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SOFT SOIL RESPONSE INVESTIGATIONS IN KITIMAT, BC – SOME PRELIMINARY RESULTS

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ABSTRACT: The north coast town of Kitimat, BC is located in a zone of moderate seismic hazard, relative to high-hazard regions of southwest BC. The town is underlain by a valley filled with unlithified glacial, soft fluvial, and marine sediments deposited on firm bedrock. Such settings are commonly prone to earthquake ground motion amplification and resonance effects. Reconnaissance field surveys were conducted to measure resonance effects in areas of thick soft soil. Results indicate substantial Horizontal-to-Vertical Spectral Ratio (HVSR) peaks at frequencies as low as 0.41 Hz using a portable seismograph. During these surveys, a local M_W 4.6 earthquake occurred to the west of Haida Gwaii (275 km away) and was recorded by both the portable seismograph at a soft soil site and at a bedrock site 2.5 km away. Comparisons of the time histories showed considerable amplitude and frequency differences between the soil and rock sites. At the soil site, an HVSR resonant peak amplitude of 8 was recorded at 0.84 Hz during ambient noise measurements, whereas an HVSR peak amplitude of 21 was observed from the surface-wave portion of the earthquake event. Particle-motion plots of various portions of the earthquake time series at the soil site showed several packets of late arriving “valley-generated” surface waves at the site resonance frequency which were not observed at the rock site. These preliminary results demonstrate the importance of conducting additional site response investigations in this region.

1. Introduction

As part of the World-Class Tanker Safety Initiative, the Geological Survey of Canada (GSC) is undertaking a range of activities to improve the assessment of geohazards in British Columbia’s North Coast (BCNC) region. This work includes the installation of a new broad-band seismograph station (KITB) at a reference bedrock site in Kitimat (Fig. 1), and numerous seismograph and GPS monitoring stations in the BCNC region.

In support of this initiative, the GSC is also carrying out soft soil studies in the town of Kitimat. It is well recognised that unconsolidated materials over bedrock can increase seismic motion at surface (Anderson et al., 1986; Martin and Dobry, 1994; Anderson et al., 1996; Kramer, 1996). This effect can be greatly amplified when the impedance contrast between soil and bedrock stiffness is large. To better predict earthquake-induced ground motions in the Kitimat region, a three-phased study of the unconsolidated sediments filling the Kitimat Valley was initiated in 2014. In the first phase of the investigation, 80 Horizontal-to-Vertical Spectral Ratio (HVSR) measurements were collected in the town of Kitimat to assess the variation in fundamental site frequencies within the valley. These results have been analysed to guide the selection of high-resolution seismic reflection profile alignments to be collected during the second phase of the investigation in June of 2015. We anticipate that the basin structure and sediment velocity information interpreted from the seismic profiles will allow for ground motion modelling scenarios (phase three) to be carried out in the town of Kitimat and region. An improved understanding of local earthquake site response in this area of significant new infrastructure development may directly contribute to reduced losses from future large earthquakes.

This paper discusses the initial results of the HVSR measurements, and describes observations made when a M_W 4.6 earthquake occured (275 km away) while soil and rock station seismographs were recording in March of 2014.

