Frequent-Interval SDMT and Continuous SCPTu for Detailed Shear Wave Velocity Profiling in Soils

T. Ku[1] and P.W. Mayne[2]
[1]*Geosystems Engineering, Georgia Institute of Technology, Atlanta, GA USA*
[2]*Geosystems Engineering, Georgia Institute of Technology, Atlanta, GA USA*
E-mail: taeseo@gatech.edu; paul.mayne@gatech.edu

ABSTRACT: Two new approaches to downhole shear wave velocity (V_s) measurements are presented, including frequent-interval method by seismic flat dilatometer (FiSDMT) and continuous-interval method by seismic piezocone testing (CiSCPTu). A recently-awarded patent for a roto-autoseis source assists in both methods by generation of fast and repeatable wavelets that are recorded by the probes during advancement. In the case of frequent-interval SDMT, either pseudo-interval or true-interval V_s data are procured at the same depth intervals of 0.2-m as the normal lift-off pressure (p_0) and expansion pressure (p_1) and therefore is a slowest version of downhole testing. This offers the advantage of accurate and detailed small-strain stiffness measurements (i.e., G_{max}) that can be useful in careful settlement calculations, pavement subgrade designs, and paleoliquefaction studies with shallow fine resolution requirements. In the continuous SCPTu, the autoseis generates wavelets as frequently as every 1 or 2 seconds, thus a fastest type of downhole testing. As there are considerable issues with signals that are complex because of refraction effects, variable penetration rates, noise, and vibration, special measures in processing are required in order to extract the V_s profile. The result offers continuous profiles of q_t, f_s, u_2, and V_s with depth from a single sounding.

Keywords: cone penetration, dilatometer, geophysics, in-situ testing, shear wave velocity, seismic flat dilatometer, seismic piezocone

1. INTRODUCTION

The shear wave velocity (V_s) is an important property which provides the initial stiffness needed in geotechnical design problems such as settlement predictions, deformation behaviour, and dynamic analyses (Tatsuoka et al. 1997; Jardine et al. 2005). The small strain shear modulus (G_{max} or G_0) corresponds to the initial tangential stiffness and beginning of all stress-strain-strength curves in soils under static and dynamic conditions. This shear modulus can be directly determined by in-situ V_s measurements: $G_{max} = \rho_t \cdot V_s^2$, where ρ_t is the total mass density of soil. The determination of the G_{max} profile is critical for dynamic ground response analyses and site amplification caused by earthquake shaking. In addition, field V_s measurements can be used for liquefaction resistance assessment in soils (Andrus and Stokoe 1997, 2000).

Various geophysical techniques have been developed towards in-situ V_s profiling (Campanella 1994). Downhole testing (DHT) and crosshole testing (CHT) are invasive methods that have been the most commonly adopted in geotechnical applications (Woods 1978). Conventional DHT and CHT require rotary drilling and casing of boreholes, grouting, inclinometer measurements, and repetitious repositioning of downhole geophones and/or hammers at 1.5-m depths for testing. These common tests are quite expensive and time-consuming. In contrast, non-invasive V_s techniques include: surface reflection survey (SRLS), surface refraction survey (SFRS), and Rayleigh wave methods (SASW, MASW, CSW, PSW, ReMi) which are conducted with sensors at the ground surface. These non-invasive methods usually provide a much coarser resolution of V_s profiles with step intervals of 5 to 20 meters per layer.

In practice, the alternative seismic cone penetration test (SCPT) and seismic flat dilatometer test (SDMT) using direct-push technology are more efficient means for in-situ V_s profiling by DHT, thus provide a comprehensive site investigation approach (Campanella et al. 1986, Robertson et al. 1986; Martin and Mayne 1998). In addition to being faster and more economical, they provide additional readings such as: cone tip resistance (q_t), sleeve friction (f_s), and porewater pressure (u_2) from seismic piezocone tests (SCPTu) or alternatively: lift-off pressure (p_0) and expansion pressure (p_1) from SDMT. Thus, more information is available from a single sounding. Figure 1 illustrates the general setup and procedures of field V_s measurements using the SCPT or SDMT.

Using a horizontal seismic surface source, downhole type shear waves of the vertically-propagated and horizontally-polarized mode (V_{sVH}) are generated during the geophysics portion of testing. Whereas multiple receivers such as geophones or accelerometers allow true-interval V_s analyses, a single seismic receiver is also capable of evaluating V_s via pseudo-interval measurements. Provided that time differences (Δt) and distances (ΔR) are accurate, it has been shown that pseudo-interval analysis is sufficient to obtain a reliable in-situ V_s profile (Robertson et al. 1986; Burghignoli et al. 1991). In terms of V_s profiling intervals, the 1.5-m interval by conventional DHT and CHT is usually replaced by a 1-m interval in standard SDMT and SCPTu. Yet, it is also plausible that V_s measurements can be procured at more frequent vertical depth intervals by stopping more often, and in fact, continuous V_s data may be collected with a special seismic source in very fast production times. Herein this study, issues and examples of the detailed V_s profiling by FiSDMT and CiSCPTu will be discussed.

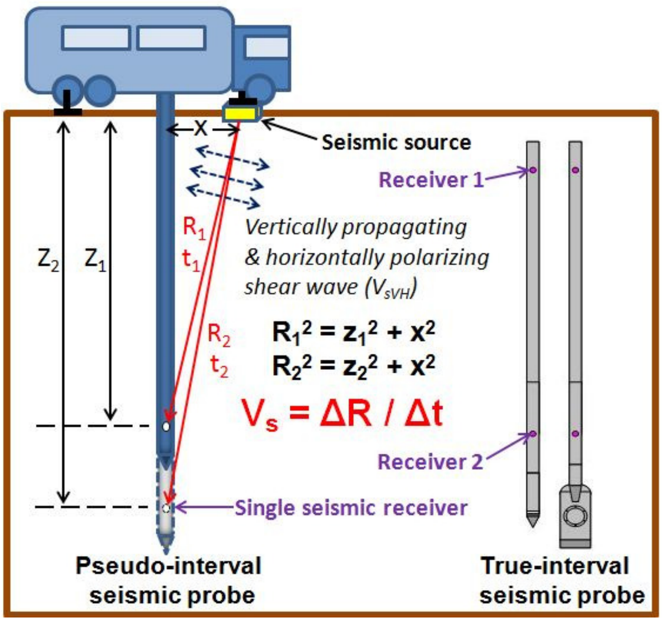

Figure 1 General setup of downhole type V_s measurement system using direct-push SCPT or SDMT

2. BACKGROUD OF EXPERIMENTS

For reliable V_s measurement and evaluation, it is critical to generate consistent and repeatable shear wave impulses. Several series of horizontal seismic sources and advanced data acquisition systems have been developed by Georgia Tech research group. Eventually, a portable automated triggering system became available. The new seismic source named 'RotoAutoSeis' can deliver vertically-propagated and horizontally-polarized shear wave signals at controlled speeds of between 1 to 10 sec. Two versions of the latest series of RotoAutoSeis units are shown in Figure 2.

