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Surface and downhole shear wave seismic methods for thick soil site investigations☆

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Abstract

Shear wave velocity–depth information is required for predicting the ground motion response to earthquakes in areas where significant soil cover exists over firm bedrock. Rather than estimating this critical parameter, it can be reliably measured using a suite of surface (non-invasive) and downhole (invasive) seismic methods. Shear wave velocities from surface measurements can be obtained using SH refraction techniques. Array lengths as large as 1000 m and depth of penetration to 250 m have been achieved in some areas. High resolution shear wave reflection techniques utilizing the common midpoint method can delineate the overburden-bedrock surface as well as reflecting boundaries within the overburden. Reflection data can also be used to obtain direct estimates of fundamental site periods from shear wave reflections without the requirement of measuring average shear wave velocity and total thickness of unconsolidated overburden above the bedrock surface. Accurate measurements of vertical shear wave velocities can be obtained using a seismic cone penetrometer in soft sediments, or with a well-locked geophone array in a borehole. Examples from thick soil sites in Canada demonstrate the type of shear wave velocity information that can be obtained with these geophysical techniques, and show how these data can be used to provide a first look at predicted ground motion response for thick soil sites.

Keywords: Seismic cone penetrometer; Geophysical; Geophone array

1. Introduction

As a result of recent significant earthquakes such as those that have affected Mexico City (1985), San Francisco (1989), and Los Angeles areas (1995), it has become apparent that the structure of the unconsolidated materials of young sedimentary basins can have a profound effect on the areal distribution of ground motion amplification, resulting in variability in the severity of damage to buildings, transportation corridors and other lifeline infrastructure. In such sedimentary basins where large shear wave velocity contrasts occur at the sediment–bedrock interface or within the unconsolidated sediments of the basin, studies have shown that in addition to shear wave velocity gradient amplification, these boundaries support the development of infra-overburden reflections which can constructively interfere (or resonate) to intensify ground motion amplification over narrow frequency bands. Ground motions can be further altered by focusing (or defocusing) of the earthquake energy at ground surface if the velocity boundary(s) at depth are of a non-planar, concave (or convex) shape [1]. As well, it is thought that the basin edges may support the development of surface wave mode conversion from impinging earthquake motion, resulting in the radiation of surface waves throughout the basin with possibly constructive interference over localized areas.

Several studies of these ground motion amplification effects of basin shapes, both computer modeling as well as case histories, have been published [2–4]. In most cases, the authors of these works have stressed the basic requirement of knowledge of geological structure of soft soils and rocks of sedimentary basins as it relates to the variations of geophysical parameters such as compressional and shear wave velocities, density, and attenuation in order to properly assess, and to predict, the complex pattern of surface ground motion resulting from significant earthquakes. Various geophysical methods can be applied to delineate near-surface structure. Descriptions and applications of a broad spectrum of these techniques can be found in Stanley Ward's [5] compendium on geotechnical and environmental geophysics.

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Of the required parameters for modeling, perhaps the most important is shear wave velocity, and yet this parameter is the one most often estimated from published values or derived from compressional wave velocities [4]. Accurate shear wave velocities are essential to understanding the response of thick soil sites to earthquake shaking. This paper discusses both surface (non-invasive) and borehole (invasive) techniques for measuring shear wave velocities, and for the delineation of shear wave velocity structure (related to geological structure) within soft soil basins. We attempt to provide some guidance as to the potential and limitations of each of these techniques. Examples of applications come from thick soil sites in Canadian high earthquake hazard zones from current ongoing projects of the Geological Survey of Canada.

2. Surface (non-invasive) methods

Surface seismic methods are attractive for most site surveys since they are non-invasive and relatively inexpensive. Such techniques should be considered for 'first look' or reconnaissance investigations where the objective is to ascertain the presence or absence of lateral variations of shear wave structure or to establish average velocity–depth functions.

2.1. Shear wave refraction methods

Refraction techniques for near surface surveying (either P or S) have been well described in the literature [6]. The receivers used in shear wave refraction work are typically low-frequency (< 14 Hz natural frequency) horizontal geophones oriented at right-angles to the line of survey (SH mode). As wind and cultural noise (traffic, etc.) are in the frequency range of interest, care must be taken to ensure good ground coupling (e.g. by burying or loading the geophones). The output from the geophone array is recorded on an engineering seismograph that can digitally 'stack' sequential hammer blows and switch geophone polarity. Using the polarity reversing capability, it is possible to stack signals from the two orientations of a polarized source. Alternatively, the two different stacked polarity records can be saved independently and stacked during post-acquisition processing (the preferred approach).

A polarized shear wave seismic source used routinely in this work is a steel I-beam imbedded in the ground and struck on either side with a 7.5 kg sledge hammer to generate polarized shear (SH) energy. We have found this source to be adequate, in most cases, for source-geophone offsets of up to 200 m. For deeper penetration, we have used an in-hole 'Buffalo gun' [7] to detonate an 8-gauge black powder blank shot-gun shell approximately 1 m below the ground surface. Although this is a 'point impulsive' source commonly used for P-wave surveys, it also generates considerable shear wave energy; however, control on the polarization of the shear wave energy is not possible.

In our regional studies, stand-alone soundings are made for 'spot' determinations of shear wave velocity as a function of depth, using a simple 'true reversed' seismic array. To ensure 30–50 m of penetration in soft soils, typical array lengths are ~200 m with geophone spacings in the range of 3–5 m. Information to greater depths requires longer spread lengths, as shown in an example from the Fraser River delta, south of Vancouver, British Columbia (Fig. 1). The curved nature of the travel time–distance plot (Fig. 1(b)) is indicative of increasing velocity with depth within the Holocene sediments. The interpretation of abrupt velocity boundaries in the presence of velocity gradients can be problematical, but 'reduced travel time' plots (Fig. 1(b)) can serve to indicate the source-geophone distance at which the velocity discontinuity occurs, and to enhance the variation in apparent velocities. In this example, a 'breakover' onto a higher velocity layer has been interpreted at larger distances (> 500 m offset) on both forward and reverse limbs of the plot.