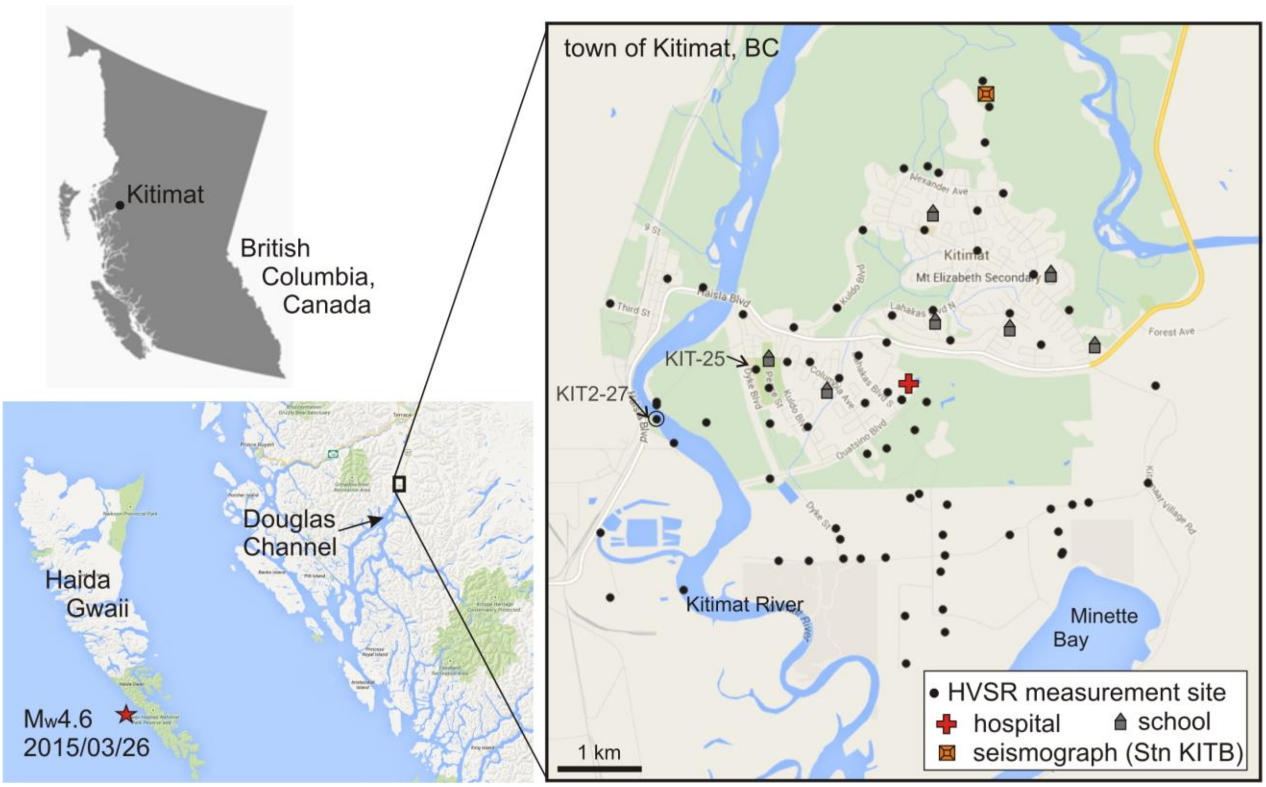

Fig. 1 – Location map of HVSR measurements in the town of Kitimat, BC.

2. Site Investigations

2.1. Site Conditions

The town of Kitimat is located on the farthest inland reach of the Douglas Channel, one of the largest fjords of the BC coast (Fig. 1). From Kitimat, the inland expression of the fjord, the Kitsumkalum-Lakelse Valley, extends some 90 km northward, well beyond the city of Terrace, BC (Dolmage, 1956). It is characterized by steep walls and a relatively flat bottom, up through which smooth rock domes are exposed. Deep drill holes in Terrace and Kitimat (70 and 90 mbsl respectively) intersected similar marine sediments, suggesting that these materials are continuous along the valley floor and extend out into the fjord (Dolmage, 1956). In the town of Kitimat, these marine silts and clays underlie the surficial floodplain sediments (sand and fluvial outwash) of the Kitimat River, and the alluvial fan sediments in tributaries of the Kitimat River north of town (Clague, 1977).

Borings in the Kitimat area over the last 50 years indicate that the town is underlain by glacial and inter-glacial deposits of gravel, sand, and (glacio) marine clays and silts, up to ~100 m in thickness in some areas. To better understand the vertical and lateral changes in sedimentary units across the town site, and thus, the potential for variation in soft soil amplification, a high-resolution seismic survey and array data collection of ambient seismic noise for determination of Vs profiles are planned for the summer of 2015. Prior to the selection of profile alignments, 80 HVSR measurements were collected across the site to target areas where soft soils are thickest and resonance frequencies are lowest.

