Evaluation of shear-wave velocity profiles from ambient vibration array recordings in SW British Columbia, Canada

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SUMMARY:
Current practice to predict amplification of earthquake motion due to the 1D sedimentary layering at a site is based primarily on the shear-wave velocity (V_S)-depth profile. Hence, cost-effective urban field techniques to measure and/or estimate V_S of the subsurface are of great interest to the earthquake engineering community. The microtremor array method involves recording ambient vibrations with an array of seismic sensors to extract phase velocity surface wave dispersion data which can be inverted for the V_S structure at a site. A variety of sediment sites in SW British Columbia, Canada, collocated with invasive V_S measurements (downhole and seismic cone penetration) and/or locations of earthquake recordings, have been chosen to assess performance of this passive-source seismic method in providing V_S profiles applicable for site response characterization. This paper presents the process of determining and evaluating acceptable V_S models at a site. A best-fit V_S profile is determined from inversion of ambient vibration array recordings, for a given model parameterization, using a hybrid optimization scheme. The most appropriate model parameterization is determined using the Bayesian information criterion, which provides the simplest model consistent with the resolving power of the data. Parameterizations considered vary in the number of layers, and include layers with constant, linear and power-law gradients. The best-fit V_S profiles are assessed for reliability by direct comparison with collocated invasive V_S measurements. Overall, fair to excellent agreement is obtained between invasive V_S measurements and the best-fit V_S profile for the three sites investigated here. These results provide confidence that sufficient detail of the V_S profile is derived via inversion of microtremor dispersion data for site response characterization.

Keywords: site response, microtremor array method, dispersion, non-linear inversion, optimization

1. INTRODUCTION

Seismic hazard assessment methodologies applied worldwide utilize the average shear-wave velocity (V_S) of the upper 30 m of the subsurface, i.e. V_{S30} (e.g. NBCC 2010). A variety of seismic techniques have been developed to characterize the subsurface V_S profile to estimate V_{S30} for this purpose. Non-invasive seismic methods that keep all equipment at the surface are inherently less expensive than invasive methods such as down-hole measurements or seismic cone penetration testing (SCPT). This paper considers estimating the V_S profile from microtremor (urban noise, ambient vibration) data. The microtremor array method is based on recording background seismic noise using a spatial array of several seismographs to extract the Rayleigh wave dispersion curve (Aki 1957; Asten & Henstridge 1984; Horike 1985), which can then be inverted for the V_S profile of the site.

In this paper, we present the best-fit V_S profile (model) at three sites in southwest British Columbia estimated using Bayesian inversion of the dispersion curve determined from microtremor array measurements. Bayesian inversion considers the model to be a random variable constrained by data and prior information, and seeks properties of the posterior probability density (PPD) that represent optimal parameter estimates and parameter uncertainties. Defining an appropriate model parameterization is an important issue in inverse problems, which is addressed here using the Bayesian information criterion (BIC). Parameterizations considered include layers with constant velocities, constant velocity gradients, and power law gradients. The recovered best-fit V_S profile (with uncertainties) is compared with existing

V_S-depth measurements made by down-hole and SCPT invasive methods. Molnar et al. (2012a,b) presents the V_S profile probability distribution obtained by the Bayesian inversion for the sites investigated here. Probability distributions of common site response predictors (e.g. V_{SZ}, V_{S30}, and amplification spectra) are computed for each site using the V_S profile probability distribution, which is more useful for earthquake site response characterization than a single, albeit best-fit, V_S profile.

1.1. Inversion methodology

The inversion methodology is outlined fully in Molnar et al. (2010). Key points of the methodology are reiterated here.

A probabilistic formulation provides the full solution to the inverse problem in the form of the posterior probability density over the model space. Bayesian inversion is based on the assumption that the model represents a random variable which we seek to describe statistically. If **d** and **m** represent data and model vectors considered as random variables with N and M elements, respectively, Bayes' rule can be written

$$P(\mathbf{m} \mid \mathbf{d}) \propto P(\mathbf{d} \mid \mathbf{m}) P(\mathbf{m}) \tag{1.1}$$

where $P(\mathbf{m})$ represents prior information, and the conditional probability $P(\mathbf{d}|\mathbf{m})$ is interpreted as a function of **m** for the (fixed) measured data **d**, defining the likelihood function,

$$L(\mathbf{m}) \propto \exp[-E(\mathbf{m})] \tag{1.2}$$

where E is the data misfit function. Combining data and prior as a generalized misfit,

$$\varphi(\mathbf{m}) \equiv E(\mathbf{m}) - \log_e P(\mathbf{m}) \tag{1.3}$$

the PPD can be written as

$$P(\mathbf{m} \mid \mathbf{d}) = \frac{\exp[-\varphi(\mathbf{m})]}{\int \exp[-\varphi(\mathbf{m}', \mathbf{d})] d\mathbf{m}'} \tag{1.4}$$

where the domain of integration spans the M-dimension parameter space.

