Geotechnical and Geophysical Site Characterisation 5 – Lehane, Acosta-Martínez & Kelly (Eds)
© 2016 Australian Geomechanics Society, Sydney, Australia, ISBN 978-0-9946261-2-7

Continuous-interval seismic piezocone testing in Piedmont residuum

S.S. Agaiby
Geosystems Engineering, Georgia Institute of Technology, Atlanta, GA, USA

E. Cargill
ConeTec Investigations, Charles City, VA, USA

T. Ku
Civil & Environmental Engineering, National University of Singapore, Singapore

P.W. Mayne
Civil & Environmental Engineering, Georgia Institute of Technology, Atlanta, GA, USA

ABSTRACT: Results from continuous-interval seismic piezocone testing (CiSCPTu) are reported for a test site located on the Georgia Tech campus that is situated in the Appalachian Piedmont geologic province and underlain by residual fine sandy silts to silty fine sands weathered from gneiss, schist, and granite. The CiSCPTu uses an electro-mechanical auto hammer to deliver repeated impact-type seismic waves that are picked up while the penetrometer is advancing. Filtering and post-processing of signals and waves are required for the interpretation of wavelets. The derived profile of shear wave velocity is found to be in good agreement with conventional seismic cone tests (SCPT) and Rayleigh wave (e.g., MASW) measurements performed at the site.

1 INTRODUCTION

1.1 *Shear Wave Velocity*

A fundamental parameter of the ground is the shear wave velocity (V_s) which can be measured in the field using either invasive and/or non-invasive geophysics, as well as obtained on small lab specimens. Shear waves can be measured in all geomaterials ranging from clays and silts to sands and gravels and mixed soil types, as well as fractured to intact rocks, and man-made ground (e.g., compacted fills, mine tailings). Thus, it serves as an excellent benchmark in comparing stiffness and stress state in most geotechnical applications. In-situ V_s profiling can provide a preliminary means to evaluate soil properties, such as unit weight (Moon et al. 2015), stress history (Mayne 2005), and undrained shear strength of clays (Agaiby & Mayne 2015). The shear wave profile is a necessary input for static and dynamic geotechnical analyses since it directly provides the small-strain shear modulus:

$$G_{\max} = G_0 = \rho_t \cdot V_s^2 \tag{1}$$

where ρ_t is total mass density that is evaluated from:

$$\rho_t = \frac{\gamma_{sat}}{g_a} \tag{2}$$

and the saturated unit weight is evaluated from:

$$\gamma_{sat} = \frac{G_s + e_0}{1 + e_0}\gamma_w \tag{3}$$

where G_s is soil's specific gravity, e_0 is void ratio, γ_w is the unit weight of water = 9.81 kN/m^3 and g_a is acceleration due to gravity = 9.81 m/sec^2. The initial shear modulus (G_{max} or G_0) represents the fundamental stiffness and the beginning of the stress-strain-strength curve of the geomaterial under study. While its magnitude can be determined on small laboratory specimens from undisturbed samples (e.g., resonant column, ultrasonics, bender elements, and/or triaxial tests with local strain sensors), these approaches have several issues, specifically: sampling disturbance difficulties (Tatsuoka 1992), loss of ageing and diagenesis effects (Anderson & Stokoe 1978), and stress relief (Landon et al. 2004). Hence, V_s is best measured in-situ rather than in the laboratory.

1.2 *Shear Wave Velocity Measurement Techniques*

In-situ methods for the measurement of shear wave velocity can be classified into two main categories: invasive and non-invasive methods (Wightman et al. 2003). Invasive methods include cased borehole methods such as: crosshole test (CHT), downhole test (DHT), uphole test (UHT), and P-S suspension logger, as well as direct push methods: seismic cone penetration test (SCPT) and seismic flat dilatometer test (SDMT) that are efficient versions of the DHT mode, in addition to continuous-interval seismic piezocone testing (CiSCPTu) which is discussed in this paper.

Non-invasive methods include refraction survey, reflection survey, and surface wave methods that use either active sources to measure Rayleigh waves, including: spectral analyses of surface waves (SASW), multi-channel analyses of surface waves (MASW), and continuous surface wave method (CSW), or passive source techniques, such as passive surface waves (PSW)/microtremor array measurements (MAM) or reflection microseis (ReMi).