To produce consistent shear wave signals, an AC or DC powered electric motor connected to mechanical gears is used to deliver seismic strikes by a rotating mass hammer. In the field, electrical power of the portable seismic source is available from a vehicle battery, generator, or power supply of the cone truck. The rate of hammer strikes can be adjusted by changing the motor speed. Figure 3 illustrates the mechanical gear operation system. The hammer is attached to a large diameter gear and operated by a small diameter gear connected to the electric motor. Further details regarding this automated source are discussed in McGillivray and Mayne (2008). Repeatable shear wavelets generated by the RotoAutoSeis assist in reliable V_s evaluations for both SDMT and SCPT. A conventional SCPTu often employs paired sets of reversed polarized left- and right- shear waves for a cross-over analysis (Campanella et al. 1986). While this is not possible with RotoAutoSeis since it operates in one direction, better results are actually obtained by implementation of more robust processing techniques, including cross-correlation, frequency-domain analytics, and/or other enhanced data processing methods.

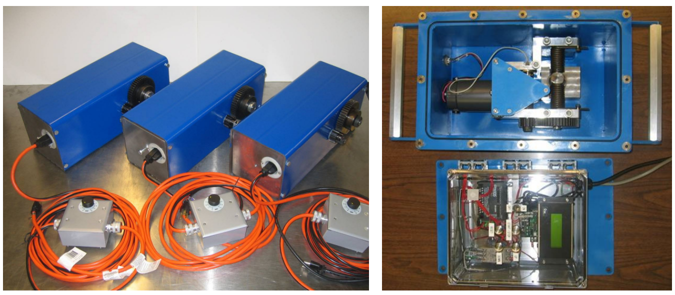

Figure 2 Two recent versions of GT RotoAutoSeis device including (a) design prototypes, and (b) commercial unit

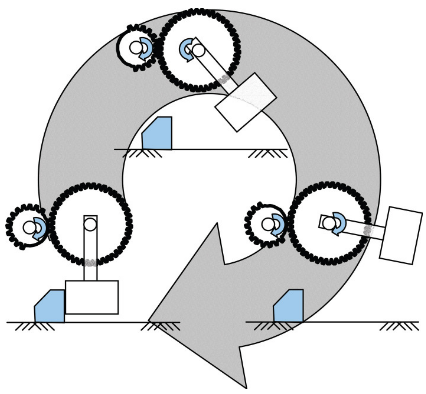

Figure 3 Schematic of mechanical gear system of RotoAutoSeis (McGillivray and Mayne 2008)

3. FREQUENT-INTERVAL SDMT (FiSDMT)

Compared to the conventional DHT and CHT which require rotary drilling and casing, the SDMT is efficient in both cost and field production time for V_s data collection. In addition, it is possible to obtain more frequent-interval V_s measurements along with the basic pressure readings (i.e., p_0, p_1) from standard dilatometer testing. The frequent-interval seismic flat dilatometer (FiSDMT) provides the V_s measurements every 0.2-meter depth interval, thus a much finer in-situ V_s profile is obtained. The enhanced resolution of the field V_s profile has more opportunity to delineate the geostratigraphy and detect the existence of possible thin soft layers. Moreover, the detailed V_s measurements are more conducive for accurate predictions of foundation movements, subgrade response, soil liquefaction potential, and other geotechnical concerns.

An example FiSDMT sounding is shown in Figure 4. The SDMT measurements were taken at the test site of the Treporti circular embankment northeast of Venice (McGillivray and Mayne 2008). For the V_s measurements, a true-interval seismic dilatometer system was used. The test site has complex interbedded alluvial-marine layers which consist of medium to fine sand (SP-SM), silt (ML), and silty clay (CL). The descriptions and properties of the soil layers have been detailed elsewhere (Simonini 2004, Simonini et al. 2007). Results from a standard downhole shear wave velocity profile produced by an adjacent SCPT sounding are also presented for reference and benchmarking purposes.

Compared to the conventional coarse one-meter interval V_s data from the SCPT, it is evident that the FiSDMT provides much finer detailing in the V_s profile at 200 mm intervals. Both methods successfully detect the stiffer-harder layers at the 3 m and 7 m depth marks, yet the frequent-interval V_s does a better job in tracking the actual variations and subtle changes. Both V_s profiles were developed using cross-correlation. In terms of V_s evaluations, additional details will be discussed in the upcoming section on continuous-interval readings because of the need for more careful considerations of factors that include: noise, vibration, very short distances, filtering, windowing, and fast time differences.