The maximum *a posteriori* (MAP) or most probable model is estimated by maximizing the PPD:

$$\hat{\mathbf{m}} = Arg_{\max}\{P(\mathbf{m} \mid \mathbf{d})\} = Arg_{\min}\{\varphi(\mathbf{m})\}. \tag{1.5}$$

In this paper, $\varphi(\mathbf{m})$ is minimized numerically using adaptive simplex simulated annealing (ASSA), a hybrid optimization algorithm that adaptively combines the local downhill simplex method within a very fast simulated annealing global search (Dosso et al. 2001). Model parameter uncertainties, such as the 95% highest-probability density (HPD) interval, are estimated from the PPD using the Markov-chain Monte Carlo method of Metropolis-Hastings sampling, applied for efficiency in a principal-component parameter space (Dosso et al. 2009).

Prior information considered in this paper consists of uniform distributions for each parameter on bounded intervals. Intervals are chosen to limit parameters to physically reasonable values, but are wide enough to allow the data (not the prior) to primarily determine the solution.

The type of model parameterization to use in shear-wave velocity modeling is often unknown *a priori*. Adopting too few parameters (e.g. layers) can lead to under-fitting the data, biasing parameter estimates and under-estimating parameter uncertainties. In contrast, adopting too many parameters can over-fit the data leading to spurious model structure and under-determined parameters with excessive variance. In some cases, prior geologic information can provide an indication of the V_S structure at a site; however, even in such cases, the dispersion data may not be able to resolve the indicated level of structure, resulting in an over-parameterized (under-determined) problem. The goal is to determine the simplest parameterization consistent with the resolving power of the data. The strategy applied here examines a variety of possible V_S parameterizations, and the Bayesian information criterion (BIC) is minimized,

$$BIC = 2E(\hat{\mathbf{m}}) + M \log_e N \tag{1.6}$$

which determines the most appropriate parameterization by applying a penalty for the number of parameters (Schwartz 1978). Parameterizations considered differ in the number of layers and also in the representation of V_S over the layers. Shear-wave velocity models can be composed of combinations of three types of layers in which V_S is either constant, varies linearly with depth, or varies according to a power law relationship with depth. An alternative approach is trans-dimensional inversion, where the number of parameters is treated as an explicit unknown and is sampled in the inversion. This has the advantage of including the effect of the uncertainty in parameterization in the parameter uncertainty estimates. Dettmer et al. (2012) performed trans-dimensional inversion of microtremor array dispersion data for Fraser River delta site 1 and the Victoria site.

Numerical computation of dispersion curves is carried out in this paper using the Haskell-Thomson approach in which the subsoil is modelled as a stack of homogeneous layers characterized by four parameters: V_S, compressional-wave velocity (V_P), density (ρ), and layer thickness (h), overlying a homogeneous half-space. All four parameters are considered as unknowns in the Bayesian inversions carried out here.

2. APPLICATION TO SOUTHWESTERN BRITISH COLUMBIA, CANADA

Southwestern British Columbia is the most seismically active area in Canada, coinciding with the northern portion of the Cascadia subduction zone. This region has the greatest seismic risk in the country (Onur et al. 2005) due to its large and growing population and key infrastructure (e.g. port, transportation, power facilities) which are subject to large earthquakes. The two largest urban centres in southwestern British Columbia, Vancouver and Victoria, are situated in two very different geological settings. The thick sequence of deltaic Fraser River sediments in Greater Vancouver is susceptible to high amplification and liquefaction during earthquakes (Hunter et al. 1998). The delta is composed of up to 300 m of Holocene deltaic sands and silts from the Fraser River overlying up to 500 m of over-consolidated Pleistocene glacial material, resulting in up to 800 m of material over Tertiary sedimentary bedrock. From compilation of ~500 surface refraction, downhole, and SCPT measurements conducted across the Fraser River delta (Hunter et al. 1998), the gross shear-wave velocity in the upper 100 m of the Holocene deltaic sediments is found to increase significantly with depth as a result of loading, and is well represented by a power-law gradient (Hunter & Christian 2001). This Holocene-Pleistocene boundary is characterized by an abrupt increase in V_S by a factor of 1.5 to 3.0 (Hunter et al. 1998). In contrast, the local geology of Victoria generally exhibits a strong near-surface impedance contrast with < 30 m of marine clayey silt deposited atop of over-consolidated glacial material and/or hard bedrock. Monahan & Levson (2001) determined the average V_S of the clayey silt as 137 ± 30 m/s (based on 115 measurements) and of the glacial material as 475 ± 78 m/s (17 measurements). Exposures of hard bedrock in Victoria are classified as NEHRP (National Earthquake Hazards Reduction Program) site class A, with V_{S30} greater than 1500 m/s.