2 CONTINUOUS SHEAR WAVE GENERATION

2.1 *Introducing the Rotoautoseis*

The conventional geophysical techniques carried out in boreholes such as crosshole and downhole tests are relatively slow and sometimes inconvenient as they require a number of procedures including: rotary drilling, installation of plastic casing, grouting, slope inclinometer, and positioning of geophones for seismic readings. Many of these obstacles are overcome using direct-push technologies such as SCPT or SDMT where the vertically-propagating horizontally-polarized shear wave velocity, or V_{sVH} mode, is measured at regular intervals of 1m without the need for drilled-cased-grouted boreholes. However, direct-push techniques usually generate the V_s profile at 1-m intervals as the advancing probe stops at the rod breaks which can affect the resolution and the quality of the measured shear wavelets. To obtain a more detailed clear successive continuous shear wave velocity profile with a higher resolution and expedited shorter field testing time, a portable automated triggering system named “rotoautoseis” has been developed and introduced by Mayne and McGillivray (2008). Together with an enhanced data acquisition system, the automatic seismic surface source can generate consistent repeatable strikes via an electromechanical gear system per every 1 to 10 seconds. Additional details with basic schematic and diagrams of the rotoautoseis are presented by McGillivray and Mayne (2008).

The automated impulse source system can be used with conventional piezocone testing to generate continuous shear waves during the standard penetration rate of 20 mm/sec. Thus, all readings (q_t, f_s, u_2, V_s) are collected during non-stopping cone pushing and the test is called continuous-interval seismic piezocone test (CiSCPTu).

Since a significantly larger number of shear wavelets are generated and measured, a consequence is that more sophisticated and elaborate techniques are needed for interpreting the signals and evaluating the shear wave velocity profile data. Careful post-processing analyses are required to handle errors from noisy signals, overlapping refracted and reflected wavelets, and readings taken over very short distance intervals. A brief description of the post processing procedure for continuous shear wave profiling is presented in this paper with fuller details presented elsewhere (Ku & Mayne 2012; Ku et al., 2013a, 2013b).

3 SITE DESCRIPTION

3.1 *Georgia Tech W21 Test Site*

The test site is located in the middle of the Georgia Tech campus at parking lot W21 near the intersection of Hemphill Street and Ferst Drive in Atlanta, Georgia, USA. The state of Georgia is composed of four separate geologic areas, as illustrated in Figure 1: Piedmont; Blue Ridge, Coastal Plain, and Valley & Ridge /Plateau. As such, the natural soils and rocks, as well as compacted fills made from native geomaterials in these regions, can behave somewhat differently from each other because of their geologic origins. Atlanta is located in upper northwestern part of the state.

We can group the Appalachian Piedmont and Blue Ridge together due to their similarity. At one time, a range of mountains over 12 km in height dominated the region but have since essentially vanished due to extensive erosion, weathering, decomposition, and exposure to the elements over many millennia (Chew 1993). Parent bedrock is comprised primarily of gneiss and schist of Pre-Cambrian Z-age, with lesser amounts of igneous intrusives (granites) that appeared in Paleozoic times. The remaining terrain and ground conditions are underlain by residua that were derived by the in-place weathering of the metamorphic and igneous bedrock. The residual soils are often found to be silty, ranging from micaceous fine sandy silts to silty fine sands, that transition with depth to saprolites, partially-weathered rocks, and bedrock refusal. Locally, the layman's term for the upper few centimeters of native soils are called "Georgia red clay" due to the red-orange-tan colors due to iron oxides.

4 IN SITU TESTING PROCEDURE

Both invasive and non-invasive techniques were conducted at the W21 parking lot test site at the Georgia Tech campus for quantifying the shear wave velocity profile with depth. Figure 2 presents the schematics of the 3 geophysical methods conducted at the test site: (a) downhole test (DHT) via ASTM D 7400 using seismic piezocone testing with a large 25-tonne cone truck, (b) non-invasive multi-channel analyses of surface waves (MASW) test measuring Rayleigh waves; and (c) continuous-interval seismic piezocone test (CiSCPTu) with an autosource.