2.2. Horizontal-to-Vertical Spectral Ratio (HVSR) Measurements

In areas where soft soils overlie competent materials (rock or till), vertically travelling weak motion earthquake energy can resonate with very high amplitudes. The frequency (or period) of this resonance is governed by the average shear wave velocity of the soft soil and the thickness of the layer. Nakamura (1989) introduced a method to estimate the fundamental site period, T_0, or site frequency, f_0 (equivalent to $1/T_0$) using ambient seismic noise in the same frequency range as earthquake energy. The HVSR can indicate a peak frequency equivalent to the resonant frequency of the site. Between 2001 and 2004, a project named "**S**ite **E**ffect**s** Assessment Using **Am**bient **E**xcitations" (SESEAME) was undertaken by 14 European research institutes which studied the ambient noise technique in detail. The guidelines for best practices using this technique have been published (SESAME, 2004) and are now considered standards for the method.

Three-component seismometers specifically designed for HVSR measurements (Micromed Trominos) were used to collect f_0 at 80 sites within Kitimat (Fig. 1). Data were collected by three person teams over two field trips in March 2014 (Brillon et al., 2015) and March 2015. The testing procedure for acceptance of a fundamental frequency at a particular site followed the SESAME recommendations. Using Grilla software designed for the Tromino unit, the data collection and processing parameters are provided in Table 1, and sample results from site KIT2-27 are shown in Fig. 2.

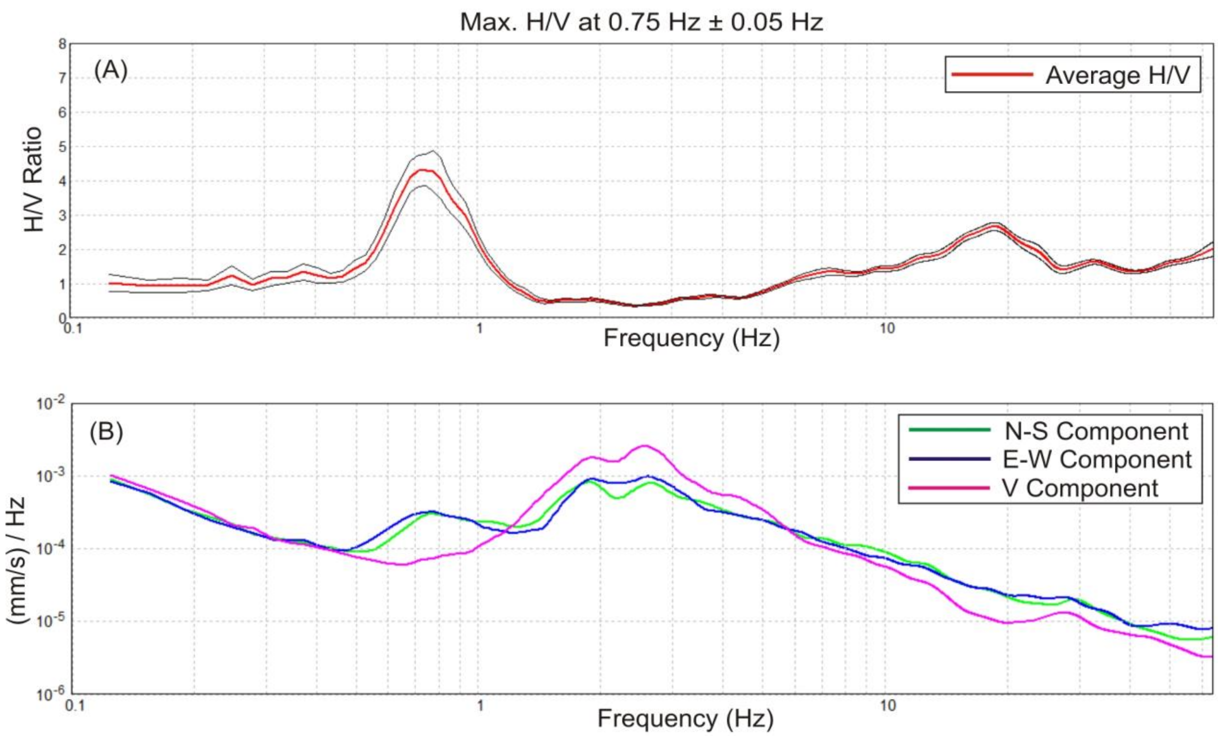

Fig. 2 – (A) Sample H/V spectral ratio for site KIT2-27 (B) North-south, east-west, and vertical average spectra for the windows used in the HVSR interpretation. Note that there is amplification on the vertical component, but it lags behind the horizontal components on the frequency axis which creates the dominant peak in panel A.

