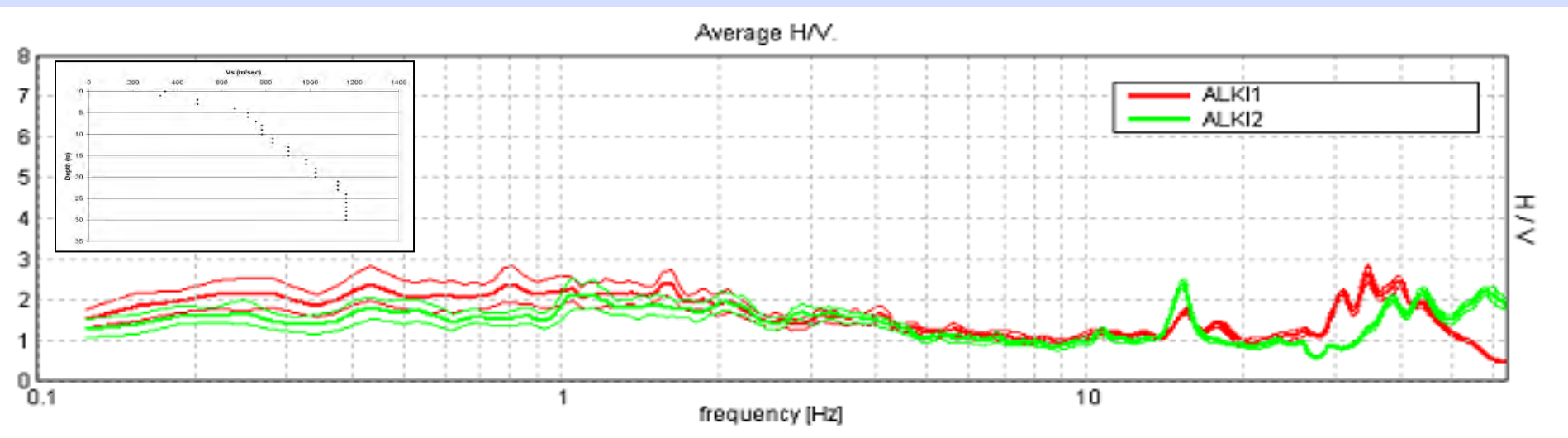
Location of single-station Ambient vibration measurements (red and blue circles) in western and northern Seattle, Hood Canal and Grays Harbor county areas.



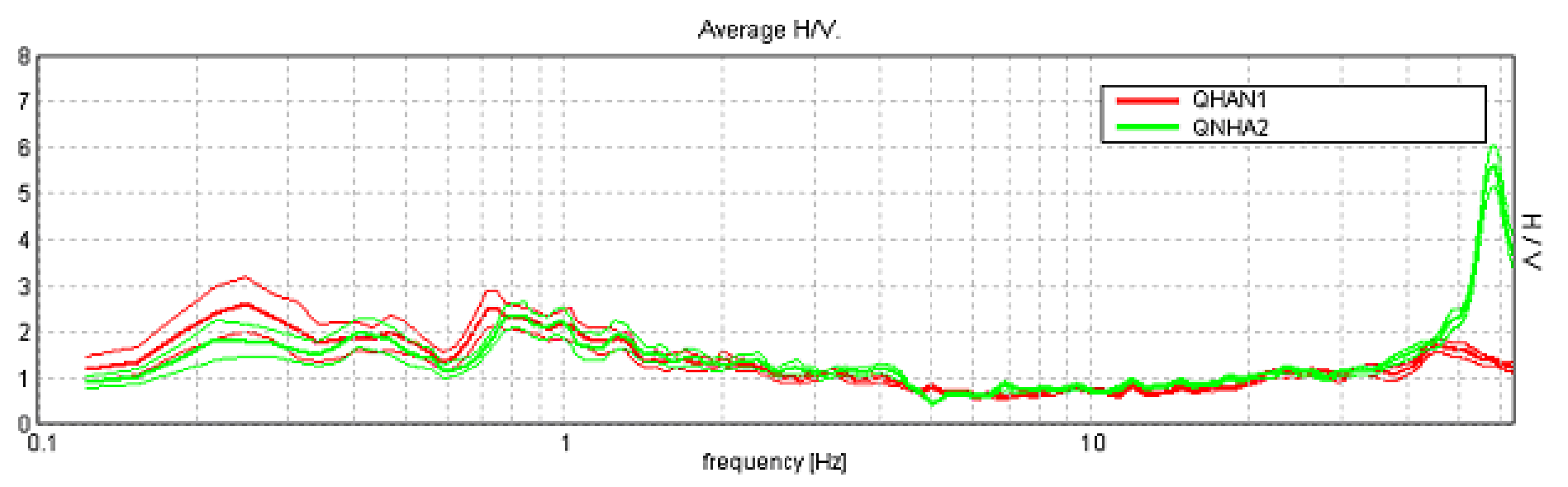
HVSR curves relative to the three measurements performed at the **Everett Fire station**. Thick lines indicate the average HVSR value, while the thin lines include the 90% confidence interval for the estimate. Significant low frequency peak (at 0.25 Hz), this may be a very deep impedance change at about 650 m (for a average Vs results in 600-700m/sec) (see lookup Table on the left)