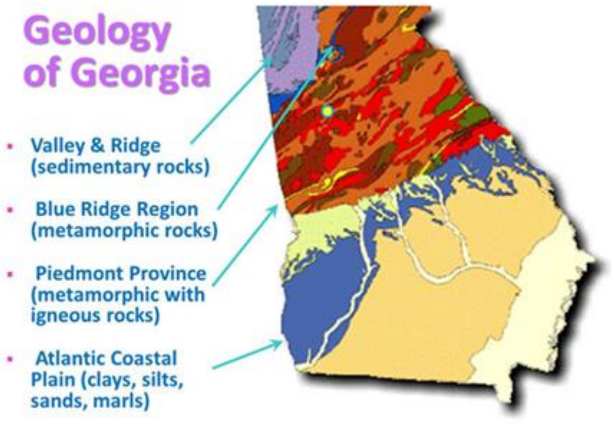

Figure 1. Geology of the state of Georgia.

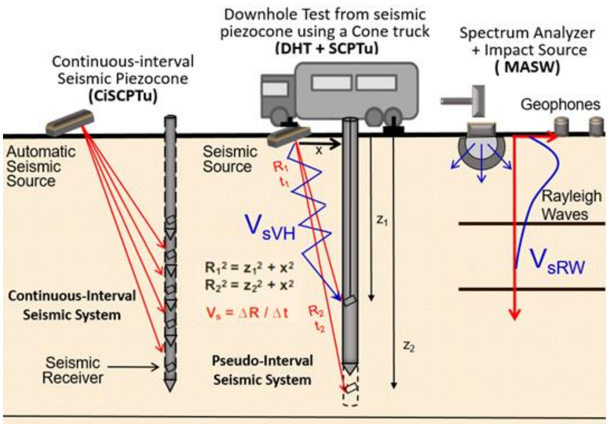

Figure 2. Schematic of different geophysical methods measuring V_s: Continuous-interval seismic piezocone test, Pseudo-interval seismic piezocone test, and non-invasive multi-channel analyses of surface waves test.

For the CiSCPTu carried out in 2015, a series of successive shear wave measurements were obtained using a rotoautoseis, a 15 cm^2 cone with a biaxial geophone positioned 0.2 m above the cone tip, and an equipped cone truck. The automated triggering system

provided uni-directional strikes for the series of continuous shear waves where it was situated at ground level with a horizontal offset of about 1m from the CPT rod string axis. Figure 3 presents successive raw shear wave signals recorded from special continuous-push where with the continuous pushing and advancement of the piezocone, shear wavelets are generated at the ground surface every 5 seconds.

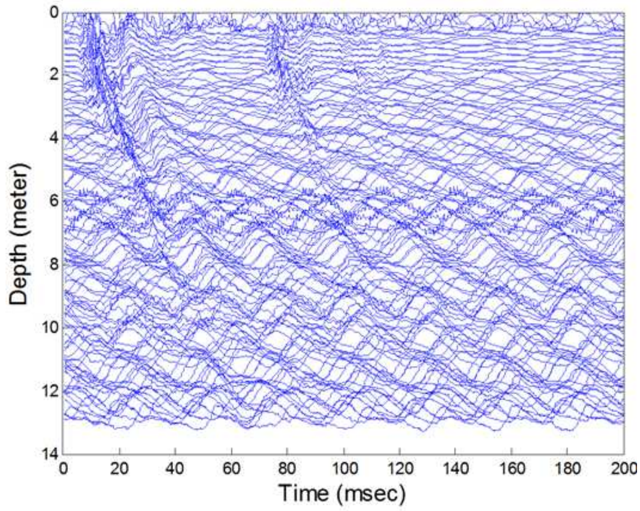

Figure 3. Successive raw continuous shear wave data from automatic seismic source at the Georgia Tech W21 test site.

The same cone truck and cone were used in conducting two standard seismic piezocone soundings (SCPTu-01 and SCPTu-02) with pseudo-interval arrays at 1-m depth intervals where paired sets of left and right strikes were accomplished using a sledge hammer and beam arrangement. Figure 4 presents the filtered 1-m interval paired left and right strike raw shear wave signals from SCPTu-01 that are used in evaluating the shear wave velocity profile. Downhole-type shear wave velocities can be calculated using the path length difference over a known time interval as shown in Figure 2. The results of the seismic piezocone readings (q_t, f_s, u_2, and 1-m interval V_s) from both soundings are presented in Figure 5 with a great agreement between the two soundings. Of additional note, SCPTu-01 was conducted in 2014 while SCPTu-02 performed in 2015.