Table 1 – Data collection and processing parameters for ambient noise measurements using a Tromino seismograph.

3 component sampling rate	128 samples/second
Orientation of sensors	Approximately N-S, E-W
Recording time	30 minutes
Processing window	60 seconds
Spectral filtering	Konno-Omachi smoothing window b = 40
Editing	Manual selection of windows with arithmetic averaging
Spectral Windows	0.1 Hz to 20 Hz

Fundamental frequencies range between 0.4 Hz and 12.7 Hz. A natural neighbor gridding technique was utilised to create the map shown in Fig. 3. HVSR measurements were co-located near borings drilled for the Kitimat Hospital, which identified that soft sediments are predominantly sand, underlain by marine silts and clays (AGRA, 1997). A seismic cone penetrometer profile collected at this site indicated that the shear wave velocities of these sediments range between 150 – 300 m/s, similar to those measured in the Holocene-aged silts of the Fraser River delta (Hunter et al, 1998).

Based on an examination of satellite imagery and the fundamental site period map, we infer the presence of two valleys filled with soft soils (Fig. 3). The first valley to the west underlies the approximate course of the present-day Kitimat River, and the second to the east may occupy an old arm of the river which once reached Minette Bay, but may have been cut off by the prograding delta front. Aside from known bedrock outcrops, the limits of these inferred valleys do not appear to have strong correlation with the surficial geology map produced by Clague (1977). An early estimate of soft soil thickness (to the top of the resonator) within these valleys is 80 - 90 m (0.5 – 0.6 Hz), based on similar calculations in the Fraser River (Hunter et al, 1998). The lateral and vertical extent of these inferred valleys will be further examined during the summer of 2015 with high-resolution seismic profiling and ambient noise array data.