Figure 1 shows the three locations chosen for microtremor array data collection in SW British Columbia, collocated with SCPT and/or downhole V_S measurements; two deep (> 100 m) sediment sites on the Fraser River delta and one shallow (< 30 m) sediment site in Victoria.

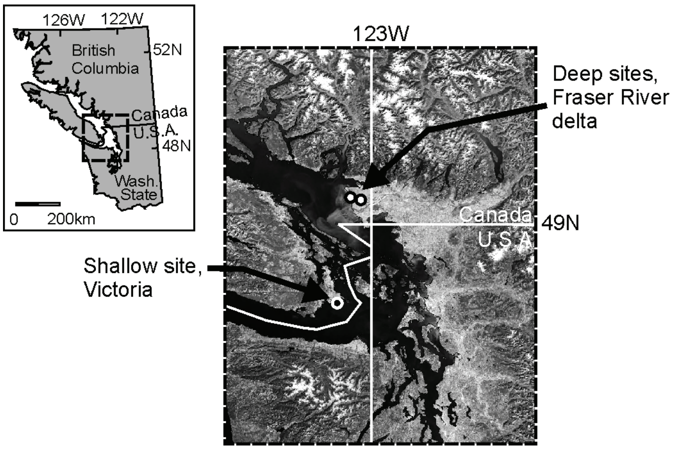


Figure 1. Locations of microtremor array collection in SW British Columbia, Canada.

2.1. Fraser River delta site 1

Microtremor array measurements were conducted on the Fraser River delta near Geological Survey of Canada borehole FD94-4; downhole V_S measurements are available to 300 m depth (Hunter et al. 1998). V_S measurements are also available from four SCPT sites within 600 m of the array centre; maximum depths of penetration are 31 to 62 m. The downhole V_S measurements generally increase with depth from 125 m/s near the surface to ~500 m/s at the Holocene-Pleistocene boundary at 235 m, with high (> 600 m/s) velocities within the underlying Pleistocene material. The four SCPT V_S profiles (maximum penetration depths from 31-62 m) display the same general trend and range of V_S values within the Holocene material. Significant velocity reversals occur at irregular intervals displaying sensitivity to fine geologic layering.

Microtremor recordings were collected using five broadband 3-component sensors set in a cross-shape. Recordings were made for six different array apertures with minimum and maximum limits of 5-10 m and 160-180 m, respectively, with recording durations of 30-45 minutes for each aperture. Both the *f-k* method and the high resolution *f-k* method, as supplied in the “Sesarray” software package of Marc Wathelet (www.geopsy.org), were applied to the Fraser River delta microtremor data. The phase velocity estimates for the two methods were essentially indistinguishable, and were combined into a single dataset. The dispersion curve, shown in Fig. 2(a), varies from ~ 400 m/s at 1.2 Hz to ~130 m/s at 6.7 Hz with 51 data at logarithmically-spaced frequencies. The curve is segmented into three frequency bands, delineated by dashed lines in Fig. 2(a). The discontinuity near 5.4 Hz is due to computing the dispersion curve from different array apertures with non-overlapping reliable frequency ranges. The gap in data from 3.4-3.8 Hz is due to spurious phase velocity estimates at these frequencies which correspond to a peak in the observed horizontal-vertical spectral ratio (not shown).