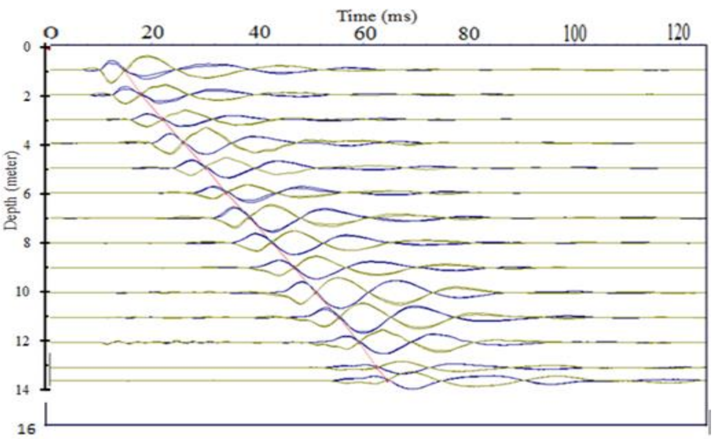

Figure 4. Filtered 1 m interval paired (left and right strike) shear wave signals from SCPTu-01 at the Georgia Tech W21 test site.

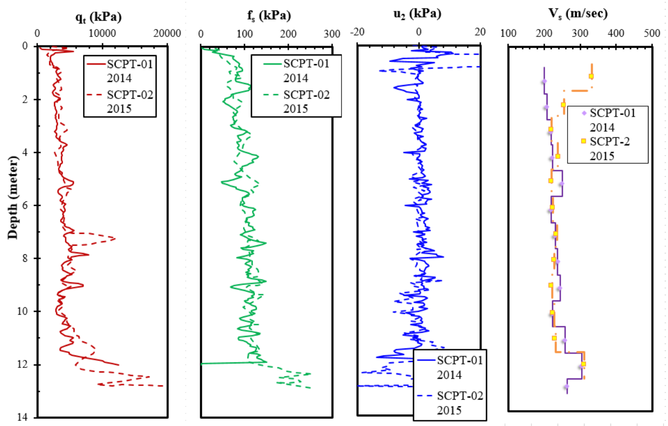

Figure 5. Results from conventional SCPTu soundings at Georgia Tech W21 test site: (a) cone tip resistance, (b) sleeve friction, (c) porewater pressure, and (d) shear wave velocity.

For the non-invasive MASW carried out in 2014, a spectrum analyzer with an impact source provided with 24 geophones were used in conducting the test. The geophones were equidistant at the ground surface and a sledge hammer was used to produce the surface wave and in seconds the wavelets were sensed using the geophones and recorded onto an on-site computer. The downhole shear wave velocity profile derived from the MASW test is plotted in Figure 6. This is shown in comparison with the conventional V_s profile from downhole testing at 1-m intervals from both soundings SCPTu-01 carried out in 2014 and SCPTu-02 carried out in 2015. It can be seen that the profiles of tests carried out in 2014 (i.e., MASW and SCPTu-01) show very good agreement, with values generally increasing from 200 m/s to about 300 m/s in the interval from the ground surface to about 13 meters. While for SCPTu-02, a clear increase in the magnitude of downhole shear wave velocity can be observed within the crust top 4 meters that can be attributed to the possibility of capillarity, desaturation, or effective stress changes in the vadose zone (soil above water table which was found to be at a depth of 12.5 meters in the location under study) where soils in unsaturated states may have an increase in the V_s at shallow depths (Cho & Santamarina, 2001).