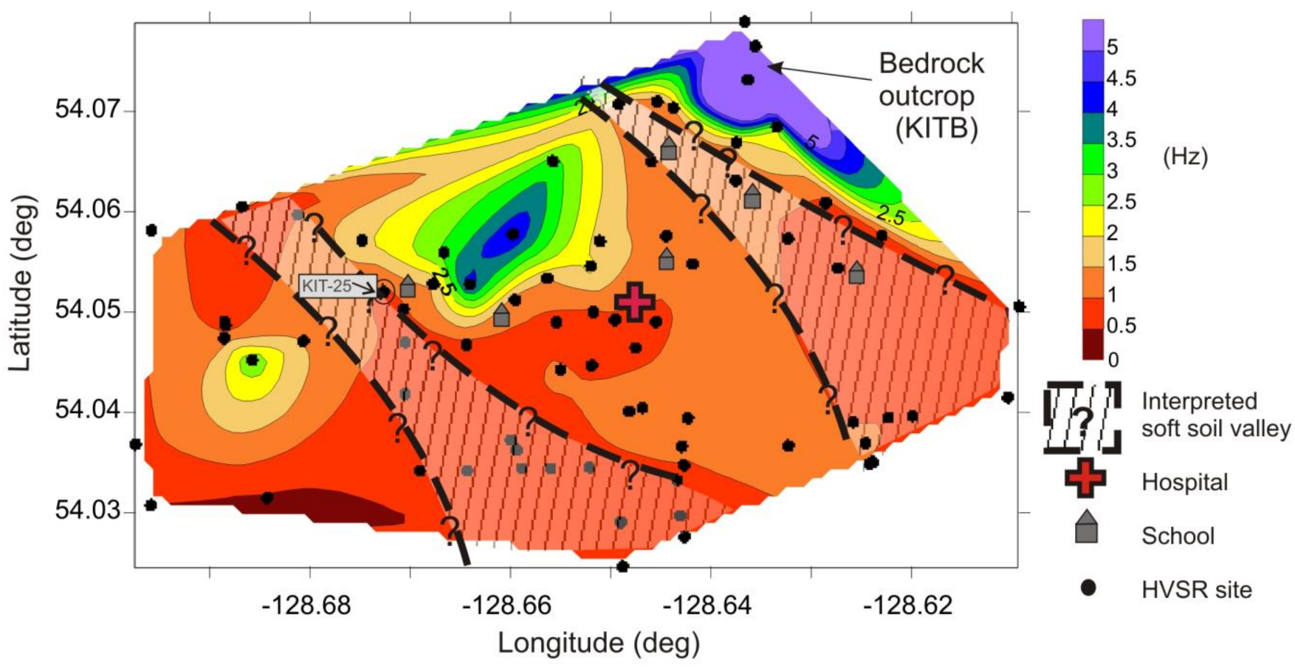

Fig. 3 – Map showing fundamental site frequencies within the town of Kitimat. Heavy dashed lines indicate the inferred boundaries of soft soil valleys. Areas in red (frequencies <1 Hz) are located over thick soil deposits. Site KIT-25 indicates where the portable seismograph recorded the M_W 4.6 earthquake.

3. Earthquake Analyses

During the course of the HVSR surveying in 2014, an offshore M_W 4.6 earthquake occurred just to the west of Haida Gwaii (2014/03/26, Lat 52.42º, Lon -131.78º). The event was approximately 10 km deep, and occurred 275 km from the town of Kitimat. The earthquake was recorded both at HVSR site KIT-25, which is a relatively thick soil site on the edge of the town near the Riverlodge Recreation Centre, and at a bedrock seismograph station (KITB) operated by the Canadian Hazard Information Service (Fig. 1). The raw seismic traces, as recorded by the three-component geophone system (passband 0.3 to 60 Hz, digital rate 128 samples per second), is shown in Fig. 4 along with the traces recorded at KITB approximately 2.5 km to the NE of HVSR site KIT-25. Since the associated GPS function on the Tromino was not operational during the recording, the recording time is only approximate compared to KITB.

The HVSR at KIT-25 indicated a fundamental resonant frequency of 0.84 +/- 0.01 Hz. A comparison of this HVSR along with pre-earthquake event noise, early, and later arrivals is shown in Fig. 5. This recording is typical of those observed on thick soft soils elsewhere in Canada (e.g. Ottawa and St. Lawrence Valleys). Ambient noise levels are usually quite high, resulting in emergent first arrivals. The horizontal component traces (N-S and E-W) show dominant frequencies associated with the fundamental resonance frequency and higher harmonics in the pre-event noise, early compressional and shear arrivals, as well as later arrivals of “ring-on” surface wave packets. In contrast, the bedrock site shows low signal levels and no apparent dominant resonant “ringing” in later arriving wave packets.

Unlike HVSRs developed from ambient noise measurements (from multiple azimuthal directions), the HVSRs from earthquake events commonly show peaks which might be associated with higher harmonic resonances. The frequency values and the strengths of these peaks may, in part, be conditioned by the shear wave velocity gradient within the soil in association with the 3-D structure of the buried resonator surface.

For this earthquake, event spectra (not shown) of both early arrivals and later shear-type events indicate the presence of site resonance amplitude maxima on the horizontal motions. In an attempt to interpret the nature of this resonance energy, it is possible to apply a narrow pass band filter bracketing the approximate site frequency. For this event, a filter from 0.55 Hz to 1.15 Hz (3 DB points on the edges of the filter) was applied, centered around 0.84 Hz. The resulting seismograph record (Fig. 6, top panel), when compared to the raw record (Fig. 4), indicates that the bulk of the seismic energy at soil site KIT-25 is contained within the narrow frequency band of the filter.

Particle motion plots of seismic records can help to determine the type and possible azimuthal direction of later arriving events. Fig. 6 shows typical 2 second hodographs of A: the first arriving energy packet, B: an early shear arrival, C and D: surface waves. Note that most of the later arriving seismic energy is contained in the horizontal components, suggesting that the seismic events are probably travelling as Rayleigh and Love modes which have been initially converted at the resonator boundary (soft sediment over rock or till) which may occur at depth within the buried valley, or at surface at the rock outcrop along the edge of the valley. Frequency conversion of first arrival P wave and shear wave body-wave energy (from very low frequency to the soil resonant frequency) is also a common occurrence. Events C and D show two examples of large amplitude horizontal motion hodographs for the “surface wave” portion of the seismogram with differing alignments of particle-motion commonly seen in buried valley soil sites.