A variety of model parameterizations incorporating the three possible parameter gradients were examined for inverting the Fraser River delta dispersion data. To obtain inversion and model selection results, MAP model estimation was carried out using nonlinear (ASSA) optimization. Prior information was taken to consist of uniform distributions over wide intervals for all parameters: 2-200 m for h, 20-2000 m/s for V_S, 100-3000 m/s for V_P, and 1.2-2.7 g/cm^3 for ρ. The resulting minimum misfit values were used to calculate the BIC and are presented for nine parameterizations in Fig. 2(b). All parameterizations also include a uniform underlying half-space. The preferred parameterization with the lowest BIC value is found for a single power-law gradient layer over a uniform half-space (denoted P in Fig. 2b). This result is consistent with the general power law relationship determined for the Holocene sediments of the Fraser River delta (Hunter & Christian 2001). When a uniform layer is added below the power-law layer (PU), the minimum misfit does not decrease significantly and the BIC increases due to the larger number of parameters. Misfit values lower than that of the power-law parameterization can be obtained, but require more complex structure (either three or four uniform layers, U3 or U4, or a linear gradient layer over two or three uniform layers, LU2 or LU3), such that lower BIC values are not found. Fig. 2a shows the agreement between the dispersion curve computed for the MAP model (solid line) and the measured microtremor dispersion data.

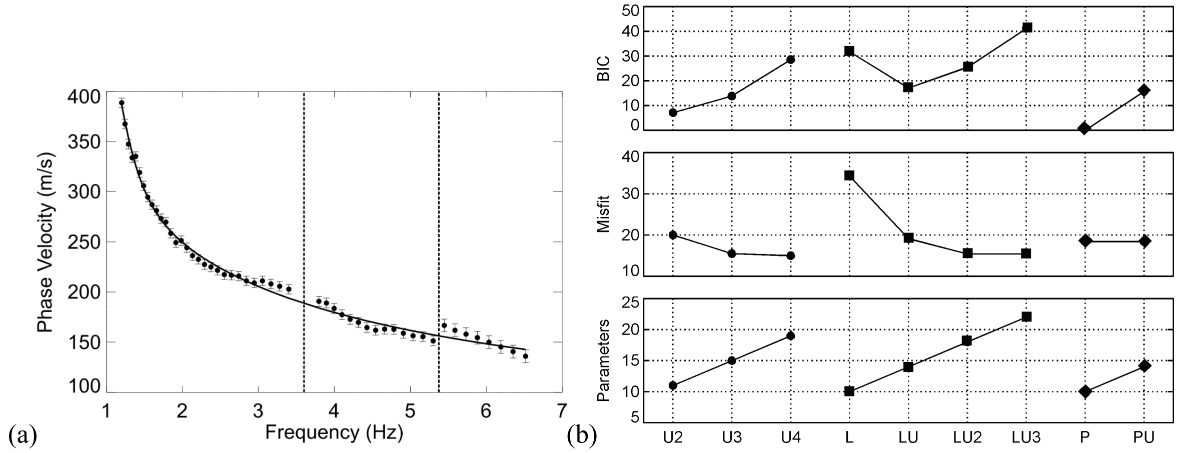


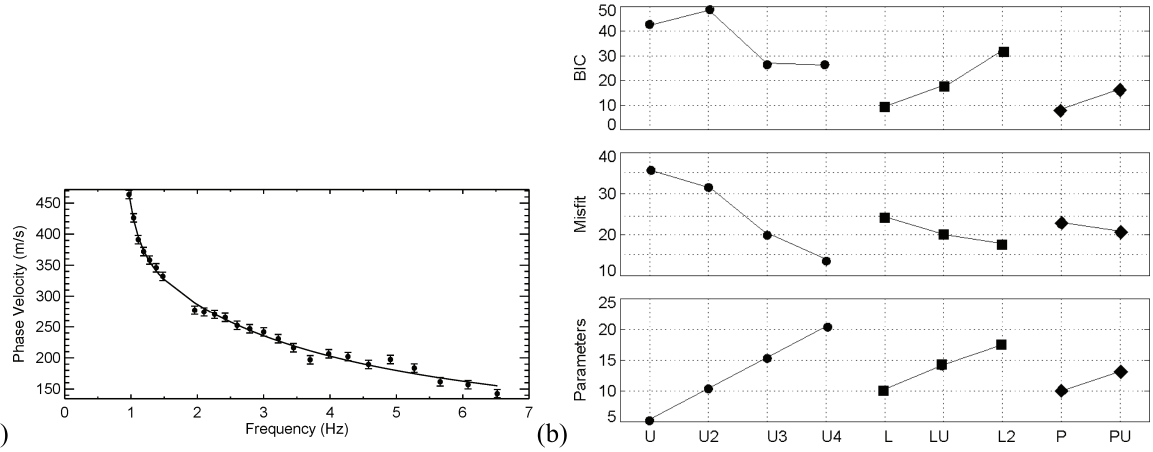
Figure 2. (a) Fraser River delta site 1 dispersion data shown as filled circles. Maximum-likelihood standard deviation error estimates indicated as error bars and solid line demonstrates fit of theoretical dispersion curve calculated for the best-fit V_S model (black line in Fig. 3). (b) Parameterization study. Models are separated into three categories based on the initial layer V_S dependence on depth: uniform (U, circles), linear gradient (L, square), or power-law gradient (P, diamonds). Additional underlying layers have uniform properties denoted by numerals. For display purposes the BIC is shifted so that the minimum value corresponds to zero.