Analyses of first arrival travel-time plots such as shown in Fig. 1(b) use both routine layered model and curve fitting methods; a detailed description of the techniques is given by Hunter et al. [8,9]. As shown in Fig. 1(c), velocity-layering interpretations tend to yield minimum depth estimates to significant velocity boundaries, whereas curve-fitting techniques commonly give maximum depth estimates and seismic boundaries are usually indicated by changes in velocity–depth gradients. Both interpretations are useful to place limits on the velocity depth information.

Shear wave refraction methods offer a non-invasive means of determining a shear wave velocity–depth function for the near surface. The results are subject to the limitation that velocity must increase with depth. However, in many cases, normally consolidated sediments (e.g. thick deltaic, or lacustrine sand or silt sequences of Holocene or Pleistocene age) exhibit increasing shear wave velocities with depth and standard refraction seismic methods can be successfully applied. Geophone and source emplacements create minimum surface disturbance, and in most rural and suburban environments, many suitable stand-alone shear wave refraction sites can be found (e.g. lawns, parks). It should be noted that the shear wave velocities measured using refraction techniques are in the horizontal plane. These values may be in variance with those measured with downhole or seismic cone techniques if horizontal-to-vertical anisotropy exists.

2.2. Rayleigh wave techniques

Stokoe and Nazarian [10] introduced a seismic method based on the analysis of the vertical component of Rayleigh waves. The 'spectral analysis of surface waves' (SASW) technique uses two vertical geophones at varying horizontal spacings in-line and at varying distance from a broad-band

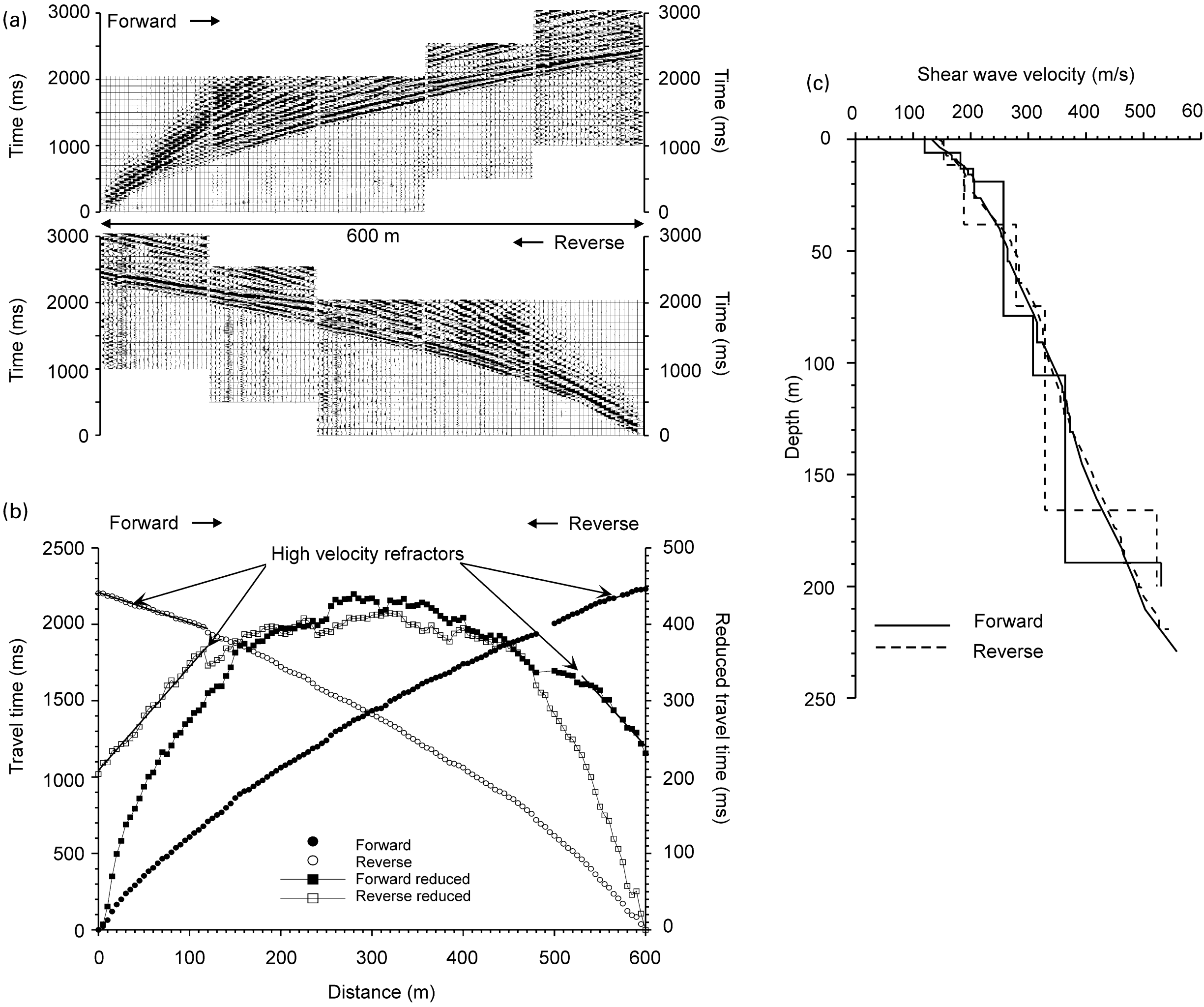

Fig. 1. (a) Composite forward and reverse seismic records covering source-receiver offsets from 5 to 600 m at 5 m geophone spacings; the source was an 8-gauge in-hole 'Buffalo' gun. (b) Plots of first arrival travel-times and 'reduced' travel-times $T_R = T - X/V_R$ vs. distance; V_R is referred to as the 'reducing' velocity, and X is the source–receiver separation (in this case $V_R = 300$ m/s). (c) Velocity–depth interpretations of the data in (b) using both the layered model and curve fit routines.