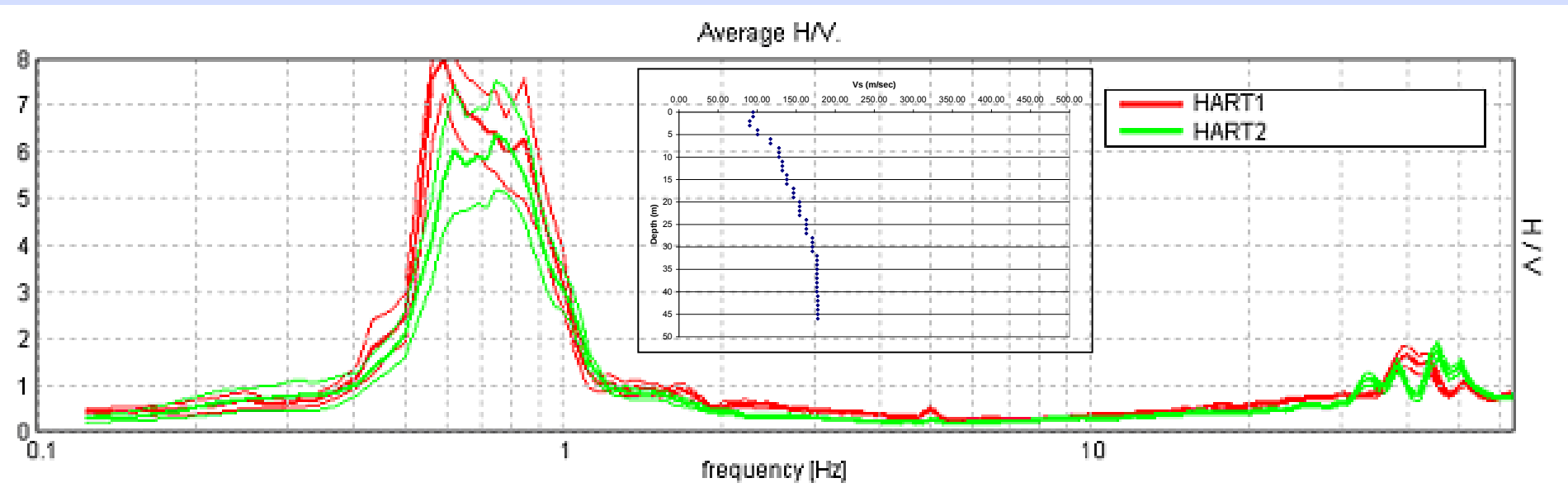
Two HVSR significant HVSR maxima are revealed in the intermediate frequency range (45-6 Hz) and in the low frequency range (0.3 Hz), respectively, at **Camano Island**. This indicates the presence of a relatively sharp seismic impedance contrast at a depth of about 10-13 m. The expected average V_s velocity should be of the order of 400-450 m/s. A second deep interface seems to exist at a depth of about 500 m. The relevant average V_s value is of the order of 600 m/s.