2.2. Fraser River delta site 2

Microtremor array measurements were conducted on the Fraser River delta within 150 m of the Geological Survey of Canada borehole FD88-1; downhole V_S measurements are available to 58 m depth (Hunter et al. 1998). V_S measurements are also available from six SCPT sites within 170 m of the array centre, and two other SCPT sites at 300 m and 500 m distance; maximum depths of penetration are 29 to 43 m. Generally, V_S increases from ~90 m/s near surface to ~330 m/s at 58 m depth, with significant velocity reversals in the 25-35 m depth range (Hunter et al. 1991). Hence, the upper 60 m at this site is composed of Holocene deltaic sands and silts, which overlies either over-consolidated Pleistocene glacial material or Tertiary sedimentary bedrock at an unknown depth. Interpretation of the depth to Pleistocene and Tertiary horizons at this site is ~180 m and ~500 m, respectively (J. Hunter, personal supplication). North of this site, Luternauer and Hunter (1996) interpret depth to Pleistocene glacial material is > 190 m.

Microtremor recordings were collected at the western (seaward) edge of the Fraser River delta in a T-shaped array geometry using four broadband 3-component sensors. Recordings were made for six different array apertures with minimum and maximum limits of 6-20 m and 145-290 m, respectively. Similar *f-k* processing techniques as the previous Fraser River delta site were applied to extract the dispersion curve. Fig. 3(a) presents the dispersion curve for the Fraser River delta site which varies from ~450 m/s at 1.0 Hz to ~150 m/s at 6.5 Hz with 25 data at logarithmically spaced frequencies.

Another parameterization study incorporating the three possible parameter gradients was examined for inverting the Fraser River delta site 2 dispersion data. The preferred parameterization with the lowest BIC value is found for a single power-law gradient layer over a uniform half-space (denoted P in Fig. 2b), similar to Fraser River delta site 1. Fig. 2a shows the agreement between the dispersion curve computed for the MAP model (solid line) and the measured microtremor dispersion data.



(a) (b)

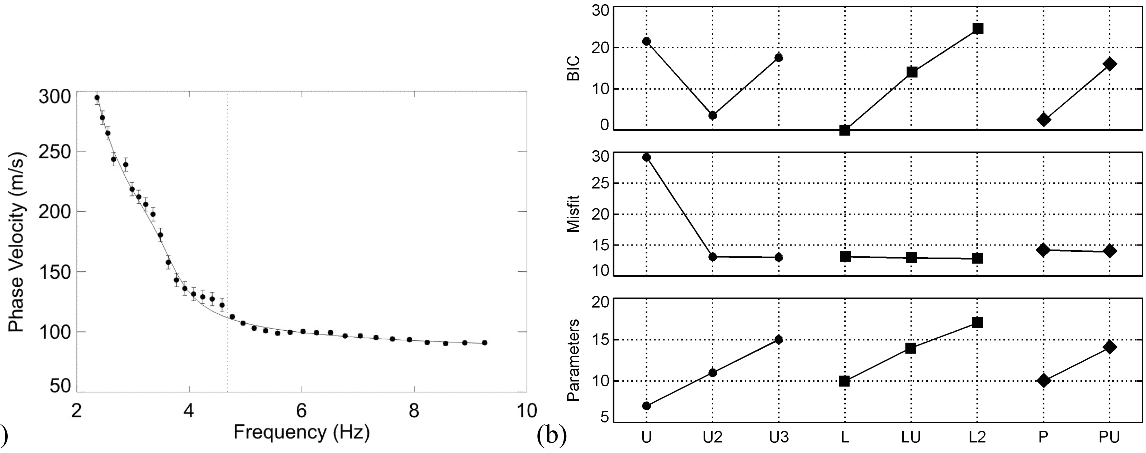
Figure 3. Fraser River delta site 2 (a) dispersion data and (b) parameterization study. Details as in Figure 2.