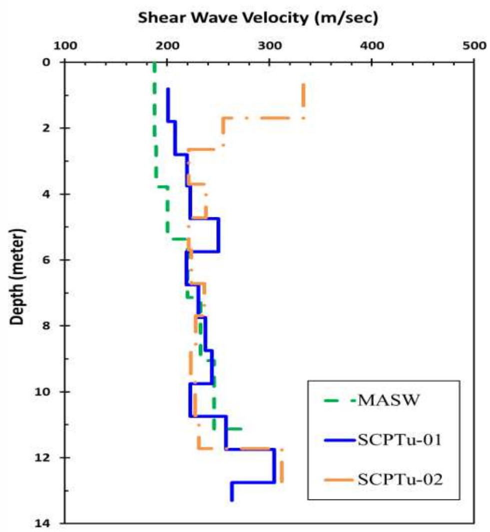

Figure 6. Downhole results showing a comparison of invasive (SCPTu) and non-invasive (MASW) shear wave velocity measuring techniques at the Georgia Tech W21 test site.

4 CONTINOUS SHEAR WAVE VELOCITY EVALUATION

4.1 *Signal Processing*

Shear wave time series signals should first be detrended and then filtered in order to eliminate any noise or interference in the measured wavelets. Detrending is a statistical operation for removing abnormal unexpected trends or any signal distortion such that the detrended raw data signals approach a baseline value. Filtering should be carefully conducted at the lowest possible level in both time and frequency domains to reduce the noise level (Santamarina & Fratta 1998, Ku et al. 2013a). In the current study, noise levels were mitigated using a band-pass filter to capture the desired frequency range of interest as presented in Figure 7 where a low- and high-cutoff frequency filter ranging from 150Hz to 350Hz was applied on the basis of visual examinations of fluctuations in signals.

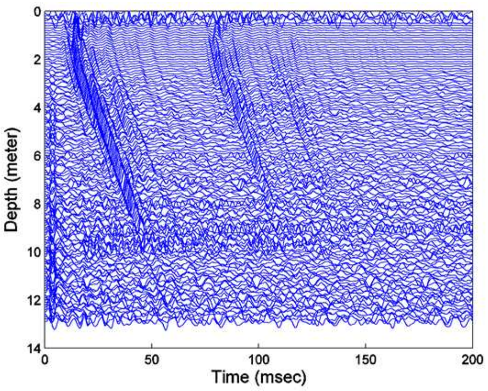

Figure 7. Successive continuous shear wave data after applying a band filter ranging from 150Hz to 350Hz.

After applying a band-pass filter to the raw wavelets, windowing was used to minimize the effect of spectral leakage of the data (Santamarina & Fratta 1998) and to provide better V_s evaluations for the cross correlation method (Liao & Mayne 2006). Figure 8 shows the filtered successive continuous shear wavelets after windowing where only the zone of interest for the expected main shear wave remains. Typically, a combined window using both a rectangular window for the majority of the signal and a hamming window for the tailing areas is applied.

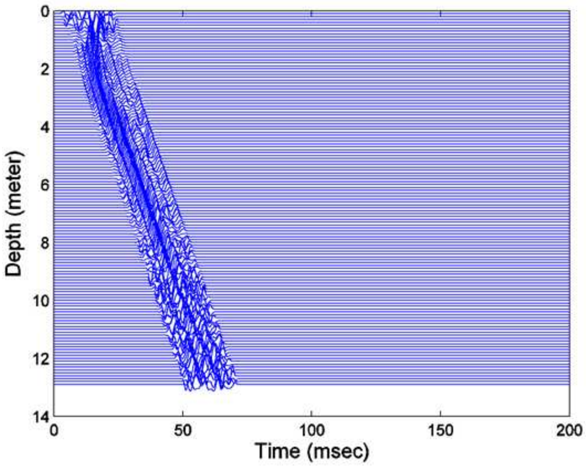

Figure 8. Successive continuous filtered shear wave data with window

After detrending, filtering, and windowing are completed, the cascaded continuous shear waves are evident and can be used for evaluating the shear wave velocity profile with depth. The simplest method in signal post processing and evaluation involve manually choosing the first arrival, first peak, and/or first crossover point. However, these manual methods are time consuming in the field work where paired opposite strikes are needed for the crossover and also time consuming in the evaluation process where the points are visually picked. Accordingly, cross correlation in the time domain and cross-spectral analysis in the frequency domain can be adopted using coded software packages such as MATLAB which is convenient in handling large amounts of data and can provide finer higher quality results.