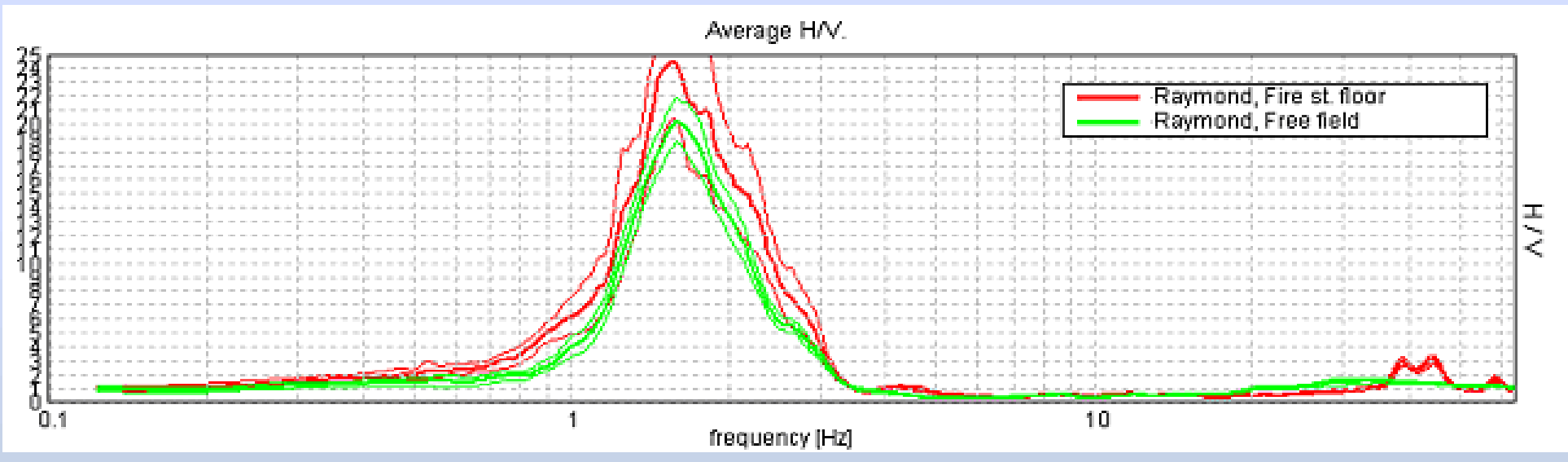
Two measurements show good agreement indicating that HVSR estimates are repeatable at **ALKI** Some of the sharp peaks in the high frequency range (>10 Hz) can be attributed to electromagnetic disturbances, and no resonance phenomena has been detected at this site, which is typical at rock sites. Vs profile estimated from MASW survey shows that no significant shallow soft soil layer a this site to generate trapped, resonating waves



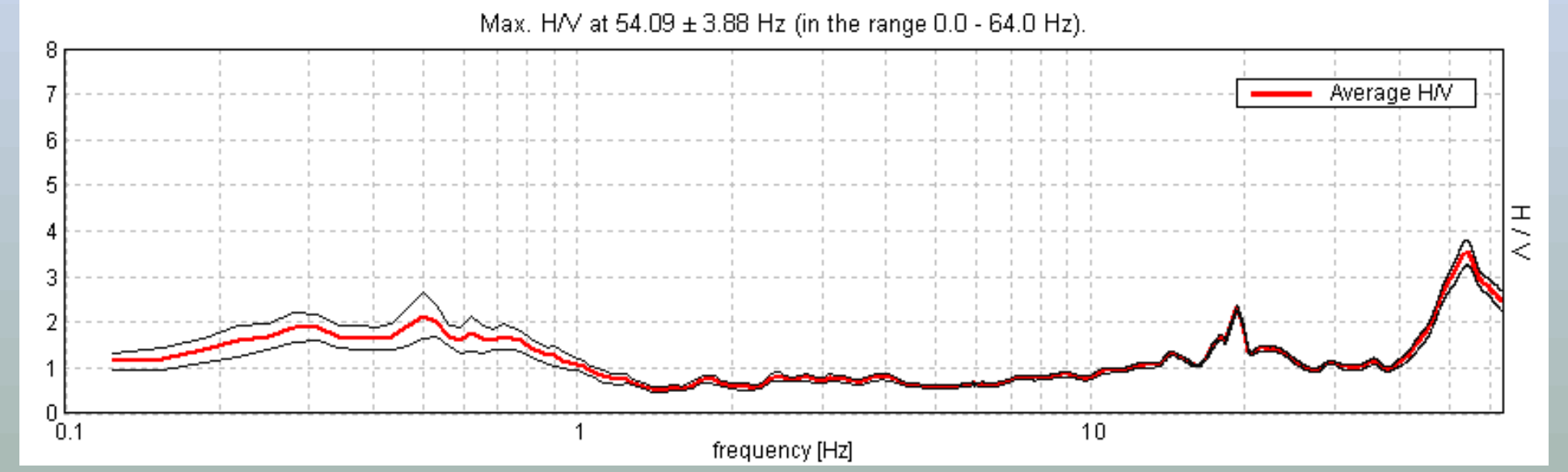
Two measurements nearby the **QHAN** a good agreement (at least in the frequency range <40 Hz) indicating that HVSR estimates are reliable. At least one low frequency peak is revealed at about 0.25 Hz. This could correspond to a deep lithologic transition located a depth of about 650 m (average V_s down to this interface of about 600-700 m/s).