2.3. Victoria site

At the Victoria site, the centre of the microtremor array is within 5 m of an SCPT site and within 30 m of Geological Survey of Canada earthquake recording site VCT04. The cone penetrated through low velocity material to 17 m depth before meeting refusal. The harmonic average V_S of the upper 17 m based on the SCPT measurements is 108 m/s. Stiff material below 17 m is likely over-consolidated glacial material (V_S of 475 ± 78 m/s) and/or hard bedrock (V_S > 1500 m/s). Thus, the Victoria site likely has a strong near-surface impedance contrast of a factor of ~4 or more.

A semi-circular array geometry of six sensors (one every 36°) was used to record microtremors, although the data could not be retrieved for one sensor. The radius of the array was varied five times over several hours, with minimum and maximum values of 5 and 35 m, respectively. The resulting dispersion curve for the Victoria site is shown in Fig. 4a and varies from nearly 300 m/s at 2.4 Hz to ~90 m/s at 9.3 Hz with 35 logarithmically spaced data.

The preferred parameterization with the lowest BIC value is found for a single linear V_S gradient layer over a uniform half-space (denoted L in Fig. 4b). Similar misfits are obtained for nearly all of the model parameterizations considered, indicating the data are readily fit with a variety of parameterizations. Selecting an appropriate model parameterization based on an objective minimum-structure criterion (i.e. the BIC) is particularly effective in this case.



(a) (b)

Figure 4. Victoria site (a) dispersion data and (b) parameterization study. Details as in Figure 2.

3. COMPARISON WITH INVASIVE V_S MEASUREMENTS

Fig. 5 compares the invasive V_S measurements with the MAP model and 95% HPD credibility interval from the Bayesian inversion of microtremor dispersion data for Fraser River delta site 1. For direct comparison, the invasive V_S measurements at the downhole and four SCPT sites are averaged together over the logarithmic depth partitioning of the MAP model. The mean V_S of the invasive methods closely approximates a power-law depth relation as previously noted for the upper 100 m of sediments of the Fraser River delta (Hunter & Christian 2001). Excellent agreement in V_S structure from the surface to over 110 m depth is obtained, with shear-wave velocities of the MAP model within one standard deviation of the average invasive V_S measurements. Below this depth the credibility interval widens yet defines a transition to higher velocities (> 450 m/s by 160 m depth). Overall excellent agreement is obtained between the invasive V_S measurements and the inversion result; the average relative difference between the invasive measurements (average of SCPT and downhole data) and the inversion result (MAP model) to 120 m depth is 5%. The downhole measurements at Fraser River delta site 1 do not show an abrupt velocity increase until 235 m depth. Hence, the velocity contrast observed in the Bayesian microtremor inversion result between 110-160 m is not related to an abrupt geologic change, but results from general sensitivity of the dispersion data to velocities higher than can be represented by the power-law gradient at greater depth, albeit with poor resolution.