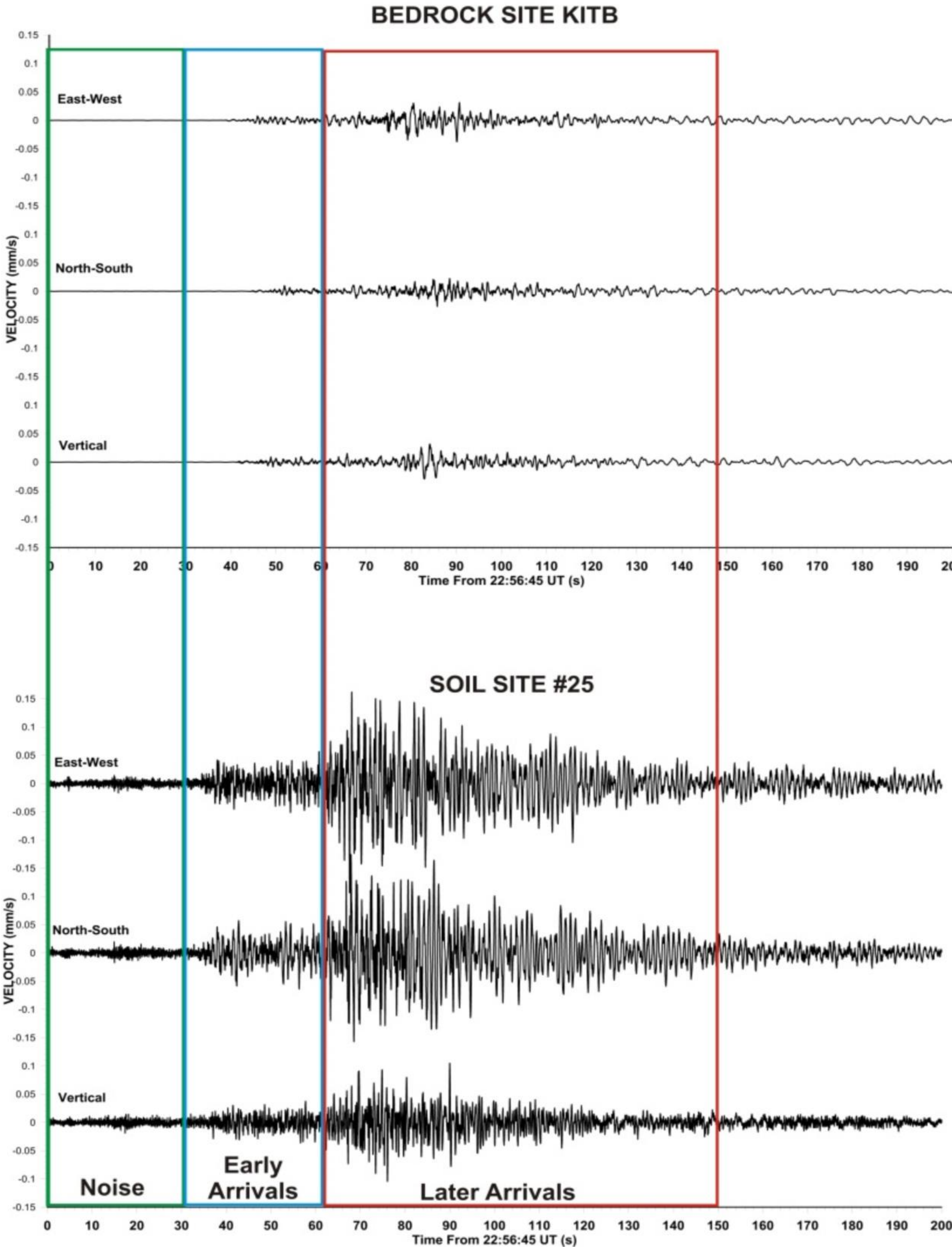

Fig. 4 - Three-component ground velocity seismograph records (pass band filtered 0.3 – 60 Hz) for the bedrock site KITB and the Tromino soil site KIT-25. All traces shown at the same gain levels.