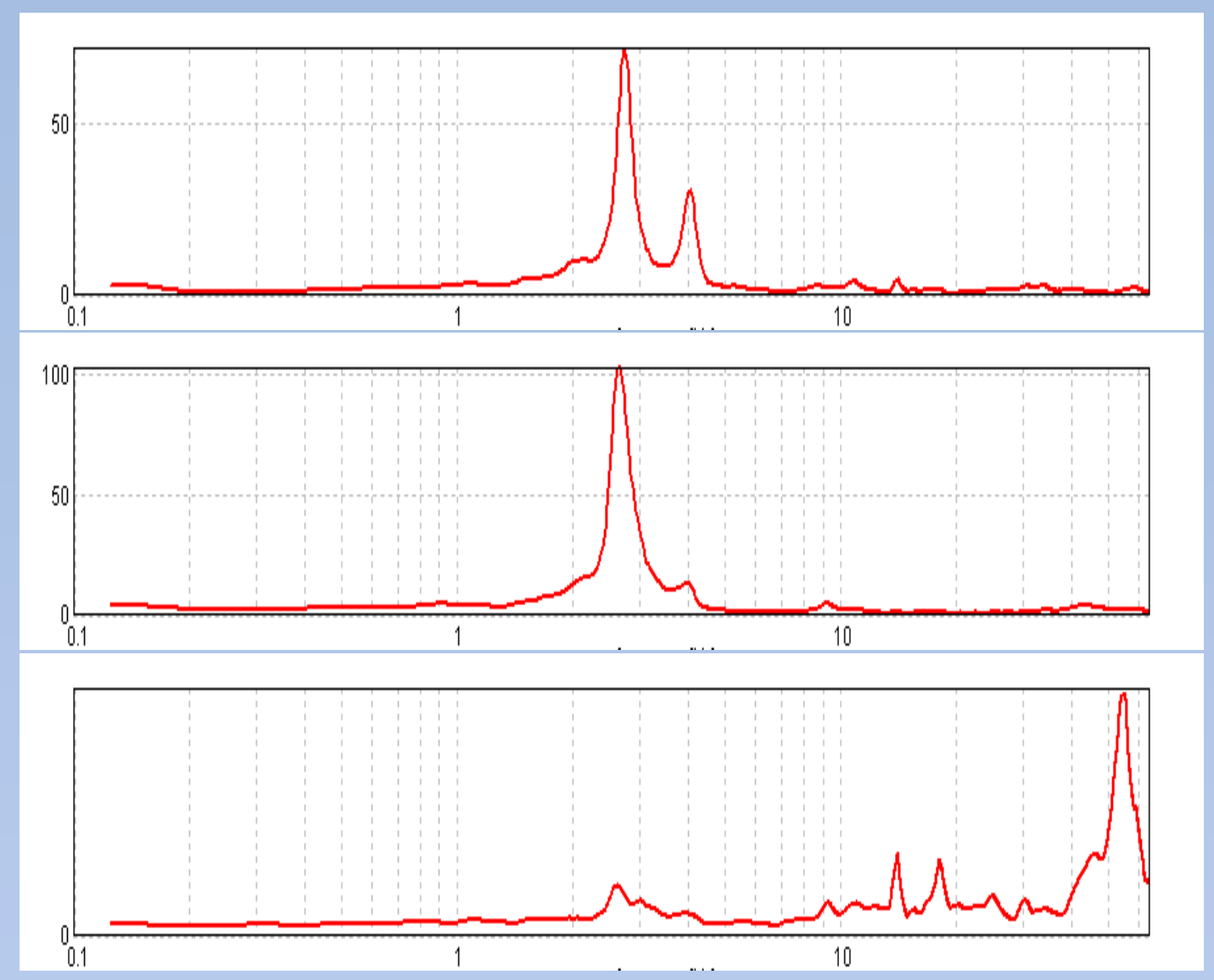
The two HVSR curves measured at the **HART** indicate the presence of a very sharp impedance contrast, responsible for the sharp HVSR peak in the frequency range 0.6-0.8 Hz. This corresponds to a possible strong impedance contrast located at a depth of about 150-200 m from the surface. The relatively large width if this peak could be the effect of mixing of two nearby peaks or to possible strong variations in the buried topography. The estimated average V_s down to the lithologic transition is of the order of 450-500 m/s.



HVSR measurement carried out in the free field and at the floor of **Raymond** fire station how a sharp clear peak at 1.6 Hz, that indicates the presence of a sharp impedance contrast at the site under study. This could be compatible with a sharp lithologic transition at a depth of about 60m. The average V_S estimated for the sedimentary cover is about 360 m/s.