4.2 *Cross Correlation Analysis in the Frequency and Time Domain*

This technique is usually recommended when successive wavelets have the same nature and characteristics, such as those that are generated with the rotoautoseis. The cross correlation function is used to evaluate the time shift between two independent wavelets by finding the lag time corresponding to the maximum covariance or maximum cross correlation in the time domain. The function reaches a maximum value when two consecutive signals that have similar shapes either overlap or coincide (Ku et al., 2013b).

The cross-spectral analysis is a technique used to identify the correlation between two time series at given frequencies (e.g., peak frequency). The analysis provides a phase spectrum in the frequency domain allowing the calculation of time shifts and phase velocities between two different wavelets. More details on the analysis technique can be found in Ku et al. (2013a, 2013b).

4.3 *Obtaining Final Corrected Continuous V_s Profile*

After applying both the cross-correlation and cross-spectral analyses on the filtered successive continuous shear wavelets, the results were somewhat sensitive and scattered. This can be attributed to different factors and issues that arise during the in-situ testing procedure, or also in the post-processing analyses such as the extremely short time lapse, cone penetration test rate variants, unfiltered noise, and the possibility of refracted and reflected signals. Hence, to obtain a representative corrected V_s profile with depth, a running-mean filter coefficient vector for the time interval (Δt) is applied for the V_s profiles obtained from both analyzing techniques. A special zero-phase forward and reverse digital filtering technique is used following the recommendations of Trauth (2010). By increasing the order of the running-mean filter (10^{th} in the presented study), a more accurate and a less scattered V_s profile with depth is obtained.

4.4 *Comparison of V_s Evaluation Methods*

Figure 9 shows the evaluated V_s profiles with depth for the different testing techniques carried out at the Georgia Tech test site. Both of the derived continuous V_s profiles using cross-correlation and spectral analysis seem to match well with the reference downhole test using the SCPTu and the MASW test data when adopting the 10^{th} order running mean filter. By comparing the different methods, a slight difference in the shear wave velocity magnitude can be observed which be attributed to time effects causing possible desaturation or water level fluctuations that can cause an increase in the shear wave velocity magnitude over time. Despite the presence of some minor deviations, all four evaluation methods show overall good agreement in the V_s profiles.

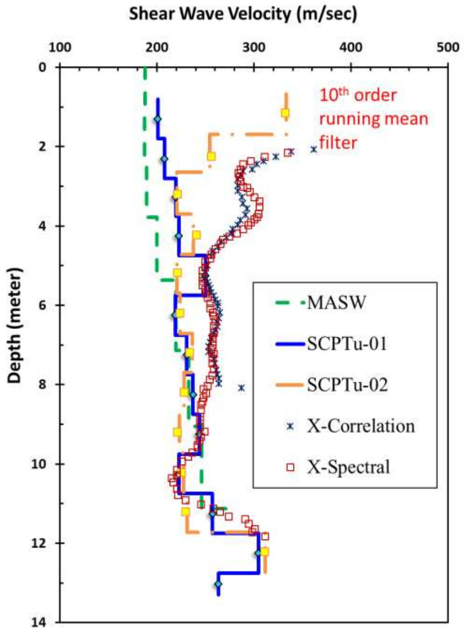

Figure 9. Downhole results showing a comparison of various shear wave velocity measuring techniques: MASW, SCPTu, and CiSCPTu using x-correlation and x-spectral methods.

5 SUMMARY AND CONCLUSIONS

A new W21 test site at the Georgia Tech campus was used to compare different geophysical techniques for measuring shear wave velocity profiles with depth in residual sandy silts to silty sands of the Appalachian Piedmont geology. The non-invasive technique of MASW test was carried out using 24 geophones measuring shear wave velocity from Rayleigh wave measurement with depth. Invasive techniques carried out at the test site included 2 conventional downhole tests (DHT) via SCPTu soundings (conducted two years apart) using a large cone truck and a pseudo-interval seismic system. In addition, a continuous-interval seismic piezocone test (CiSCPTu) using the electromechanical rotoautoseis to provide repeatable strikes approximately every 5 seconds.

The successive raw shear wavelets were detrended, filtered, and windowed. The filtered shear waves were analyzed using both the cross correlation method in the time domain and the cross-spectral analysis in the frequency domain, followed by the application of a high order running-mean filter. Both methods provided very comparable and consistent results when compared to the conventional 1-m interval downhole data and the non-invasive MASW data.