seismic source. Phase velocity–wavelength measurements of the wave field are made to produce a dispersion curve of phase velocity versus frequency from which the shear wave velocity–depth function is interpreted using an iterative model-fitting technique. The success of the method depends on the source spectral energy content and the ability to record a broad spectrum of frequency components. We have tested this method in the Fraser River delta using a 7.5 kg sledgehammer and steel plate as a seismic source and two 2 Hz vertical geophones at offsets from 0.25 to 12 m [11]. On inversion of the dispersion curve, reliable shear wave velocity–depth information was obtained to an average depth of 20 m below surface. Fig. 2(a) shows a comparison of SASW results to that measured from seismic cone penetration testing (SCPT) for a site in Holocene sediments after Hunter et al. [12]. The two data sets are similar; differences may result from shear wave velocity anisotropy between vertical and horizontal travel paths.

In the last few years a multi-geophone variant of SASW called multi-channel analysis of surface waves (MASW), has been developed by Park et al. [13]. Similar to the SASW approach, the method also derives S-wave velocities for a layered earth model by inverting Rayleigh wave phase velocities. Tests of the MASW technique were carried out at several sites in the Fraser River delta where borehole shear wave velocity information was available, using a 24 channel array of vertical broad-band geophones (4.5 Hz) at 5 m spacings. The source was a 20 kg vertically oriented steel weight accelerated downwards using an industrial elastic band to impact on a steel plate. For surveys conducted adjacent to six borehole sites, the root-mean-square error between borehole-measured shear wave velocities and calculated velocities based on the inverted S-wave velocity model ranged between 1 and 4 m/s [14]. A 'blind' test was conducted at a seventh borehole site where the near surface shear wave velocities differ somewhat from the other sites.

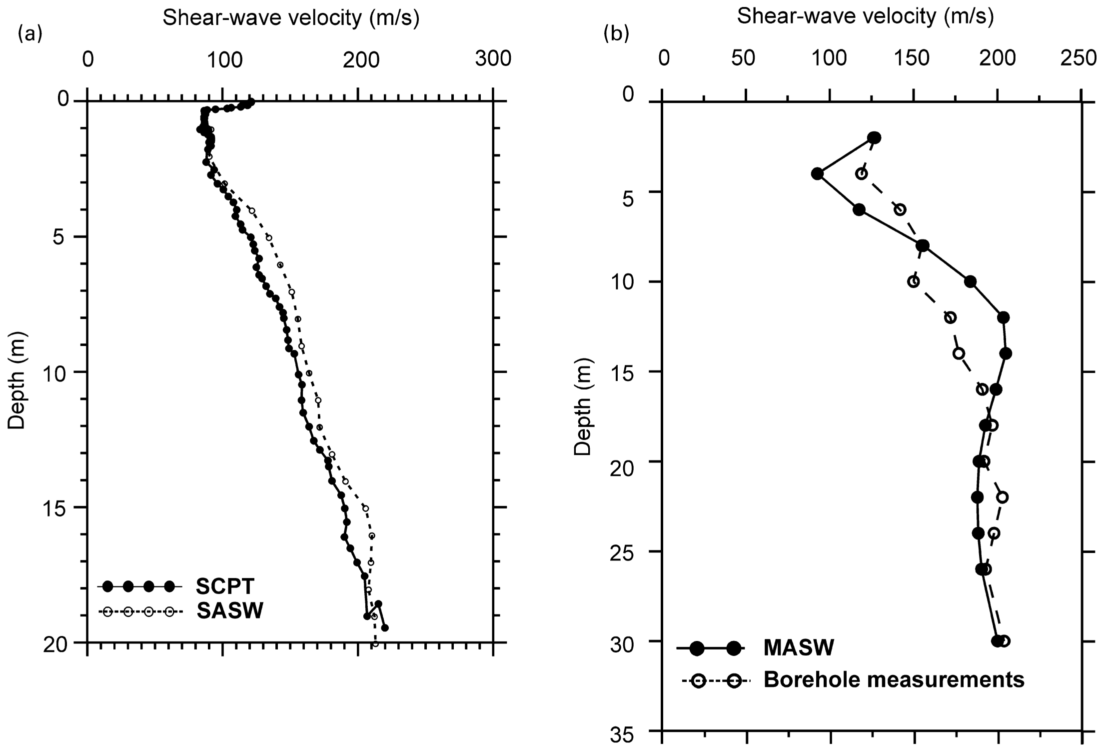

Fig. 2. (a) A comparison of shear wave velocities determined from a multi-layer fit of SASW data, and a three-point (2 m) least-squares fit of shear wave data acquired with a SCPT at a site in the Fraser River delta, British Columbia. (b) Final shear wave velocity–depth iterative inversion from MASW data compared to measured downhole values for a 'blind' test at a borehole in the Fraser River delta, British Columbia.

The MASW velocity profile for this test (Fig. 2(b)) also showed excellent agreement with borehole measurements; the relative difference between the results of the two techniques was only 9%.

Modeling of SASW and MASW data assumes horizontal shear wave velocity layers; hence these techniques are suitable for stand-alone one-dimensional shear wave velocity–depth measurements. Estimates of two-dimensional velocity variations can be obtained by occupying successive array positions along a survey line. As with the surface refraction technique, shear wave velocities are measured in the horizontal plane.

2.3. Shear wave reflection methods

In the last two decades shallow, high resolution reflection profiling has been increasingly utilized to map structure within near-surface unconsolidated sediments [15]. This work has primarily been based on compressional (P) wave methodologies, but recently, high-resolution, shear wave reflection surveying techniques have been developed [16]. These applications present several challenges; for example, ambient noise (e.g. cultural, wind, etc.) can be large, and geophone array geometries to obtain the 'optimum window' for observing shear wave reflected energy can differ significantly from those typical for conventional high resolution P-wave surveys. On the other hand, results from shear wave surveys (velocities and reflection times to significant seismic impedance contrasts) can be used directly in site effect investigations. Here we show three example shear wave reflection sections, acquired in different geological and cultural environments, to illustrate the type of information that can be obtained with these techniques.