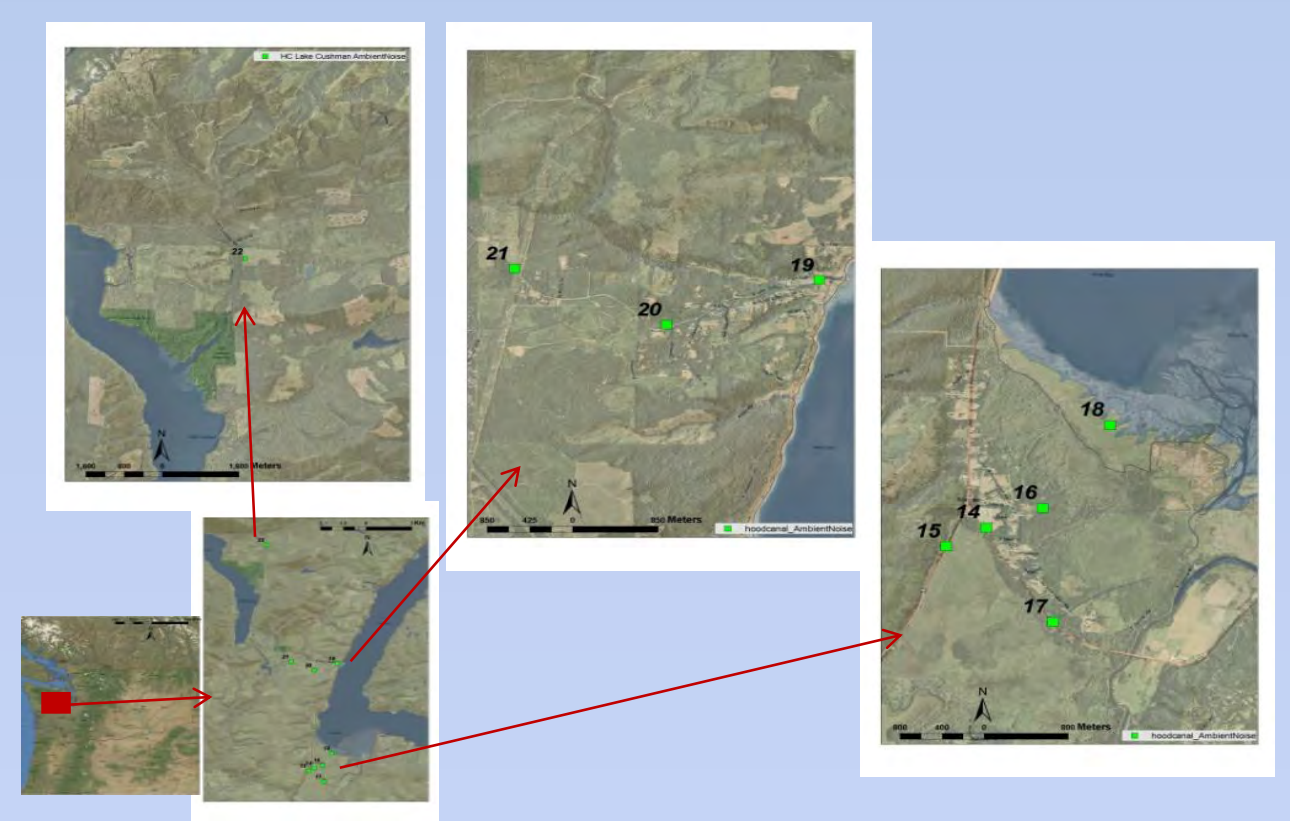


At **SEA** (Univ Washington site) a high frequency (>50 Hz) peak can be associated with a very shallow transition (>1 m). The low frequency one (0.5 Hz) appears quite smooth, suggesting the presence of a gradual transition between different lithologies at a depth of the order of 250 m. The average V_s up to this depth should be on the order of 600-700 m/s.