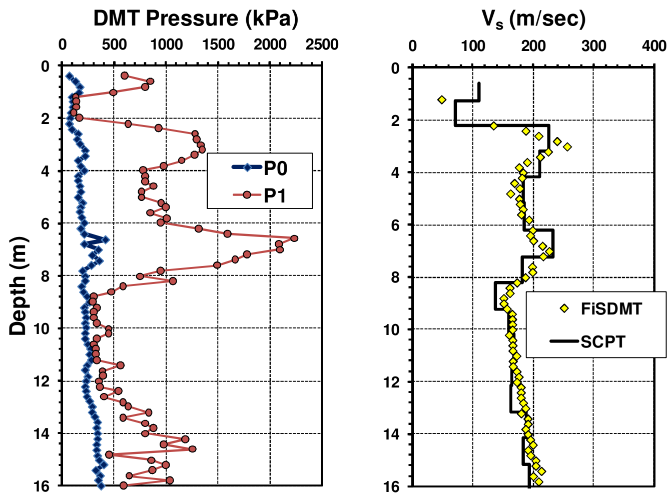

Figure 4 Frequent-interval SDMT soundings (p_0, p_1, 0.2-m interval V_s) and SCPT soundings (1-interval V_s) at Treporti site

Of course, the frequent-interval method is not limited to implementation with the seismic flat dilatometer, but also can be applied to conventional borehole type downhole tests (DHT), as well as seismic cone (SCPT) and/or use of special geophysics probes. One just needs to stop more frequently to obtain the shear wave velocities at closer intervals. In Figure 5, the results of special tests conducted at the Department of Energy site near Aiken, South Carolina are shown for a representative FiSCPTu in old Eocene deposits of the Atlantic Coastal Plain geology. These measurements were obtained by conducting two separate probings in the same hole: (a) initially, a CPTu sounding was advanced using a 10-cm^2 penetrometer to collect cone resistance (q_t), sleeve friction (f_s), and porewater pressure (u_2) readings at 0.02-m intervals with depth, followed by: (b) a sounding at the same location using a special 15-cm^2 geophysical true-interval probe that consisted of 6 geophones, specifically 3 sets of paired orthogonal horizontal geophones at different elevations. The vertical offset distance between each pair of geophones was approximately 0.5 m. The geophysics probe was incrementally advanced at 0.2-m intervals to collect the V_s data.

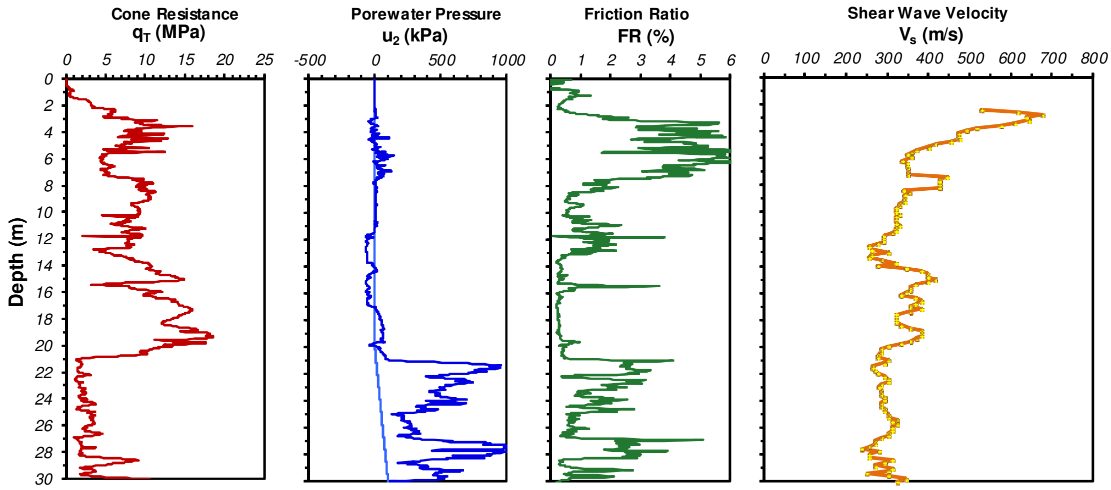

Figure 5. Results of frequent-interval seismic piezocone (FiSCPTu) obtained using a penetrometer and geophysics probe in Aiken, SC

4. CONTINUOUS-INTERVAL SCPTu (CiSCPTu)

4.1 CiSCPTu data and site description

As noted, the automated seismic source (RotoAutoSeis) is capable of delivering repeatable seismic impacts at controlled speed. This makes it possible to record continuous shear waves during advancement of cone. When the cone penetrates soil media at a standard rate of 20 mm/sec, automated seismic impacts per every 5 seconds produce successive 100-mm interval V_s measurements which are an order of magnitude finer compared to standard 1-m depth intervals. The continuous-interval seismic piezocone test (CiSCPTu) only stops at rod-breaks, therefore it is considered the fastest type of downhole testing. A single sounding provides multiple and independent readings with depth: q_t, f_s, u_2, and V_s.

In terms of V_s evaluations, it is important to obtain correct time differences (Δt) between consecutive shear wave arrivals, regardless of true-interval or pseudo-interval type measurements. Particularly, in the case of continuous shear wavelets which have very short distance intervals, accurate determinations of Δt are critical for reliable V_s determinations because of the effects of their very small magnitudes and corresponding short distances (ΔR). To avoid potential sensitive errors, a robust V_s interpretation tool is required. Herein, the feasibility of the continuous V_s profiling by CiSCPTu and related technical issues are discussed based on shear wave data taken at an industrial site in Richmond, British Columbia.

The ground conditions at the Richmond project site consist of about 1 m of gravelly sand fill overlying natural alluvial and deltaic deposits of silty clay to 7 meters, a thick sand stratum which extends to 30 m, underlain by a thick layer of soft to firm clayey silt which resides beyond the termination depths of exploration at 45 m. Groundwater lies about 3.5 m deep at this location. A total of 445 successive shear wave signals were generated for the special continuous shear wave measurements at the Richmond site. The shear waves were collected at 100-mm vertical intervals down to 45 meters using a pseudo-interval seismic penetrometer (i.e., one bi-axial geophone). The sampling rate of signals was 20 kHz with a record length of 400 ms. The distance from the center of the autoseis unit to the axis of the SCPTu push rods was 1.25 meters.

A summary of the continuous record of raw wavelets is shown in Figure 6. The primary shear wave is seen clearly as a falling cascade. For illustration purposes, the selected waveforms and frequency components of two consecutive raw signals recorded at 45.0 and 45.1 meter depths are provided in the subfigures. Due to the short distance interval of 100 mm, the identification of the time delay is not clearly evident. For the selected two raw signals, slightly different peak frequencies were observed at approximately 35 Hz in addition to some issues with noise and vibration.