In areas where the target horizons are hundreds of meters below ground surface, and/or where ambient noise levels are high, large shear wave sources are required. Fig. 3(a) shows a 12-fold common mid-point SH section shot with a truck mounted 'minivib' (IVI Ltd, Tulsa, OK). These data were acquired at a difficult urban site in the Fraser River delta, where there are high noise levels from nearby automobile, marine and aircraft traffic. This section yielded reflections in the range of 1300 ms two-way travel time and a sequence of deeper reflections at 2300–2500 ms. Only large velocity discontinuities can produce the observed significant reflection energy in this low signal-to-noise environment, and in this geological setting, such discontinuities are known to be associated with the occurrence of Pleistocene glacial tills (180–200 m) and with the top of the sedimentary tertiary bedrock sequence (470 m). This bedrock depth interpretation is the only deep subsurface information available in this particular portion of the Fraser delta, and despite the lack of borehole ground truth, such information is considered extremely valuable for the development of structural models for earthquake ground response estimation.

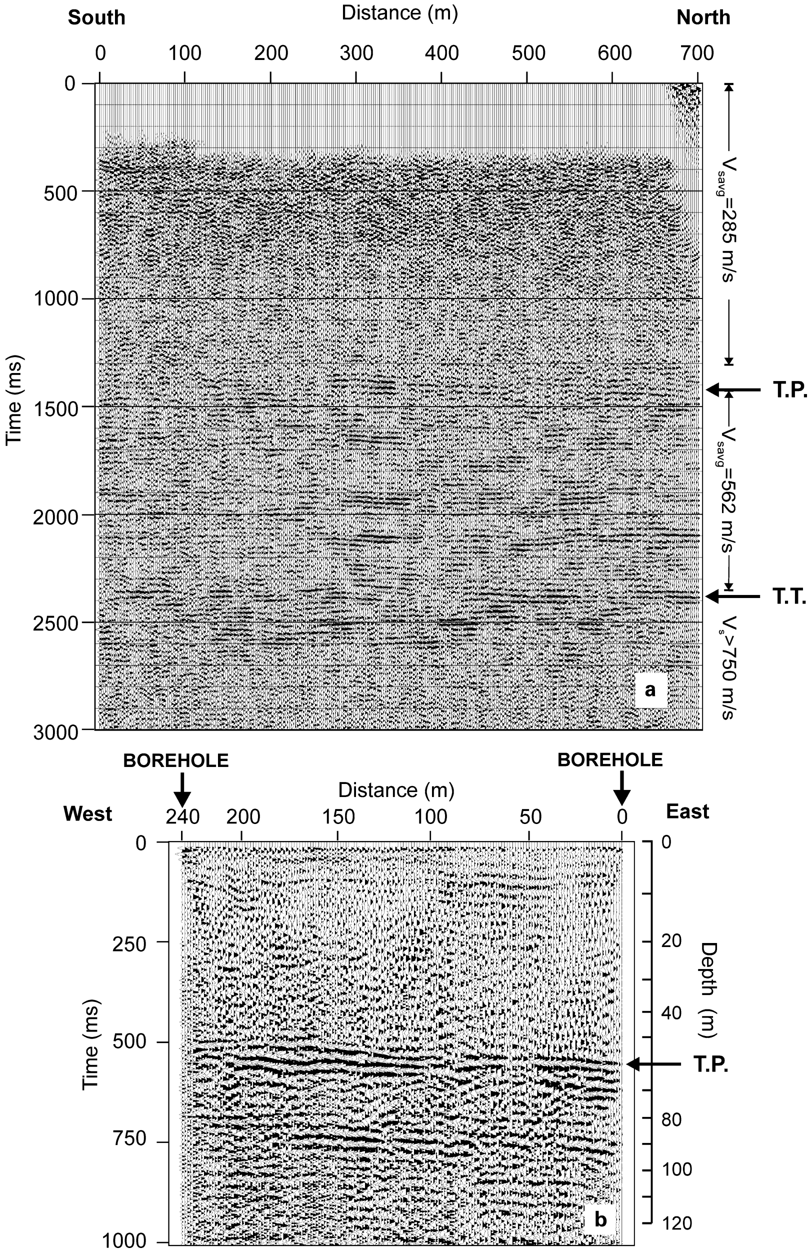

Fig. 3. (a) A 12-fold CMP stack of SH reflection data acquired using a ‘minivib’ swept-frequency source in a ‘noisy’ urban area of the Fraser River delta, BC. The top of Pleistocene (T.P.) and Tertiary bedrock (T.T.) have been interpreted at 200 and 470 m, respectively. Depth has been calculated using the shear wave velocity function derived through the stacking process. (b) A 12-fold CMP stack of SH reflection data using a 7.5 kg hammer and I-beam source in a ‘noisy’ suburban area of the Fraser River delta, BC. The dipping reflector interpreted to be the top of Pleistocene (T.P.) was subsequently confirmed by geological and geophysical borehole studies.

In the Fraser River delta, we have also used a 7.5 kg sledge hammer struck against a steel I-beam to image overburden structure to depths of ~100 m. Fig. 3(b) shows a 12-fold common midpoint (CMP) SH section using this source and 8 Hz horizontal geophones. At this site, water-saturated Holocene deltaic silts and sands overlie an irregular Pleistocene surface composed primarily of glacially derived coarse-grained sediments. This survey delineates the topography of this Pleistocene surface (dipping to the east in Fig. 3(b)). The interpretation has been corroborated by geological drilling and downhole velocity measurements at each end of the line.