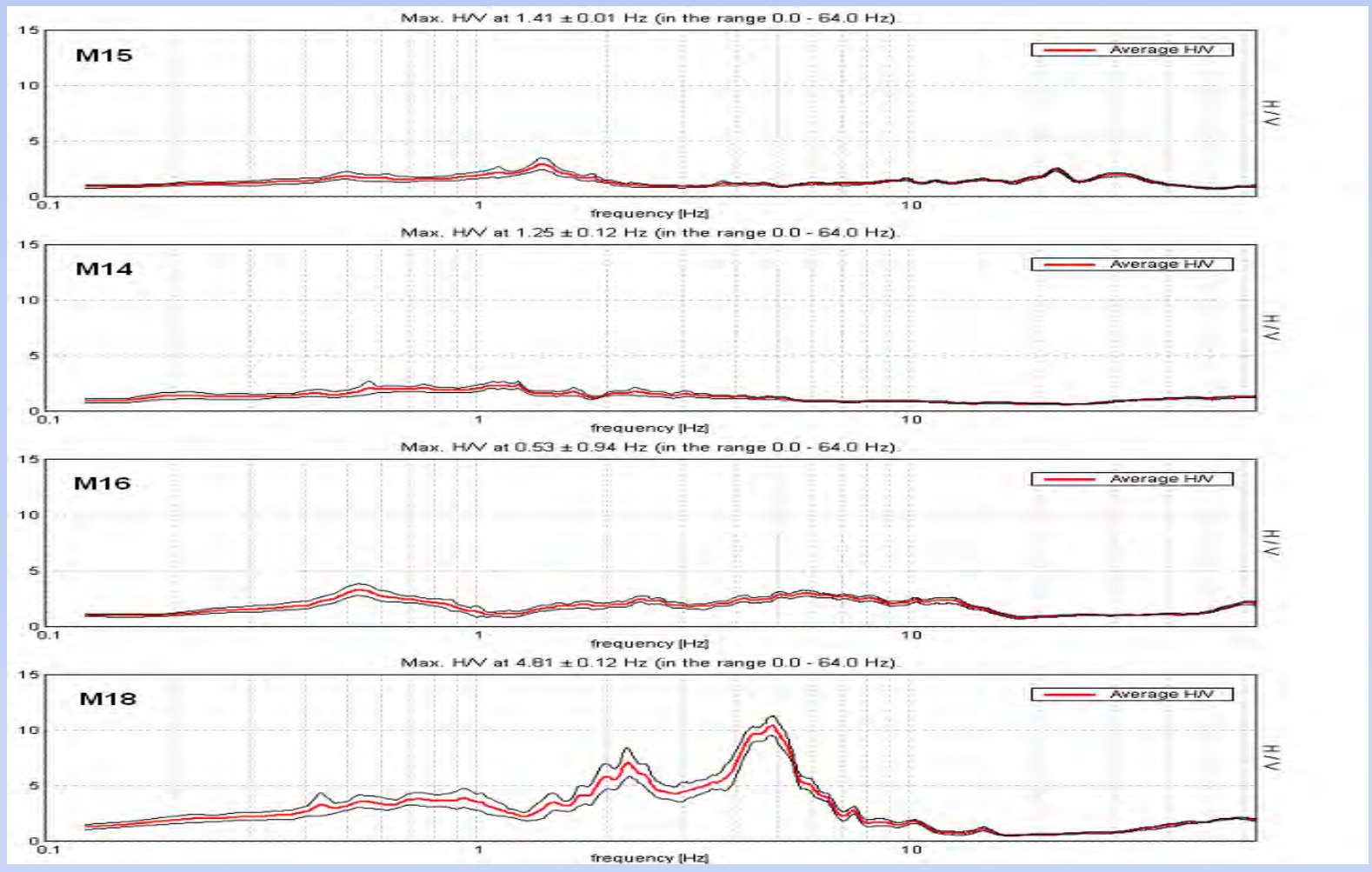


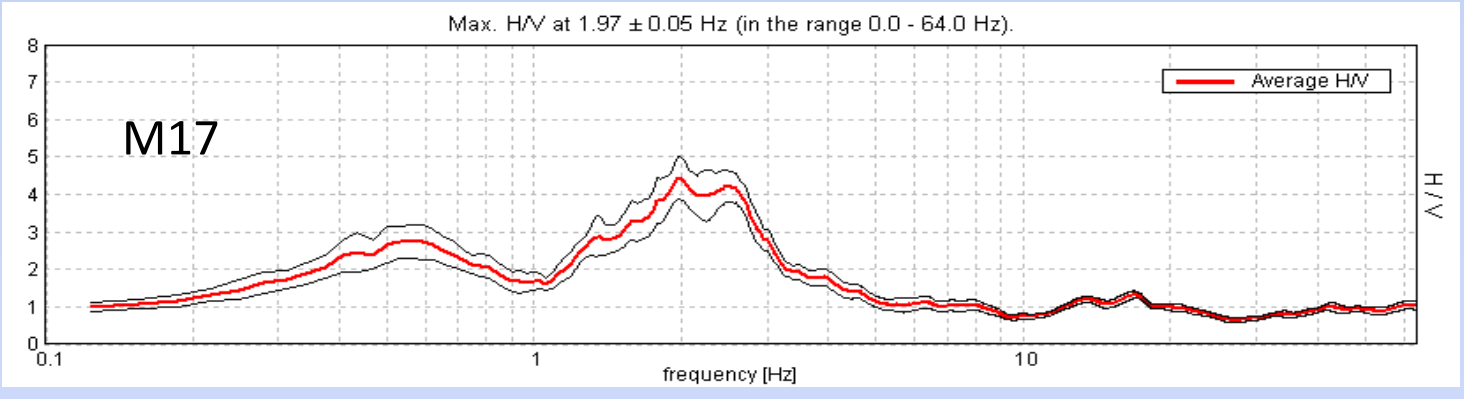
At the SEA site, resonance frequency of the building was also estimated. In this case, ambient vibrations spectral amplitudes at the building roof were compared with free field measurements .
In this case, ratios of average spectral amplitudes of ambient vibrations measured along the main directions of the buildings (longitudinal and transversal, vertical,) with free field spectral amplitudes in the same direction were considered (SSR approach). Results of this analysis are reported in Figure 3.14. This analysis indicate that the same fundamental vibration mode affects both the horizontal components (2.7 Hz). This implies that despite the significant differences in the transversal and longitudinal dimensions of the building, rigidity appears almost the same in the two directions. On the other hand, vibration amplitude appears larger in the longitudinal component. A second vibration mode (4.0 Hz) appears in the longitudinal component only. The significant differences between these resonance frequencies and the one of the sedimentary cover (0.5 Hz) seem to exclude the presence of significant double resonance effects.