4.2 Signal processing of continuous shear waves

In order to determine time difference Δt between consecutive waves, clear shear wave signals should be obtained. If raw shear wave signals are significantly fuzzy, hard to identify, and/or distorted, appropriate signal processing techniques are necessary, including noise filtering and detrending. In the CiSCPTu, considerable noise and stray signals were observed with continuous shear wavelets due to causes such as: (1) rod vibrations caused by the cone penetration process, (2) truck engine operations, (3) reflected and/or refracted signals from soil layering, (4) random electromagnetic interference from external outside sources.

Generally, noise levels can be controlled by several strategies (Santamarina and Fratta 1998). Within the time domain, simple signal stacking can improve effectively the signal-to-noise ratio for raw signals which have random noises (i.e., noise mean equal to zero). However, this technique requires generating multiple signals at the same designated depth, therefore not viable for collection of continuous V_s data. Another noise control in time domain is a moving average technique by adopting a smoothing kernel (κ). This method is particularly effective for raw signals having considerable high frequency noise. On the other hand, noise control is also possible in the frequency domain. Various filtering techniques (e.g., low-pass, high-pass, band-pass filter) can be selected depending on frequency ranges of interest. Unwanted frequency components superimposed on raw signals are removed using filters. Hence, selecting an appropriate filter type and frequency range is important to preserve the critical frequency components of shear waves. In this study, all noise filterings were conducted efficiently within the frequency domain.

The aforementioned continuous raw shear wave signals obtained at the Richmond site were processed by detrending and noise filtering before V_s calculations. Detrending was conducted to eliminate signal distortion and unwanted long-term trends in general time series analyses. There are several detrending techniques depending on properties of time series. Herein, a best-fit line derived from the least-squares method was subtracted from the raw data. It seemed sufficient to remove an unwanted slight linear tendency for each recorded signal. To mitigate noise levels, a band-pass filtering (e.g., 4^{th} order Butterworth filter in this study) was applied with windowing the main shear wave zones. Windowing can minimize spectral leakage, thus result in more reliable V_s evaluations. A rectangular window was used in the middle of the main waveform. Toward this purpose, Stewart (1992) proposed the rectangular window as an appropriate window for correction of V_s calculations. At the borders between windowed and non-windowed zones, a hamming window was combined with the rectangular window.

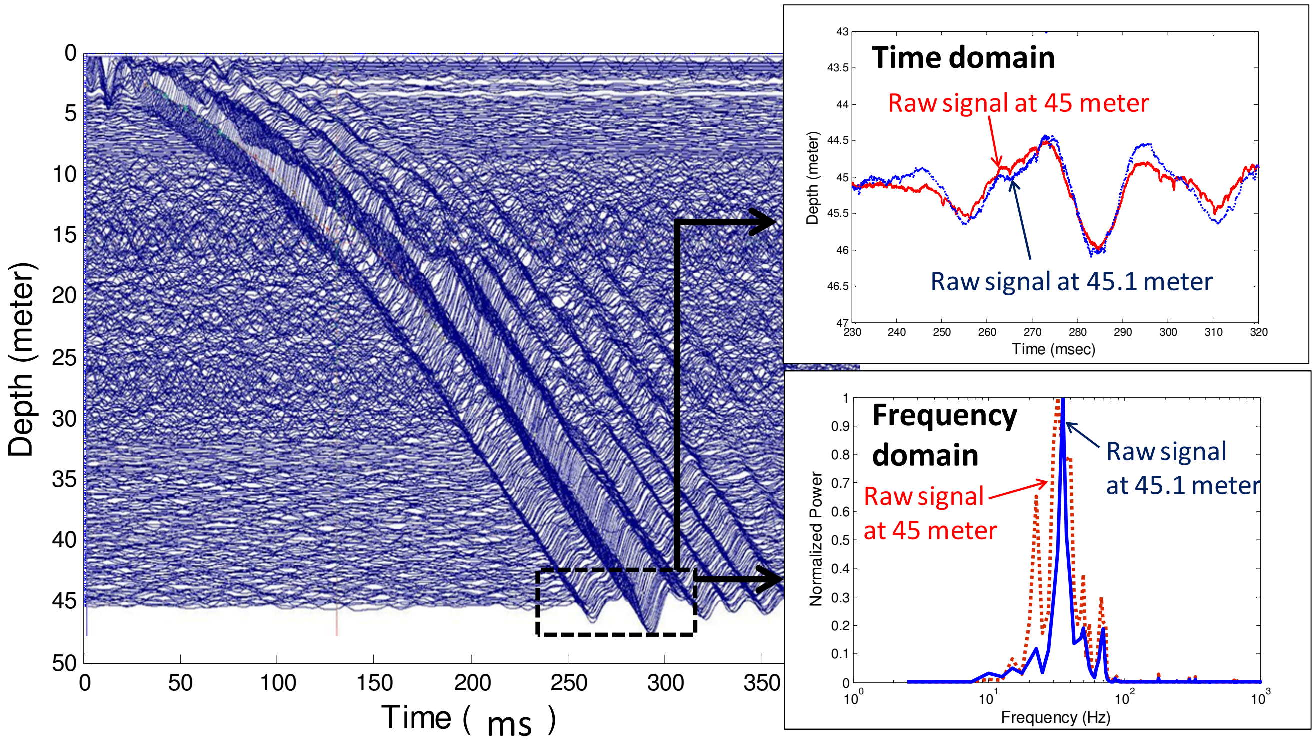

Figure 6 Continuous raw shear waves recorded every 0.1-m from CiSCPTu performed in Richmond, BC. In subfigures, two consecutive raw signals recorded at 45.0 and 45.1 meter depth are magnified in time domain and frequency domain

The frequency ranges for filtering were determined by observing squared coherence magnitudes between two consecutive raw signals because the coherence function can be a useful tool to identify potential noises (Campanella and Stewart 1992). Also, frequency domain magnitudes and waveforms of each raw signal were investigated to identify the validity of the determined band-pass filtering frequency range. Large magnitudes of the coherence indicate a significant degree of coupling between two signals at a particular frequency (f). Thus, the coherence values at frequency components corresponding to random noises are expected to have relatively low magnitudes. The coherence function is expressed as follows:

$$C_{xy} = coh^2(f) = \frac{|\Phi_{xy}(f)|^2}{\Phi_{xx}(f)\cdot\Phi_{yy}(f)} \quad \text{Eq. (1)}$$

where Φ_{xy} = cross-spectral density between time series x and y, Φ_{xx} = auto-spectral density of time series x, and Φ_{yy} = auto-spectral density of time series y. Figure 7 shows the magnitudes of the squared coherence evaluated from two consecutive raw signals recorded at 45.0 and 45.1 meter depths. It is observed that the coherence function has relatively high magnitudes for the frequency range between 30 Hz and 100 Hz. Eventually, based on further examination of coherence measurements and frequency components for all successive raw signals, the frequency range of [10 Hz, 300 Hz] was applied for band-pass noise filtering. Significantly poor raw signals that were difficult to identify clearly were deleted (e.g., signals recorded near 15 m and 26.5 m depths). Consequently, a total 418 shear wavelets were used for the V_s calculations.