Finally, on the small end of the energy scale, in some areas (e.g. Eastern Canada) we have had considerable success in acquiring shear wave reflection data using only a lightweight (1 kg) hammer impacting a small triangular piece of wood. This simple device is thought to preferentially transmit high frequency reflection energy because of

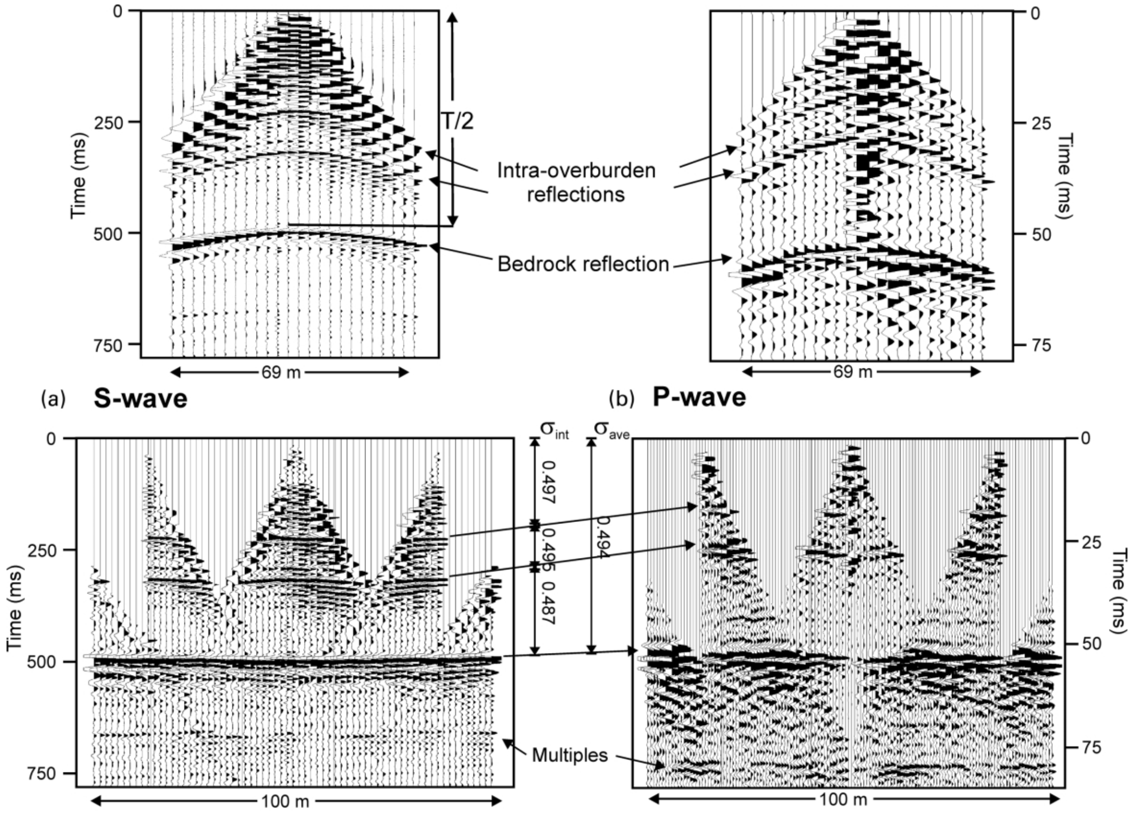

Fig. 4. A high resolution SH and P wave reflection site in Holocene sediments of the Ottawa valley, Ontario. (a) SH reflections obtained with a small 1 kg hammer and block of wood source. (b) P wave reflections obtained with a 12-gauge Buffalo gun source.

the small mass of the hammer and plate [17]. Fig. 4(a) shows a 'split-spread' SH-polarized shear wave reflection record from a thick soft soil site in the Ottawa River valley using the light hammer/wood source. The lower portion in Fig. 4(a) is a low fold CMP stacked reflection profile showing the layered structure at this site. In many circumstances shear wave reflection methods can be used for estimation of earthquake resonance effects. Williams et al. [18] have used the two-way travel time (T_0) of a shear wave reflection from a significant impedance boundary at zero offset distance to directly calculate the fundamental site period $T(T = 2T_0)$. If similar P-wave reflection information is available, as shown in Fig. 4(b), estimates of average values of Poisson's ratio (σ) to a subsurface boundary can be obtained by utilizing the vertical incidence two-way travel time $P(T_{\mathrm{Pref}})$ and $S(T_{\mathrm{Sref}})$ pairs. For small strain elastic propagation: $\sigma = (1 - 0.5R^2)/(1 - R^2)$ where $R = T_{\mathrm{Sref}}/T_{\mathrm{Pref}}$.

For the example shown in Fig. 4, the fundamental site period T is approximately 1 s and average values of Poisson's ratio are in the range of 0.487–0.494 as indicated. Such combined P and S site surveys can be a rapid cost effective means of obtaining fundamental seismic parameters, where good ambient noise and geophone–soil coupling conditions exist, and where prominent seismo-acoustic impedance boundaries occur at depth.

3. Downhole (invasive) methods

Shear wave velocities can be measured 'in situ' by a seismic cone penetrometer (SCPT) or in a cased borehole ('invasive' techniques). In contrast to the surface techniques discussed above, these methods are sensitive only to the vertical shear wave velocities and sample relatively less of the subsurface in their measurement. Since drilling boreholes is relatively expensive, downhole logging is often used to examine structure previously mapped by surface geophysical techniques or from known geological variations.

3.1. Shear wave velocities from seismic cone penetrometer testing

The cone penetration test is a popular in situ method for geotechnical investigations. Campanella and Robertson [19] first utilized this tool to measure shear wave velocities by installing a horizontal seismic detector behind the cone tip. A polarized shear source is located on surface. The cone is advanced (or pushed) at intervals of 0.5 or 1 m and shear wave velocities are determined from measured differences in arrival times of the shear wave. This velocity information can be directly correlated with the other cone-derived parameters such as soil stratigraphy and shear strength.