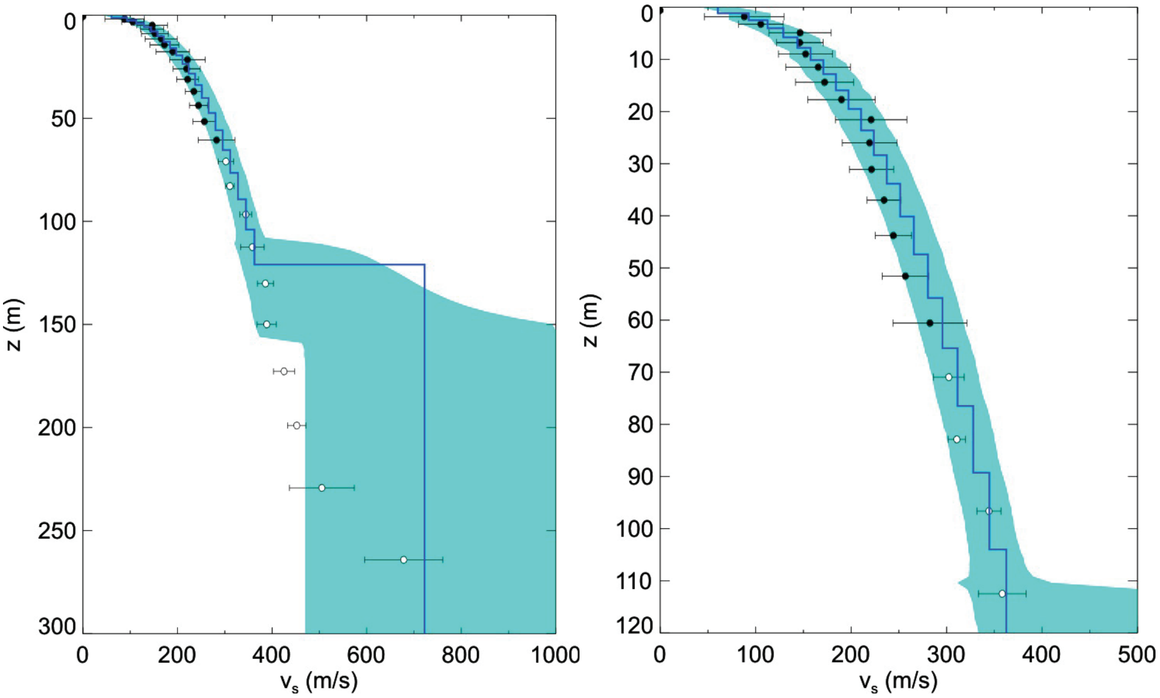


Figure 5. MAP model (solid line) and 95% HPD credibility interval (shaded region) from inversion at the Fraser River delta site 1 compared with V_S measurements from invasive down-hole and SCPT methods to (a) 300 m and (b) 120 m depth. Filled circles depict averaged down-hole and SCPT measurements to 60 m depth whereas open circles depict averaged down-hole only measurements.

Fig. 6a shows the recovered MAP V_S profile and a 95% HPD credibility interval to 120 m depth for Fraser River delta site 2. The shear-wave velocity of the power law layer is well constrained to ~200 m depth (not shown). The 95% HPD credibility interval indicates that below this depth the data no longer resolves the V_S structure. The invasive V_S measurements within the borehole and at eight SCPT sites are averaged according to the logarithmic depth partitioning of the MAP model. The average relative difference is 25% to 60 m depth.

Fig. 6b presents excellent agreement between the invasive SCPT V_S measurements with the MAP model for the Victoria site. The depth of the significant velocity increase in the MAP model corresponds closely to the 17.3 m depth of cone penetration refusal; however, it should be noted that the credibility interval for this transition extends from about 15-18 m. The half-space velocity is poorly resolved. The inversion results for the Victoria site show a well-determined transition at 15-18 m depth between low velocity (< 150 m/s) and higher velocity (> 500 m/s) material, which likely represents the physical contact between soft clayey silts and stiffer glacial till and/or hard bedrock as known from refusal of cone penetration at 17.3 m depth.