4.3 Continuous V_s evaluation

4.3.1 Time difference (Δt) determination in time domain

In terms of in-situ V_s calculations (i.e., V_s = ΔR/Δt), the time difference (Δt) between shear wave arrivals can be determined by several methods. A simple technique is manually finding the first arrival, first peak, or first crossover point within the time domain (Stokoe and Woods 1972, Robertson et al. 1986, Sully and Campanella 1995, Liao and Mayne 2006). If raw shear wave signals are clearly observed, these methods can provide reliable results. However, it can be difficult to find reliable points specifically from disturbed or distorted signals (Campanella and Stewart 1992, Liao and Mayne 2006). Furthermore, manual picking methods are not suitable for continuous V_s data which have hundreds of datasets and the process becomes rather tedious and time-consuming, as well as dependent upon the experience of the individual. Moreover, the common cross-over method requires two strikes (pairs of left and right hits) to generate oppositely polarized shear waves. This is not applicable to the continuous triggering system that is uni-directional. Therefore, alternate efficient and robust V_s evaluation tools are necessary for processing of the continuous V_s data.

Cross-correlation analysis can be a suitable approach for CiV_s evaluations. Recently, this method was readily conducted using time domain with progress in computer speed and data storage capacity. The cross-correlation analysis between two discrete time series can be defined as following general expression:

$$C(j) = \sum_i (x_i)\cdot(y_{i+j}) \quad \text{Eq. (2)}$$

where x and y are two independent signals and j is time shift. The correlation coefficient value (r) is a normalized form using the cross-correlation function:

$$r = \frac{\sum[(x_i - \bar{x})\cdot(y_{i+j} - \bar{y})]}{\sqrt{\sum(x_i - \bar{x})^2}\cdot\sqrt{\sum(y_{i+j} - \bar{y})^2}} \quad \text{Eq. (3)}$$

where $\bar{x}$ and $\bar{y}$ are average values obtained from the corresponding time series. The time shift which provides the largest magnitude of correlation coefficient corresponds to the Δt. It occurs when two consecutive signals which have similar shapes are overlapped. For Δt determination using the cross-correlation analysis, a consistent seismic source like the RotoAutoSeis is important to minimize signal attenuation and preserve equivalent signal shapes. As noted, in terms of V_s interpretation technique, windowing the main shear wave signals can help correct V_s calculations (Stewart 1992, Campanella and Steward 1992).

After signal processing of the continuous raw shear wave data at the Richmond site, the cross-correlation analysis was conducted in time domain. A special coded program using MATLAB was written for efficient automated V_s calculations. Figure 8 shows correlation coefficient values obtained from two consecutive filtered and windowed signals at 45.0 and 45.1 meter depth. A maximum *r value* of about 0.93 was observed at the Δt of 0.4 ms.

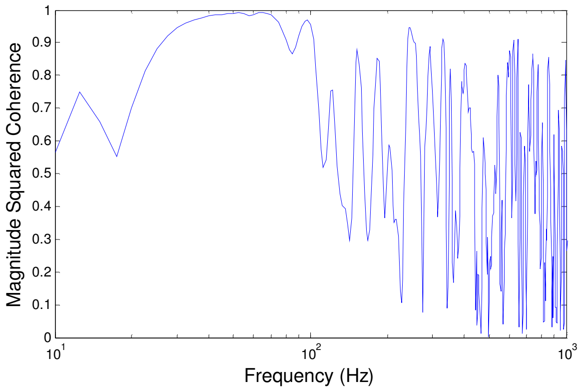

Figure 7 Coherence values evaluated from two consecutive raw signals recorded at 45.0 and 45.1 meter depth at Richmond, BC

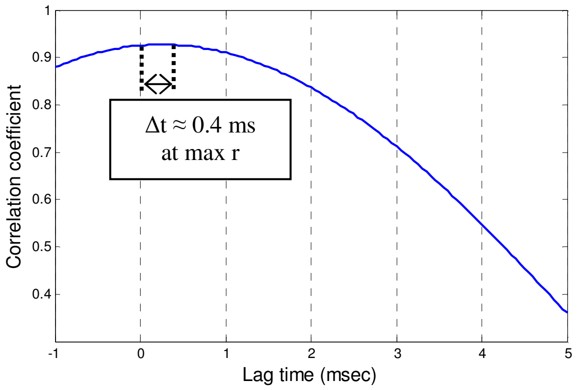

Figure 8 Magnitude of correlation coefficient (r) from two consecutive filtered signals at 45.0 and 45.1 meter depths at Richmond, BC

4.3.2 Time difference (Δt) determination in frequency domain

The Δt can be also determined using power spectral density (PSD) in the frequency domain. Basically, this approach finds a phase delay at predominant frequency of shear wave to calculate the Δt. The PSD represents powers distributed in given frequency ranges from time series signals, thus it is possible to examine the peak frequencies of shear waves. Several PSD estimation techniques were discussed in published studies (Welch 1967, Lomb 1976, Press et al. 1992, Bloomfield 2000, Trauth 2010). For the continuous shear wave data at Richmond site, frequency domain analysis was also conducted via MATLAB. Auto-spectral densities of the continuous signals were evaluated using Fast Fourier Transform (FFT), Welch method (Periodogram), and least-squares spectral analysis (LSSA). Figure 9 compares auto-spectral densities evaluated from the noted techniques based on the filtered signal recorded at 45.1 meter depth. Apparently, all techniques provide an identical peak frequency of about 35 Hz. Similarly, cross-spectral densities were examined from the periodogram (Welch method) which shows periodic tendency of signals. Figure 10 shows the cross-spectral density evaluated from two consecutive filtered signals recorded at 45.0 and 45.1 meter depth. The observed peak frequencies of both auto PSD (Figure 9) and cross PSD (Figure 10) are identical (i.e., 35 Hz). Suppose the main shear wave signals have clear dominating frequencies on their cross spectrum, the time difference (Δt) by phase lag of the peak frequency can be calculated as follow:

$$\Delta t = \theta_p{}^\circ / (360^\circ \times f_p) \qquad \text{Eq. (4)}$$

where f_p = observed peak frequency, θ_p = phase shift at peak frequency = $\tan^{-1}(Q(f_p)/Co(f_p))$, and Q is the imaginary part (quadrature spectrum) while Co is real part (cospectrum).