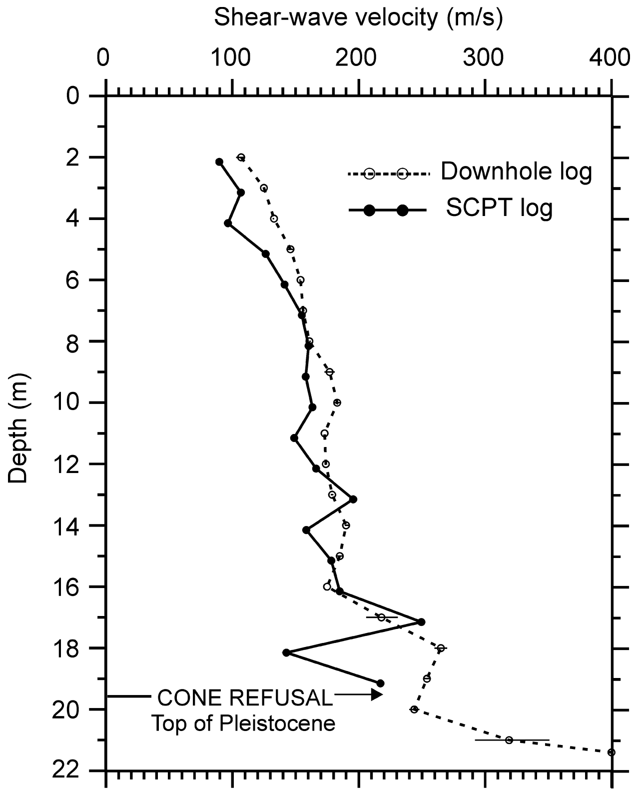

Fig. 5. Shear wave velocities from an SCPT log, the Fraser River delta, BC, compared to a seismic downhole shear wave velocity log at the same site.

The SCPT technique has the advantage of superior coupling of the geophone to the formation, but the method is limited to the maximum penetration of the system without drill-out. An example SCPT shear wave velocity log in Holocene sediments of the Fraser River delta is shown in Fig. 5, along with a downhole shear wave velocity log from an adjacent borehole. In this example, the cone met refusal at 19.6 m depth at the upper surface of the Pleistocene sediments. The downhole seismic log shows the abrupt velocity boundary associated with this geological contact. Hunter and Woeller [20] showed that, for a group of comparisons between SCPT and downhole logs in the Fraser River delta sediments, the statistical error (largely the first arrival time picking error) associated with the SCPT log is slightly lower than that of the downhole data.

3.2. Downhole shear wave logging

Downhole techniques provide accurate shear wave velocity measurements to depths of a few hundred meters. We use well-locking three-component geophone ‘pods’ (three pods at 2 m spacing) in cased boreholes, orienting the geophones from surface using low-cost methods as shown in Fig. 6(a) [21]. Surface polarizing shear sources are placed close (3–5 m) to the borehole; far enough away to reduce coupling of energy to the borehole casing, but as close as possible to minimize refractive effects (non-vertical travel paths). Such an array can be utilized to obtain interval velocity information which is independent of ‘zero’ (start) time of an impulsive source. A composite downhole shear wave log (one horizontal component) is shown in Fig. 6(b). If the borehole casing is poorly grouted in some areas, signal-generated noise, identified as a ‘tube’ wave, is generated. In these cases it may be necessary to use a combination of frequency filtering and interactive three-component ‘particle-motion’ plotting, or to carefully compare or stack reversed polarity records, in order to identify the onset of shear wave energy. A comparison of opposite polarity traces is shown in Fig. 6(c). Interval velocities are derived from least-squares fits of the time depth data using three, five or more adjacent points (Fig. 6(d)).

Downhole shear wave logging also allows an investigation of shear wave velocity anisotropy in unconsolidated sediments, which can be caused by grain orientation during deposition or by horizontal stress anisotropy [22]. In the Fraser River delta, we have performed tests in boreholes along an onshore–offshore causeway leading to the shelf edge at the delta front which suggest that, close to the slope break, the upper 40 m are azimuthally anisotropic with an average S-wave birefringence of 7% [23]. The observed anisotropy has direct implications on the stability of the delta front and may make this region susceptible to earthquake-induced failure.

4. Applications

The Geological Survey of Canada is currently collecting shear wave velocity data using the techniques discussed above to develop maps of vertical and lateral shear wave velocity structure of soils in high earthquake hazard areas of eastern and western Canada. In the Fraser River delta, British Columbia, there is now information from several hundred sites (Fig. 7(a)), including 115 surface shear wave refraction site surveys, 88 SCPT logs, and 52 downhole shear wave velocity logs [24]. This information provides the inputs required for a complete 3D computer modeling of ground response to earthquake shaking, but as a first step, Hunter and Christian [25] have examined individual (1D) sites in the delta to develop regional maps of:

1. NEHRP site classification [26] based on the thickness-weighted average shear wave velocity to 30 m depth (V_{S30}) (Fig. 7(b)),
2. velocity gradient amplification based on the Joyner et al. [27] 1/4 wavelength method (Fig. 7(c)) for incident 1 Hz earthquake energy, and
3. fundamental site period resonance resulting from the shear wave impedance boundary associated with the buried Pleistocene surface (Fig. 7(d)).