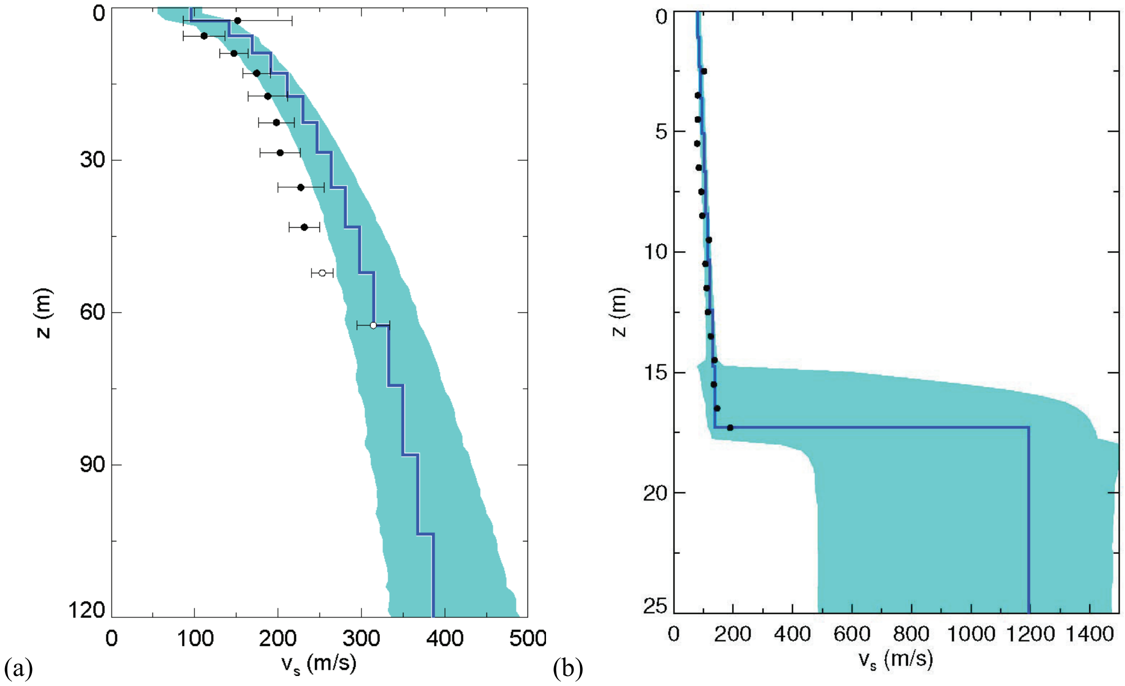


Figure 6. (a) Fraser River delta site 2 MAP model (solid line) and 95% HPD credibility interval (shaded region) compared with V_S measurements from invasive down-hole and SCPT methods. Filled circles depict averaged down-hole and SCPT measurements to 45 m depth whereas open circles depict averaged down-hole only measurements. (b) Victoria site MAP model (solid line) and 95% HPD credibility interval (shaded region) compared with V_S measurements from a single SCPT.

4. DISCUSSION AND CONCLUSIONS

This paper applies a nonlinear Bayesian inversion approach with evaluation of data error statistics and model parameterizations to retrieve the most-probable V_S profile and its uncertainty from microtremor array dispersion data. Bayesian inversion formulates an inverse problem in terms of properties of the posterior probability density of the geophysical model parameters, such as the maximum *a posteriori* model, marginal probability distributions, and credibility intervals. In this paper, the MAP model is determined by numerically minimizing the generalized (data and prior) misfit using adaptive simplex simulated annealing. Other PPD properties are determined using the Markov-chain Monte Carlo method of Metropolis-Hastings sampling and presented in Molnar et al. (2012a).

Microtremor array recordings conducted on the Fraser River delta characterized the subsurface V_S structure with tight credibility bounds to 110 m (site 1) and ~200 m (site 2) depth using array apertures up to 180 and 290 m maximum, respectively. Below 110 m and ~200 m, the 95% HPD credibility interval begins to broaden substantially. This is a valuable indication that below this depth the microtremor data do not fully constrain the shear-velocity (V_S values < 500 m/s are excluded). At the Victoria site, a layer with low V_S and a weak linear gradient is indicated to 15-18 m depth, above an abrupt increase to higher velocity material.

The type of model parameterization to use in shear-wave velocity modelling is usually unknown *a priori*. Generally, testing of different model parameterizations is conducted, and the parameterization with the minimum misfit is pursued (Cornou et al. 2005-2009). However, this approach can add unnecessary profile structure. Instead, we used the Bayesian information criterion, which provides an objective criterion for selecting the most appropriate model parameterization. The BIC indicated that Fraser River delta dispersion data are best modelled using a power law depth relation. This parameterization is consistent with a general power law relationship determined for the Holocene sediments of the Fraser River delta (Hunter & Christian 2001).

The V_S profiles determined from Bayesian microtremor inversion are assessed for reliability by comparison with invasive V_S measurements (SCPT and/or downhole), with excellent agreement obtained. The average relative difference between the invasive measurements (average of SCPT and downhole data) and the inversion result (MAP model) is 5% and 25% at Fraser River delta sites 1 (to 110 m depth) and 2 (to 60 m depth), respectively, and 11% at the Victoria site (17 m depth). For comparison, Xia et al. (2000) compared V_S profiles from linearized inversion of Rayleigh wave dispersion data acquired using an active source and a linear array of 60 geophones (referred to as multichannel analysis of surface waves, MASW) with downhole measurements at eight sites across the southern Fraser River delta and obtained average relative differences to 30 m depth of 8-26%, with an overall average of 15%. Woeller et al. (1993) documented V_S profiles from inversion of dispersion data acquired using an active source and multiple deployments of two geophones (spectral analysis of surface waves, SASW) with SCPT measurements at 15 sites on the delta, and obtained generally good agreement. It is also worth noting that differences in shear-wave velocity measurements between the two invasive methods (SCPT and downhole) at sites on the delta reported by Hunter et al. (1991; 2002) appear to be similar in size to the differences between surface-wave inversion results and invasive measurements given above.

All V_S-profiling methods considered here determine similar V_S values but penetrate to very different depths: SCPT, primarily 30 m; downhole, 60 and 300 m; and microtremor array, 18, ~110 and ~200 m. The microtremor array method is an extremely promising V_S-profiling methodology for seismic hazard assessment due to its depth of penetration and consistency of V_S results with other invasive methods, all for a much lower cost.

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