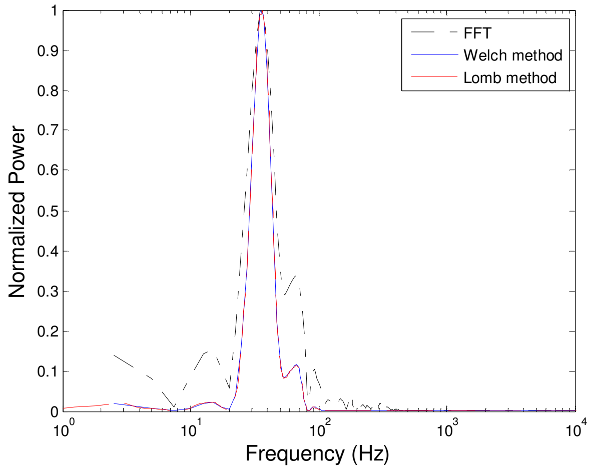

Figure 9 Normalized auto-spectral density estimated using various techniques (FFT, Welch method, Lomb method) for the filtered signal recorded at 45.1 meter depth at Richmond, BC (note: Lomb method corresponds to LSSA technique)

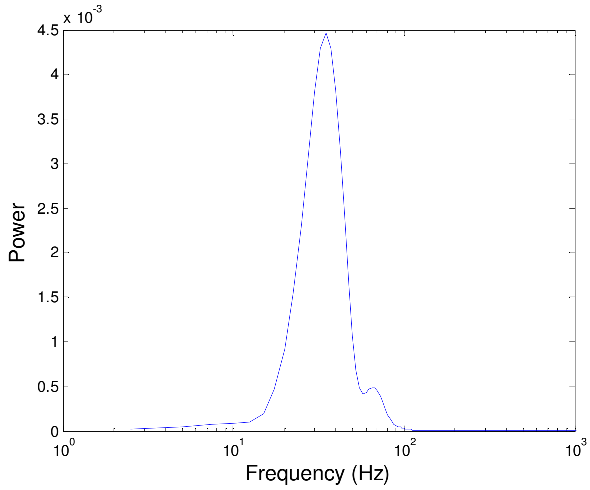

Figure 10 Cross-spectral density (periodogram) estimated from two consecutive filtered signals recorded at 45.0 and 45.1 meter depths at Richmond, BC

4.3.3 Sensitive continuous V_s result and adjustment

Using the aforementioned Δt determination techniques, the continuous V_s data were evaluated from the Richmond site. For comparison and benchmarking purposes, conventional field V_s data were also obtained at the same site including; 1-meter interval V_s from SCPTu, 0.5-meter interval V_s from SDMT, and coarser interval V_s from MASW surveys. The continuous V_s results were significantly scattered and sensitive comparing to the other in-situ V_s profiles. The scattered continuous V_s profile may be explained by several issues, which include : (1) sensitive results due to extremely small time difference (Δt) and distance (ΔR=10cm), (2) slight variations in cone penetration rate, (3) noise and vibration.

In order to mitigate the sensitive results and extract a final and reliable V_s profile, a zero-phase digital filtering technique was applied for Δt and examined on its applicability. Details of the filter function are discussed in Oppenheim and Schafer (1989). A $(n\text{-}1)^{th}$ order running-mean filter is expressed:

$$y_n = b_1 \cdot x_n + b_2 \cdot x_{n-1} + ... + b_{nb+1} \cdot x_{n-nb} - a_2 \cdot y_{n-1} - ... - a_{na+1} \cdot y_{n-na} \quad \text{Eq. (7)}$$

where y = filtered data, x = input data, b = numerator coefficient vector (here, set b = 1/n × [1,1,...,1]), a = denominator coefficient vector (here, set a = 1), nb = feedforward filter order, and na = feedback filter order. This filtering function is processed in both forward and backward directions.

Figure 11 shows the continuous V_s profiles evaluated from cross-correlation analysis in time domain and cross-spectral analysis in frequency domain with the special filtering technique; i.e., (a): 2nd order, (b): 5th order, (c): 10th order. As the continuous V_s data adopt higher order running-mean filter, it is observed that the sensitive V_s profiles (i.e., cross-correlation and cross-spectral analysis) become well matched with the downhole reference V_s. The cross-correlation method shows rather large CiV_s values at very shallow depth. This may be due to boundary effects (e.g., near-field effect, reflection) that have influence on the shear wavelets recorded near the surface. In future work, a true-interval geophone system may prove to be a more robust approach for CiV_s testing.

All available V_s results (i.e., CiV_s, 1-meter interval DHT, 0.5-meter interval SDMT, and MASW) at the Richmond site are compared in Figure 12. Although some variations are observed due to lateral hetereogeneity and spatial variability between test locations, overall the V_s evaluations show reasonable agreement. Values of the coefficient of determination (R^2) obtained from cross-correlation analyses (i.e., $r^2=R^2$) from continuous signal matchings are provided in Figure 12c.

For a finale plot, the complete CiSCPTu sounding is given in Figure 13 and provides fast and continuous q_t, f_s, u_2 and V_s readings throughout the 45 m depths. Note that these results were performed and evaluated before the reference true-interval DHT V_s profile was made at this site, thus confirming the reliability of this approach.