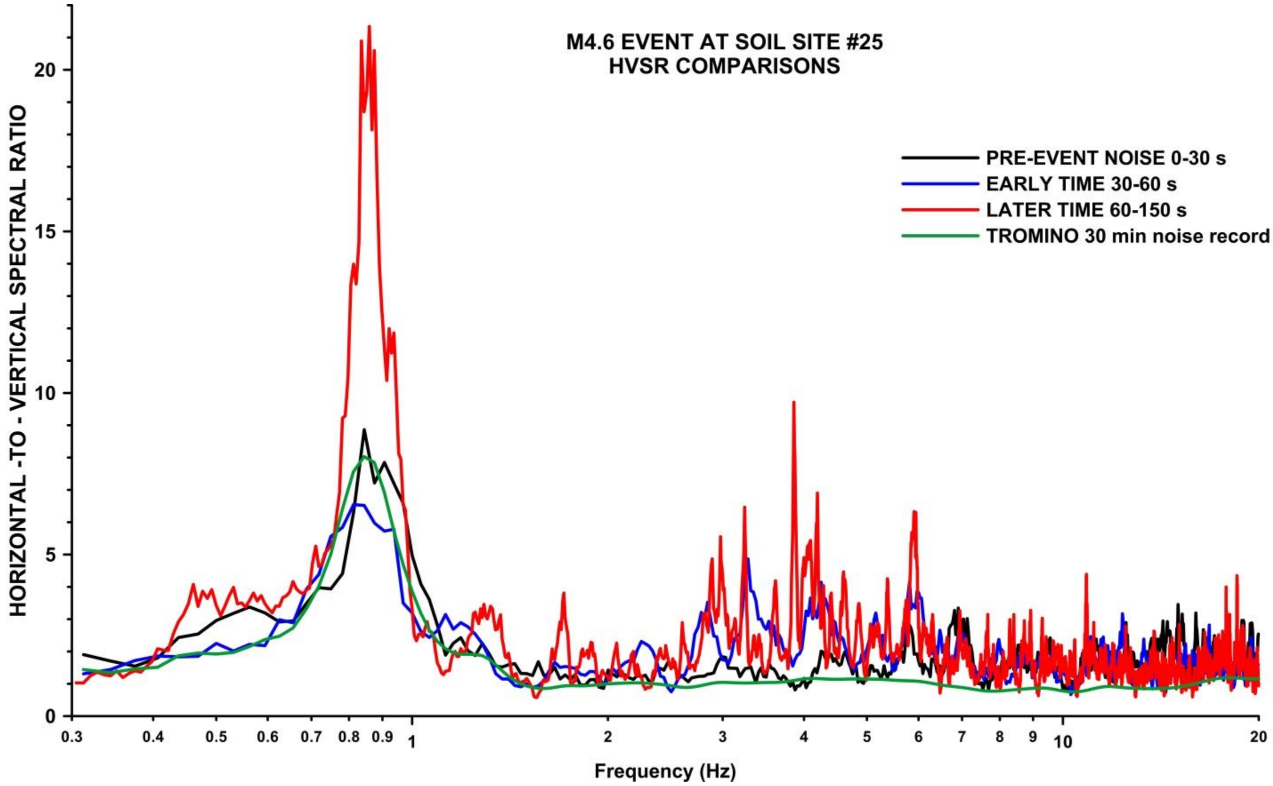

Fig. 5 - HVSRs for the M_W 4.6 earthquake event time windows (as shown in Fig. 4) recorded at soil site KIT-25, compared to the 30 minute ambient noise recording.

4. Future Soft Soil Work in Kitimat

During the summer of 2015, 8 km of high-resolution seismic profile data will be collected along five alignments, selected based on the results of the HVSR surveys. Focus will be placed on areas where soft soils are interpreted to be thickest. In addition, seismic arrays will be deployed at a number of sites to record ambient noise, allowing for a determination of shear wave velocity profiles. A recommendation will also be made for a location to install a temporary soil seismograph station to monitor variation in ground motion amplification within the town of Kitimat during local and teleseismic events.

The final stage of the project will take place in 2016-17, and will involve ground motion modelling in 2D using data near surface and earthquake data collected during the course of this project. Through undertaking this work in Kitimat, we hope to characterise the dominant factors affecting the amplification of ground-motion within the Kitsumkalum-Lakelse Valley region. This will provided a basis for assessing ground-shaking hazards in other Canadian fjords, as well as global analogues.