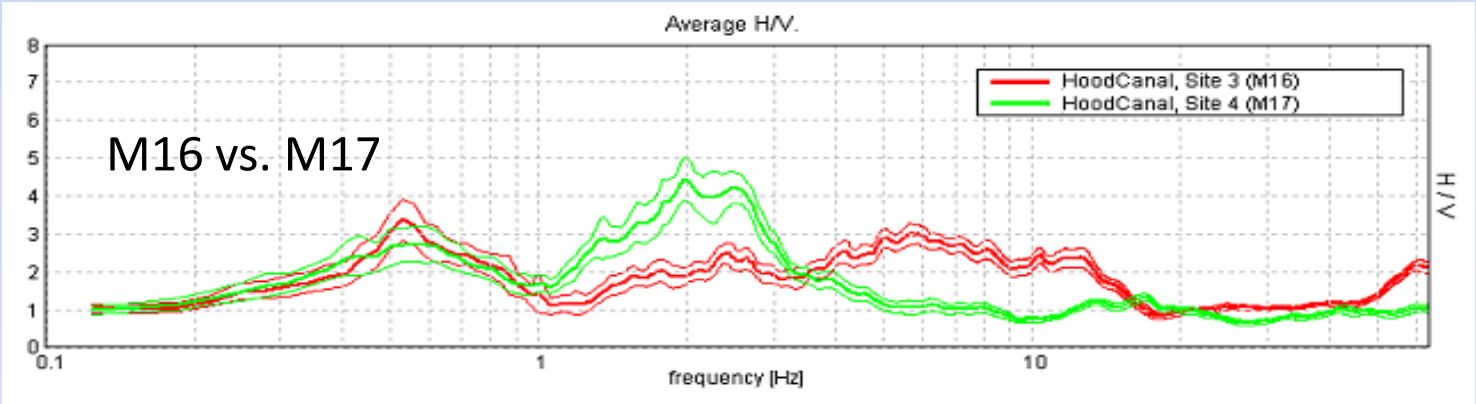
Depth to bedrock problem (Hood Canal example)