5. CONCLUSIONS

In this study, detailed in-situ V_s profiling techniques through frequent-interval seismic dilatometer (FiSDMT) and continuous-interval seismic piezocone testing (CiSCPTu) were presented. Obtaining the fine resolution of V_s profile is important for improved site investigations and better predictions regarding geotechnical design problems. The slow FiSDMT can collect V_s data at 0.2-m depth intervals, thus provide enhanced assessments of ground stiffness. Repeatable seismic impacts using the RotoAutoSeis can generate consistent shear wave signals in a quick manner. As a result, the seismic source is useful for both V_s evaluations via the FiSDMT and CiSCPTu. Particularly, the automatic triggering system plays a critical role in continuous V_s profiling as it expedites field production time.

Since continuous V_s testing produces hundreds of raw wavelet data, systematic processing schemes for V_s evaluations were presented based on cross-correlation in time domain analyses and cross-spectrum in frequency domain analyses. The pseudo-interval V_s results were sensitive at the Richmond site in British Columbia due to several issues, some of which may be resolved when a true-interval CiV_s system is developed in the future. In the interim, a special zero-phase running-mean filtering technique helps alleviate noise, vibration, shifted signals, and other processing needs.

6. ACKNOWLEDGMENTS

Georgia Tech appreciates the support of the US Dept. of Energy at the Savannah River Site and ConeTec Investigations of Vancouver towards research topics on in-situ testing methods.

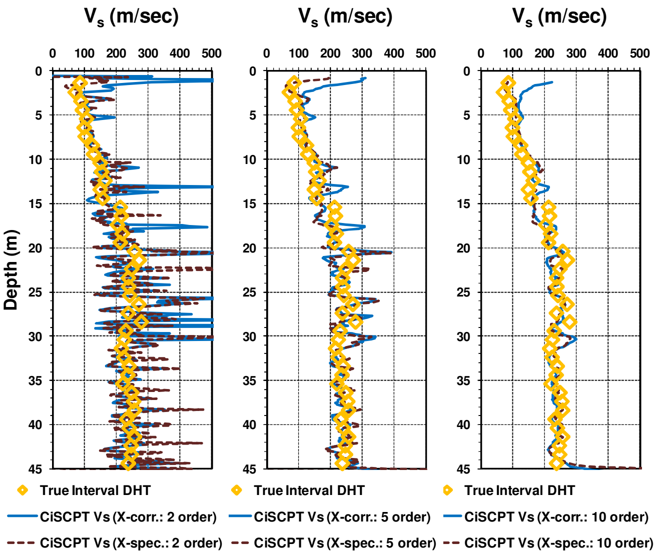

Figure 11 Continuous V_s evaluated from cross-correlation and cross-spectral analysis adopting different running-mean filters at Richmond, BC: (a) 2nd order, (b) 5th order, (c) 10th order

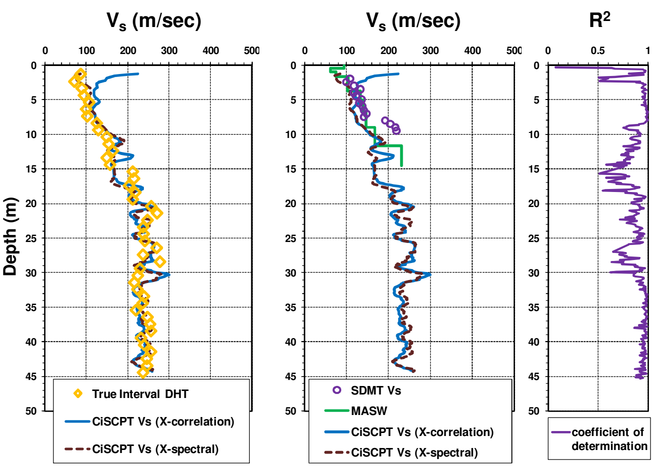

Figure 12 Comparison of various V_s data (DHT, SDMT, MASW, continuous V_s – 10th order) and coefficient of determination (R^2) values between continuous shear wave signals at Richmond, BC

7. REFERENCES

Andrus, R. D., and Stokoe, K. H., II (1997) "Liquefaction resistance based on shear wave velocity", Proc., NCEER Workshop on Evaluation of Liquefaction Resistance of Soils, National Center for Earthquake Engineering Research, State Univ. of New York at Buffalo, pp89–128.

Andrus, R. D., and Stokoe, K. H., II. (2000) "Liquefaction resistance of soils from shear-wave velocity", Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 126(11): pp1015–1025.

Bloomfield, P. (2000) Fourier analysis of time series: an introduction, Second edition, John Wiley & Sons, New York: 261 p.

Burghignoli, A., Cavalera, L., Chieppa, V. and Jamiolkowski, M. (1991) "Geotechnical characterization of Fucino clay", Proc. 10th European Conf. Soil Mechanics & Foundation Engineering, Vol. 1 (Florence), Balkema, Rotterdam: pp27-40.