These methods give simple, first-order approximations of some aspects of the predicted ground motion response. It is

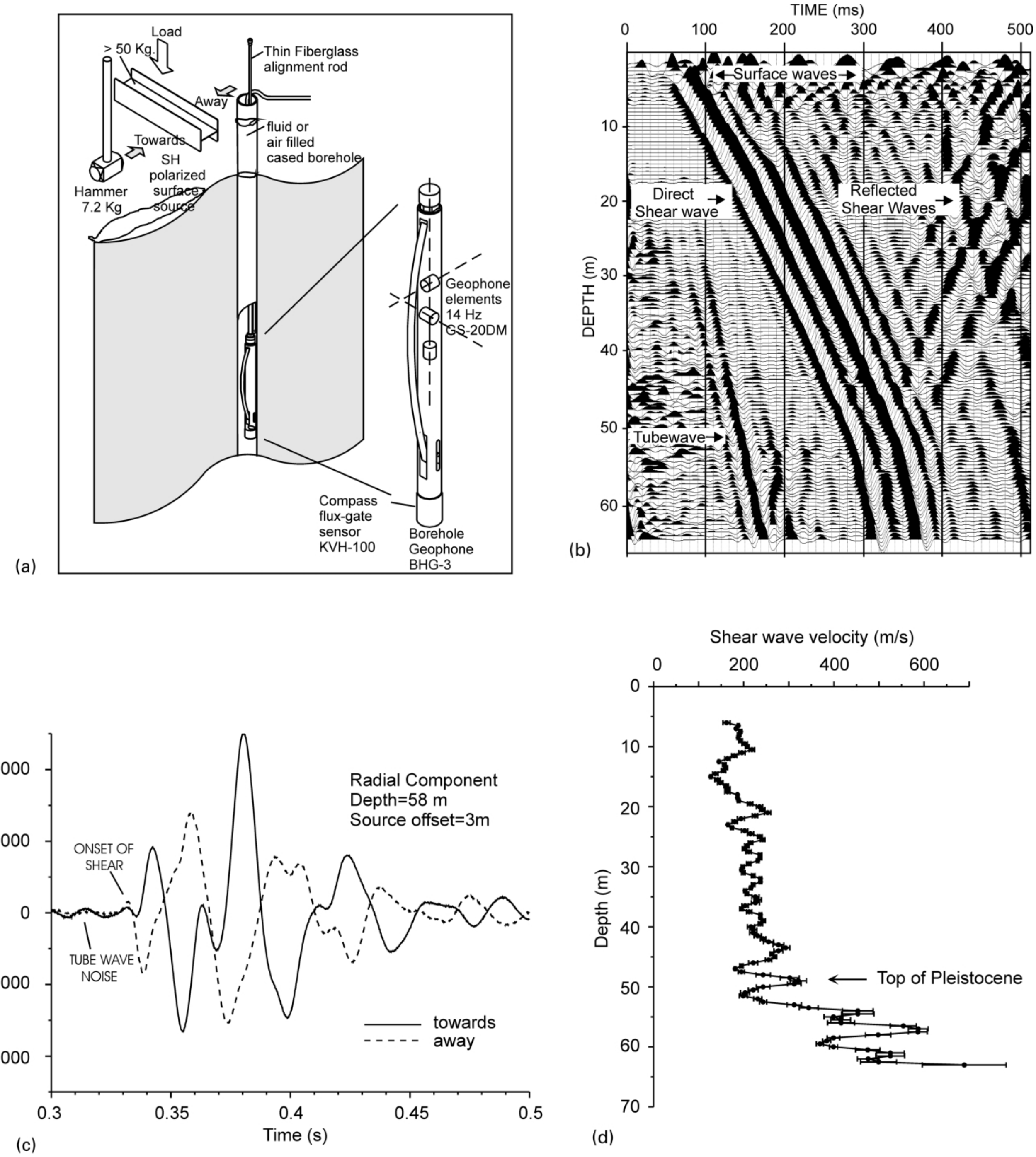

Fig. 6. Downhole shear wave velocity equipment and techniques. (a) Surface I-beam source and three-component well-locking unit rotated to the desired orientation using a thin fiberglass rod. (b) A typical composite radial component records suite (0.5 m trace spacing) showing the presence of significant 'tube' wave noise where the casing grouting is poor. (c) Overlapping 'towards' and 'away' radial compent records at one location, showing the interpreted onset of shear energy in the presence of noise. (d) A five-point (2 m) running least-squares velocity fit of the shear wave arrival time data; error bars are $\pm 2\sigma$.

immediately obvious (Fig. 7(b)–(d)) that there are considerable differences in all three parameters between the response on the Fraser delta (including the International Airport, city of Richmond, town of Ladner) and the adjacent firm ground areas of Vancouver and the Surrey Uplands. The NEHRP site characterisation map (Fig. 7(b)), sensing only the upper 30 m of sediments, classifies the delta area as either D or E. The low near-surface shear wave velocities in this area suggest that there is a possibility for liquefaction of non-cohesive soils. In contrast, the 1/4 wavelength amplification map (Fig. 7(c)) does take into account shear wave velocity distribution below 30 m depth at many sites within the delta, and provides a guide to possible 1D amplification effects (without considering shear wave attenuation). These