Transect 1





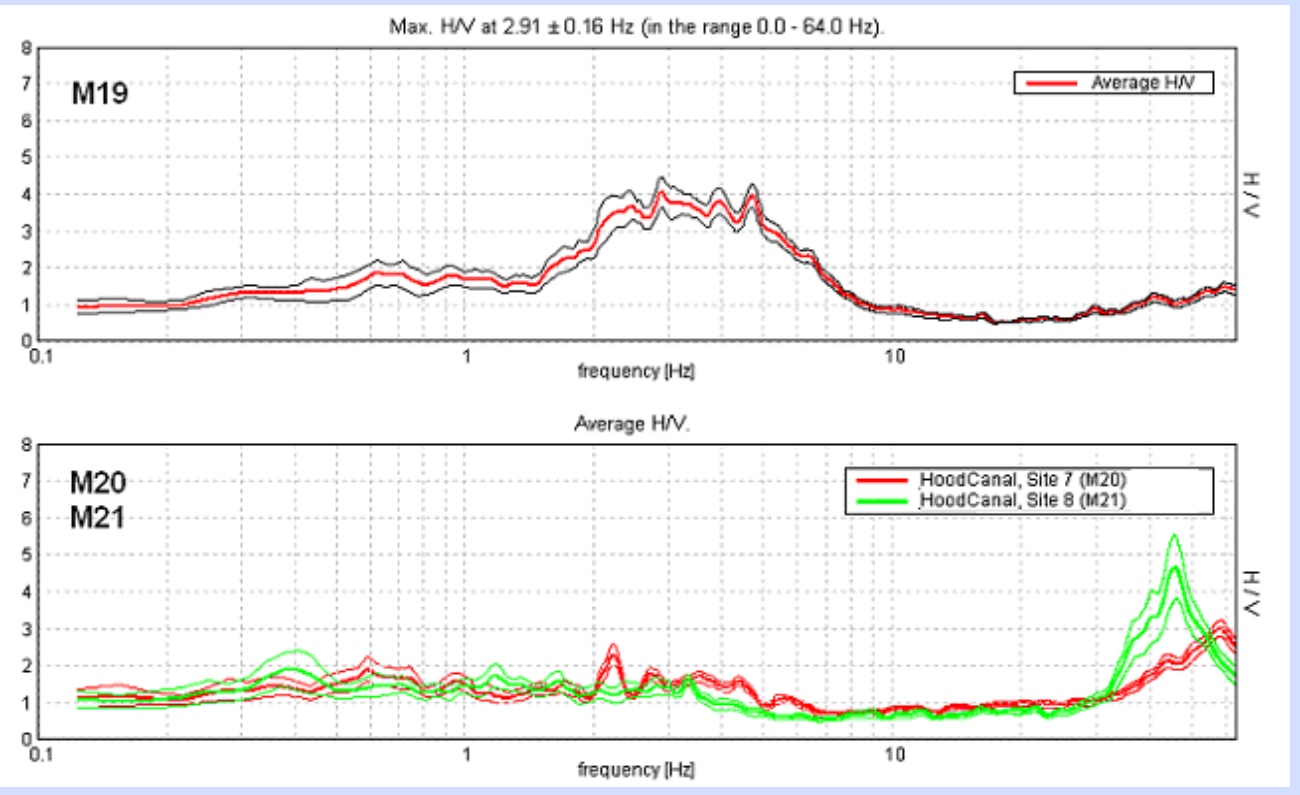


M15 suggests the presence of a weak resonance effects around 1.4 Hz, that is compatible with a weak impedance contrast at a depth of about 70m with a sedimentary cover characterized by an average V_S of the order of 380 m/s. M14 suggests a slight lowering of the above impedance weak contrasts (the relevant resonance frequency displaces from 1.4 Hz to 1.25 Hz) that can be presumably located around 80 m of depth.

Measurement M17 also suggests the presence of sharp impedance contrasts in the study area. In this case, the shallowest interface disappears, while the intermediate one that is responsible for the sharp peak at 2 Hz becomes more prominent. This is compatible with an interface located at a depth of about 40 m. A significant resonance effect around 0.5 Hz seems also to be related to a deeper lithologic interface at about 250m of depth. But as concerns the high frequency peak, strong similarities exist between M16 and M17 measurements. In particular, almost they show almost the same low frequency shape.

In M16, a clear HVSR peak appears at 0.53 Hz, that implies the presence of a deeper sharp impedance contrast (around 250 m from Table) accompanied by shallower possible lithologic variations with resonant frequencies around 2.4 and 5.7 Hz, that could correspond to depths of the order of 30 and 11 m respectively. These two peaks are enhanced in the M18 measurement. In particular, the dominance of the high frequency (4.8 Hz) HVSR maximum suggests that the shallowest interface is enhanced and deepens (from 5.7 Hz to 4.8Hz, corresponding to a slight deepening from 11 to 14 m). The second interface remains at the same frequency(but its amplitude increases) while the third deeper one becomes shallower (from 0.5 to 0.8 Hz, implying a depth variation from 250 m to 140m).

Transect 2



M19, M20 and M21 HVSR measurements in the Hood Canal area (transect)

Presence of a very shallow interface (of the order of 1 m of depth), HVSR curves obtained at the sites M20 and M21 do not show any evidence of resonance phenomena (bedrock ?). Significant resonance is instead detected at the site of M19 measurement. Here, a strong HVSR peak is revealed around 3 Hz, that could correspond to a sharp impedance contrast at a depth of about 25m (with an average V_S down to this depth of about 340 m/s). The relatively large width of the HVSR peaks could be the effect of a complex transition or of short scale morphologic variations in the resonant interface.

Conclusions

1) HVSR is an effective method for rapid assessment of depth to bedrock, specifically when it is interpreted supportive geologic and geophysical data
2) Shallow Vs profiles can be used to estimate thicker sedimentary covers with aid of power law or depth dependent parameters (h and V_0) (we generally used 0.25 and 170,respectively) and HVSR resonant frequency
3) HVSR clearly reveals that ALKI is a rock site
4) HVSR combined with SSR can be effective to understand building fundamental period in relation with soil resonance
5) More than 2 measurements are necessary to better resolve the HVSR peak specifically for characterization of the deeper (or thicker) sedimentary covers.

Reference : Albarello, D.; Cakir, R.; Walsh, T.J., 2011a, Single station Ambient Vibration Measurements in the Puget Lowland and Coastal Area, Washington: DNR-DGER internal report (in preparation).