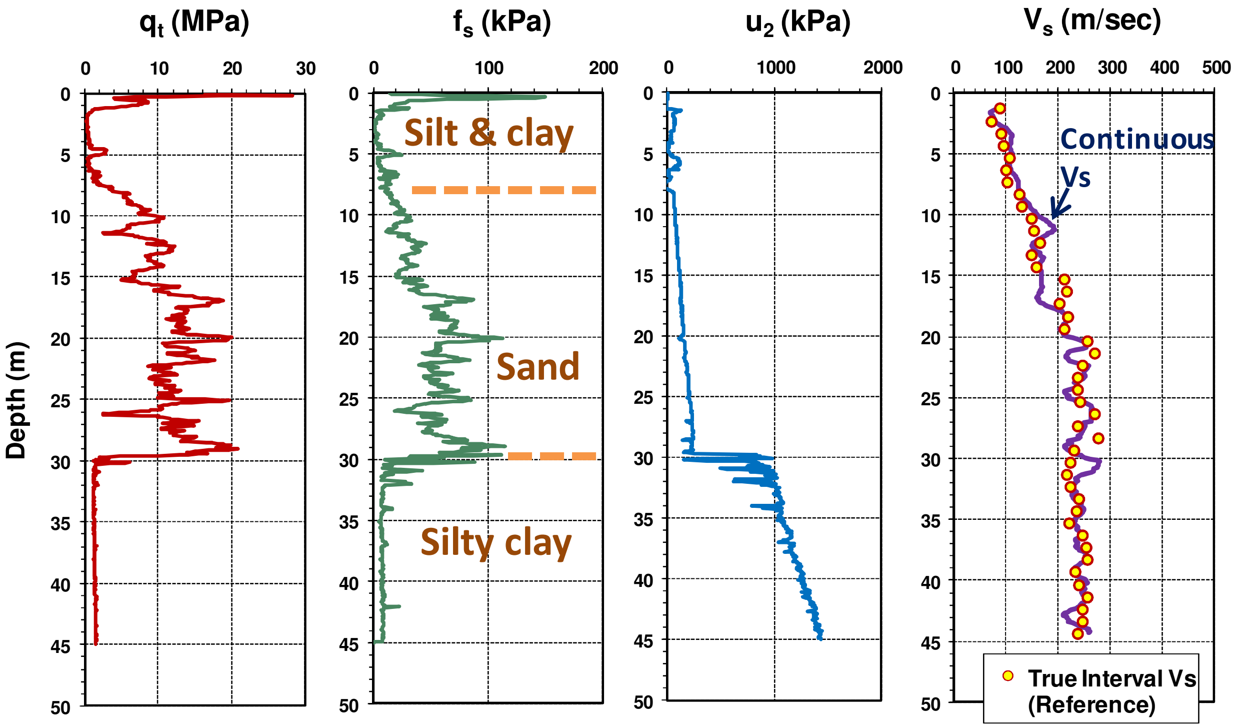

Figure 13 Results of continuous-interval seismic piezocone (CiSCPTu) and true-interval DHT at Richmond, BC site

Campanella, R.G. (1994) "Field methods for dynamic geotechnical testing", Dynamic Geotechnical Testing II (STP 1213), ASTM, West Conshohocken, PA: pp3-23.

Campanella, R.G., Robertson, P.K. and Gillespie, D. (1986) "Seismic cone penetration test", Use of In-Situ Tests in Geotechnical Engineering (GSP 6), ASCE, Reston, Virginia: pp116-130.

Campanella, R.G. and Stewart, W.P. (1992) "Seismic cone analysis using digital signal processing for dynamic site characterization", Canadian Geotechnical Journal 29(3): pp477-486.

Jardine, R.J., Standing, J.R. and Kovacevic, N. (2005) "Lessons learned from full scale observations and the practical application of advanced testing & modeling", Deformation Characteristics of Geomaterials, Vol. 2 (Proc. IS-Lyon), Taylor & Francis Group, London: pp201-245.

Liao, T. and Mayne, P.W. (2006) "Automated post-processing of shear wave signals", Proc. 8th US National Conference on Earthquake Engineering, San Francisco: 460.1-460.10.

Lomb, N.R. (1976) "Least-squares frequency analysis of unequally spaced data", Astrophysics and Space Science, Vol 39: pp447-462.

Martin, G.K. and Mayne, P.W. (1998) "Seismic flat dilatometer tests in Piedmont residual soils", Geotechnical Site Characterization, Vol. 2 (Proc. ISC-1, Atlanta), Balkema, Rotterdam: pp837-843.

McGillivray, A.V. and Mayne, P.W. (2008) "An automated seismic source for continuous-push shear wave velocity profiling with SCPT and frequent-interval SDMT", Geotechnical & Geophysical Site Characterization, Vol. 2, (Proc. ISC-3, Taipei), Taylor & Francis Group, London: pp1347-1352.

Oppenheim, A.V., and Schafer, R.W. (1989) Discrete-Time Signal Processing, Prentice Hall, Englewood Cliffs, NJ: pp311-312.

Press, W.H. Teukolsky, S.A., Vetterling, W.T., and Flannery, B.P. (1992) Numerical Recipes in C: the Art of Scientific Computing. Cambridge Univ. Press, pp575-584.

Robertson, P.K., Campanella, R.G., Gillespie, D. and Rice, A. (1986) "Seismic CPT to measure in situ shear wave velocity", Journal of Geotechnical Engineering 112(8): pp791-804.

Santamarina, J.C. and Fratta, D. (1998) Introduction to Discrete Signals and Inverse Problems in Civil Engineering, ASCE Press, Reston, Virginia: 327 p.

Simonini, P. (2004) "Characterisation of the Venice lagoon silts from in-situ tests and the performance of a test embankment", Geotechnical & Geophysical Site Characterization, Vol. 1 (Proc. ISC-2, Porto), Millpress, Rotterdam: pp187–208.

Simonini, P., Ricceri, G., and cola, S. (2007) "Geotechnical characterization and properties of Venice lagoon heterogeneous silts", Characterization and Engineering Properties of Natural Soils, Vol. 4, Taylor and Francis, London, pp2289-2327.

Stewart, W.P. (1992) "In-situ measurement of dynamic soil properties with emphasis on damping", Ph.D. thesis, Civil Engineering Dept., University of British Columbia, Vancouver, B.C.

Stokoe, K.H. and Woods, R.D. (1972) "In-situ shear wave velocity by cross-hole method", Journal of Soil Mechanics and Foundation Engineering Div., ASCE , 98(5), pp443-460.

Sully, J.P. and Campanella, R.G. (1995) "Evaluation of in-situ anisotropy from crosshole and downhole shear wave velocity measurements", Geotechnique 45(2), pp267-282.

Tatsuoka, F., Jardine, R.J., LoPresti, D.C.F., DiBenedetto, H. and Kodata, T. (1997) "Theme lecture: Characterizing the pre-failure deformation properties of geomaterials", Proc. 14th Intl. Conf. Soil Mechanics & Geotechnical Engineering, Vol. 4 (Hamburg), Balkema, Rotterdam: pp2129-2164.

Trauth, M.H. (2010). MATLAB Recipes for Earth Sciences, Third Edition. Springer, 336 p

Welch, P. D., (1967) "The use of Fast Fourier Transform for the estimation of power spectra: a method based on time averaging over short, modified periodograms", IEEE Transactions on Audio & Electroacoustics, AU-15, pp70-73.

Woods, R.D. (1978) "Measurement of dynamic soil properties", Earthquake Engineering and Soil Dynamics, Vol. 1 (Proc. Pasadena), ASCE, Reston, VA: pp91-178.