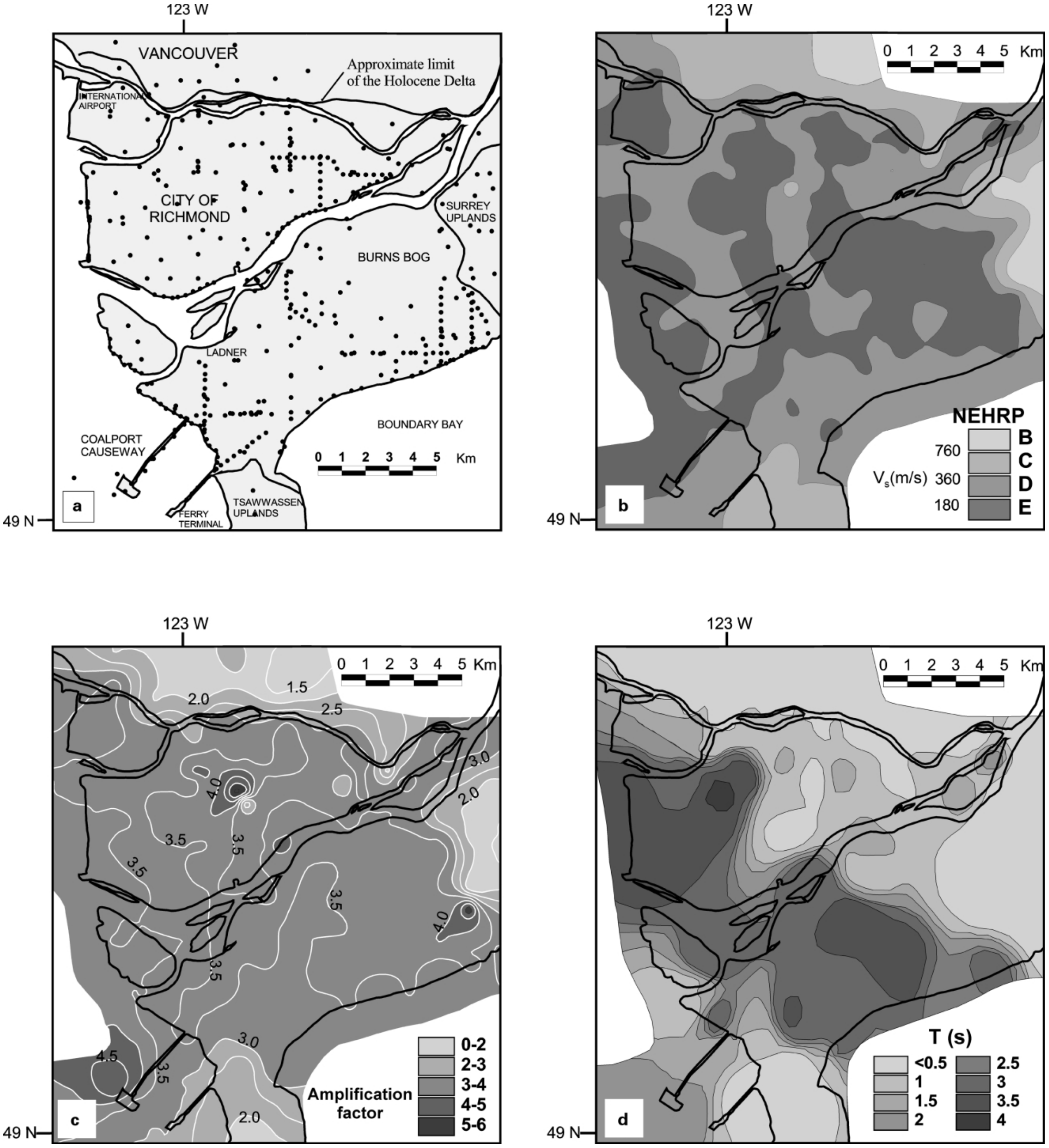

Fig. 7. (a) Location map of shear wave velocity–depth data acquired in the Fraser River delta near Vancouver BC. (b) Derived V_{S30} NEHRP site zonations. (c) 1/4 wavelength amplification for 1 Hz energy (after Joyner et al. [27]) for an assumed bedrock $V_S = 1900$ m/s, bedrock density = 2.5 g/cc, and soil density = 1.9 g/cc. No attenuation is considered. (d) Fundamental site resonance for the Holocene–Pleistocene seismic impedance boundary $T_0 = 4H/V_{AVE}$ where H = Holocene sediment thickness and V_{AVE} = thickness-weighted average shear wave velocity of the Holocene sediments.

estimates suggest that amplification factors reach 3–4 (times ground accelerations at the bedrock surface) over much of the delta. The fundamental site period map (Fig. 7(d)) reflects the structure of the seismo-acoustic boundary associated with the Pleistocene surface. This map shows that the one-dimensional fundamental site period varies between 1 and 3.5 s, indicating the extreme variability of potential resonance effects within the delta.

In eastern Canada, regional surficial geology and shear wave seismic studies are underway in a widespread zone in the Ottawa–Montreal–Quebec City corridor where high seismic hazard soft soils are associated with thick Holocene age Champlain Sea sediments (the so-called geotechnically sensitive 'Leda' clays). The near-surface geophysical techniques discussed above have been applied in a test study near Ottawa, Ont., where there is ample evidence of ground disturbance interpreted to be the result of significant paleo-earthquakes [28]. Preliminary results show the location of a deep bedrock basin (~180 m maximum depth) coincident with the presence of these disturbed near-surface sediments [29]. Shear wave reflection surveys (Fig. 4) used to provide estimates of the fundamental site period throughout the area indicate spatial variability of this parameter suggesting significant lateral differences in the ground response to earthquake shaking. The results of this study will provide future guidance to researchers requiring basic shear-wave velocity information for ground motion response modeling throughout the St Lawrence and Ottawa valleys.

5. Summary

Accurate predictions of earthquake ground motion response in thick soils require knowledge of shear wave velocities and attenuation, and their variation laterally and in depth. Too often, these parameters are estimated indirectly for ground response modeling, but they can be reliably measured using a suite of surface (non-invasive) and downhole (invasive) seismic methods. Non-invasive methods, including surface shear wave refraction, SASW, MASW, and reflection techniques, can be efficiently applied in the early stages of site characterization and zonation studies. They provide shear wave velocity estimates to depths of tens to hundreds of meters, and can be used to map structure on the overburden bedrock surface and significant seismo-acoustic boundaries within the overburden. Reflection data can also be used to obtain direct estimates of fundamental site periods from shear wave reflections. Such regional subsurface structural and velocity information should be supplemented with more detailed and site-specific one-dimensional studies using SCPT technology or a well-locked geophone array in a borehole. These downhole (invasive) techniques provide accurate measurements of vertical shear wave velocities, and can be used to acquire the data required for attenuation studies. The geophysical techniques discussed in this paper provide a cost-effective means of acquiring accurate and realistic shear wave velocity information for thick soil sites, allowing improved and more reliable estimates of ground motion response to be calculated in these critical areas.

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