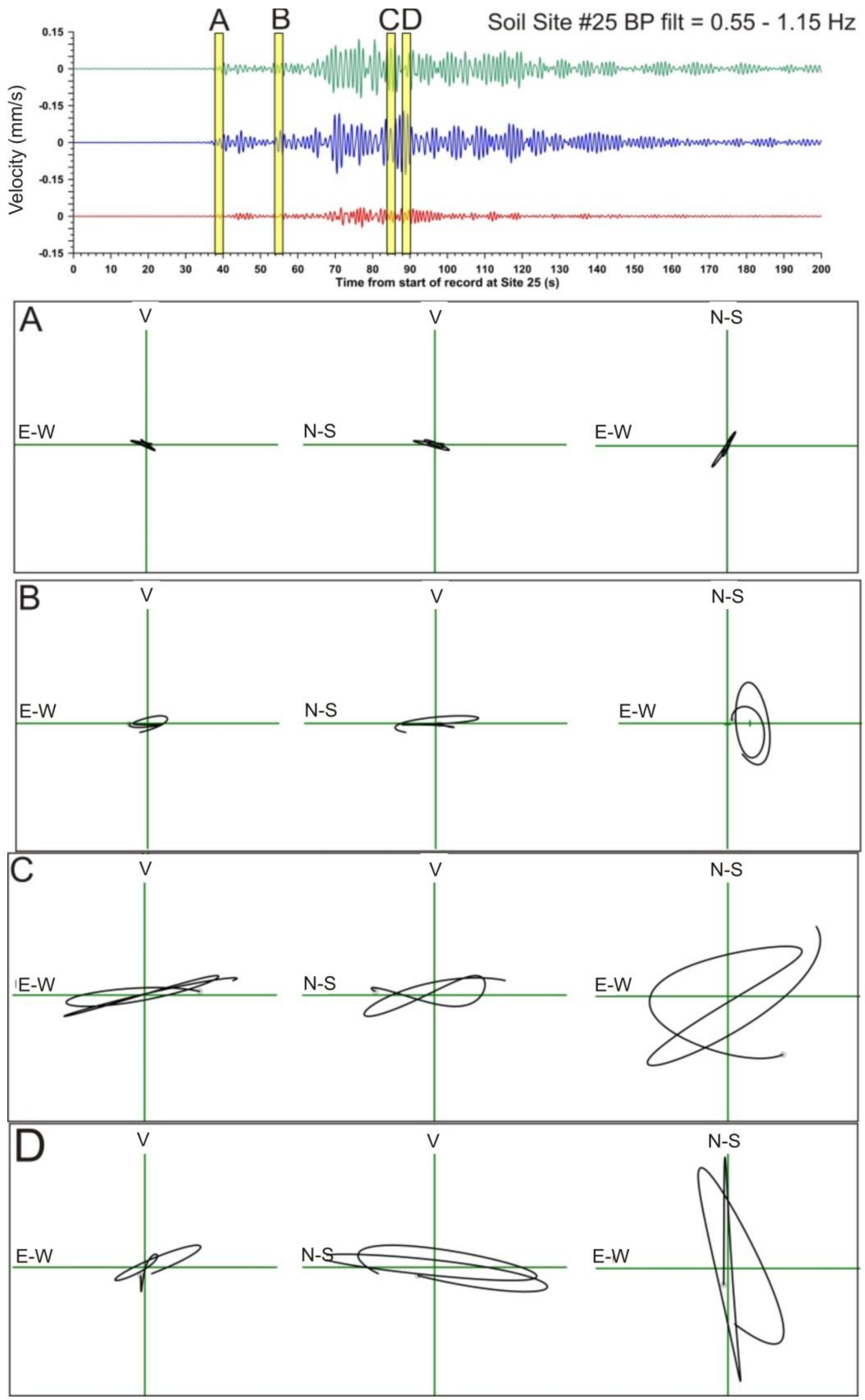

Fig. 6 - Particle motion plots of (A) First P- wave arrival, (B) shear wave, (C)-surface wave motion - azimuth 45º, (D) surface wave motion - azimuth 340º.

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