The successive signals generated by the continuous-push seismic system every 0.1 m are finer and more accurate with lower scatter, providing better more detailed resolution that can be used in geologic profiling.

6 REFERENCES

Agaiby, S.S. & Mayne, P.W. 2015. Relationship between undrained shear strength and shear wave velocity for clays., Proceedings of the 6th International Symposium on Deformation Characteristics of Geomaterials, Buenos Aires, Argentina), Vol. 6, IOS Press, Rotterdam: 358-364.

Anderson, D. G., & Stokoe, K. H., 1978. Shear modulus: A time-dependent soil property. *Dynamic Geotechnical Testing*, Special Technical Publication 654, American Society for Testing & Materials, West Conshohocken, PA: 66-90.

Chew, V.C. (1993). Underfoot: a geologic guide to the Appalachian Trail. second edition, *Proc. Appalachian Trail Conference*, Harpers Ferry, West Virginia, 237 p.

Cho, G.C. & Santamarina, J.C. 2001. Unsaturated particulate materials-particle-level studies. *Journal of Geotechnical and GeoEnvironmental Engineering*, 127(1): 84-96.

Ku, T. & Mayne, P.W. 2012. Frequent-interval SDMT and continuous SCPTu for detailed shear wave velocity profiling in soils. *Geotechnical Engineering Journal*, 43(4), South East Asian Geotechnical Society: 34-40.

Ku, T., Mayne, P.W & Cargill, E. 2013a. Continuous-interval shear wave velocity profiling by auto-source and seismic piezocone tests. *Canadian Geotechnical J.* 50(1): 382–390.

Ku, T., Weemees, I., Cargill, E., Mayne, P.W. & Woeller, D. 2013b. Post-processing continuous shear wave signals taken during cone penetrometer testing. ASTM *Geotechnical Testing J.* 36(4): 543-553.

Landon, M.M., DeGroot, D.J. & Jakubowski, J. 2004. Comparison of shear wave velocity measurements in-situ and on block samples of a marine clay. *Proceedings of the 57th Canadian Geotechnical Conference (GeoQuebec 2004):* Session 4E: 22-28.

Liao, T. & Mayne, P.W. 2006. Automated post-processing of shear wave signals, *Proc. 8th US National Conference on Earthquake Engineering*, San Francisco, pp. 460.1-460.10

Mayne, P.W. & McGillivray, A.V. 2008. Improved shear wave measurements using autoseis sources. *Deformational Characteristics of Geomaterials*, Vol. 2 (Proc. 4th ISDCG, Atlanta), Millpress/IOS Press, Amsterdam: 853-860.

Mayne, P.W. 2005. Invited keynote: Integrated ground behavior: in-situ and lab Tests, *Deformation Characteristics of Geomaterials*, Vol. 2 (Proc. IS Lyon'03). Taylor & Francis Group, London, UK: 155-177

McGillivray, A.V. & Mayne, P.W. 2008. An automated seismic source for continuous shear wave profiling. *Geotechnical & Geophysical Site Characterization,* (Proc. ISC-3, Taipei), Taylor & Francis Group, London: 1347-1352.

Moon, S.W., Khan, Q., & Ku, T. 2015. Shear wave velocity based estimation of soil unit weight and undrained shear strength on soft ground. *Proc. International Conference on Soft Ground Engineering (ICSGE2015)*, Research Publishing, Singapore: 853-861.

Santamarina, J.C. & Fratta, D. 1998. *Introduction to Discrete Signals and Inverse Problems in Civil Engineering*, ASCE, Reston, VA.

Tatsuoka, F., 1992. Deformation characteristics of soils and rocks from field and laboratory tests. *Proc. 9th Asian Regional Conf. Soil Mechanics and Foundation Engrg.*, 2, 101-170.

Trauth, M.H. 2010. *MATLAB Recipes for Earth Sciences*, 3rd ed., Springer, New York.

Wightman, W., Jalinoos, F., Sirles, P., & Hanna, K., 2003. Application of geophysical methods to highway related problems, *Report No. FHWA-IF-04-021*, Federal Highway Admin., Washington, DC: 742 pp.