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Seismic flat dilatometer tests in Piedmont residual soils

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ABSTRACT: A hybrid test combining the conventional flat dilatometer with downhole geophysical testing has been developed and referred to as the seismic flat dilatometer test (SDMT). Downhole seismic velocity measurements have been incorporated with a flat dilatometer by placing a velocity transducer in a connecting rod just above the blade. The seismic dilatometer test has the exceptional advantages of determining both estimates of soil properties and stratigraphic information, while also measuring the shear wave velocity (V_s) within a single sounding. The hybrid test is rapid, simple, and cost-effective requiring essentially no more time than a conventional dilatometer sounding. The seismic dilatometer was field tested in the Piedmont residual soils of eastern Alabama with the shear wave velocity results compared with adjacent seismic piezocone profiles, crosshole geophysical arrays, and spectral analysis of surface waves (SASW).

1 INTRODUCTION

The seismic flat dilatometer test provides excellent potential for efficient geotechnical site investigation. Many field and laboratory studies within the past sixteen years have shown the dilatometer interpretations of stratigraphy, material classification, and strength parameters to be reasonable and reliable with site specific calibration (Lutenegger 1988). With the addition of a velocity transducer, nondestructive properties such as shear wave velocity, shear strain, and small-strain shear modulus can be measured directly with minimal additional time and effort. The seismic measurements provide information about the small-strain behavior of the soil which is essential for analysis of monotonic loading (such as foundations), liquefaction analysis, evaluating dynamically loaded foundations, and earthquake engineering problems. A prototype seismic dilatometer was fabricated at Georgia Institute of Technology (Kates 1996). The seismic dilatometer was field-tested in the Piedmont residual soils near Opelika, Alabama, with the shear wave velocity results compared with adjacent seismic piezocone profiles (SCPT), crosshole geophysical arrays (CHT), and spectral analysis of surface waves (SASW).

2 SEISMIC DILATOMETER TEST SETUP

The test apparatus of the seismic flat dilatometer consists of a traditional standard stainless steel high-strength blade, internally-wired plastic tubing, and a dual-gage pressure control panel. Regulated compressed nitrogen is used to expand the membrane and obtain the lift-off (p_0) and expansion (p_1) pressures. Seismic capabilities are facilitated by the addition of a velocity transducer positioned 0.25 m above the center of the dilatometer membrane. The receiver geophone is a Geospace type 14 model L9 with a natural frequency of 28 Hz and sensitivity of 0.236 volts/cm/sec. The trigger geophone, which is a Mark Products model L-15A, is attached to the source plank to determine the start time of the shear wave. Both geophones are connected to an oscilloscope to evaluate the travel time of the wave from the source to the receiver. A portable matrix-dot printer is used to print each wave for later reference. A schematic of the field setup for the seismic dilatometer is provided as Figure 1.

The co-axial receiver geophone cable has been taped to the standard DMT tubing so that the threading process through the push rods takes minimal additional time. The receiver geophone is added to the adapter rod (which connects the blade

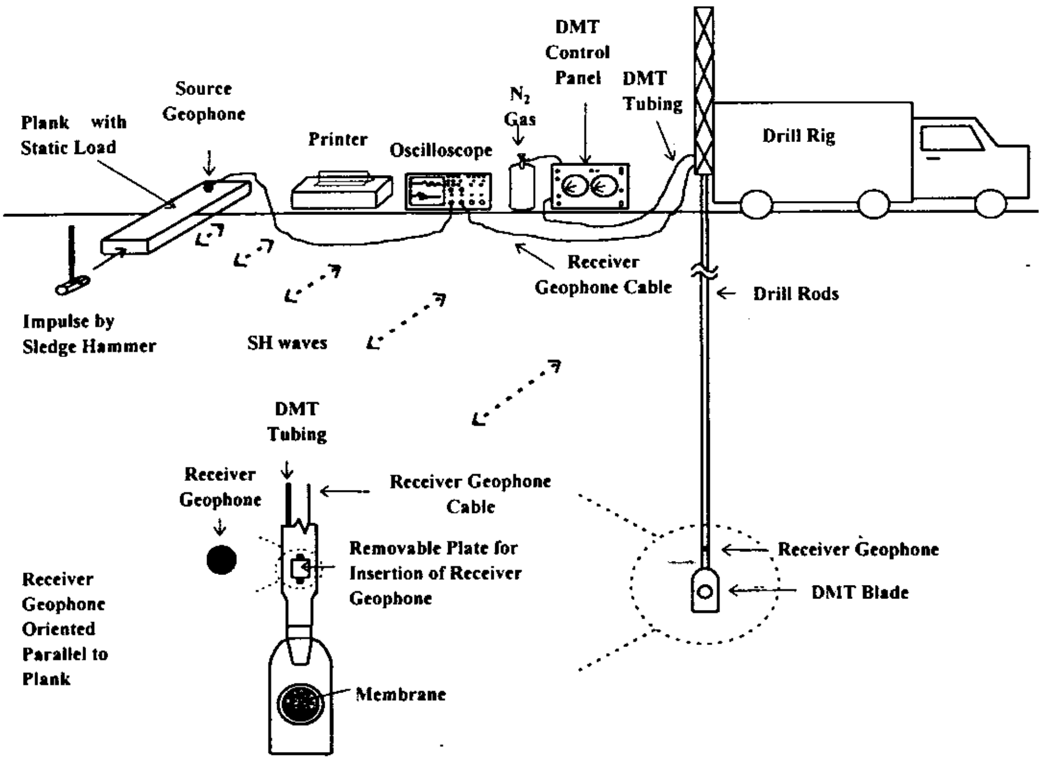

Figure 1. SDMT Test Setup.

to the push rods) by dismantling a section that was machine-cut from the rod. The plate is removed simply by loosening two set screws. With the geophone secured against the inner wall of the rod, excellent soil-to-receiver contact is assured. Once the geophone is inserted and cable connected, the test is ready to proceed.

The seismic dilatometer test progresses as a traditional flat dilatometer sounding with the wave travel time measurements taken at the short pause for each successive push rod to be added. The flat blade is pushed vertically in the ground, usually by hydraulic force, stopping at particular intervals to measure the lift-off (p_0) and expansion (p_1) pressures of the membrane (Schmertmann 1986). During the addition of each push rod (generally 0.9 m intervals), shear waves are sent through the subsurface media to determine the wave travel time. The shear wave source used for the seismic dilatometer tests was a horizontal wood board. A static load over a wooden plank assists in producing waves rich in shear and weak in compression. Prior to loading the source, any thick surface vegetation or gravel particles should be removed so that the plank is in direct contact with the soil.

Alignment of the shear wave source with consideration of the orientation of the geophone is essential to receive a signal with minimal interference from the faster compression waves. Because shear waves propagate perpendicular to the direction of particle motion, the shear wave source should be aligned perpendicular to the direct travel path of the shear waves to the dilatometer hole as seen in Figure 1. The amount of compression waves detected by the receiver geophone is minimized with this arrangement because compression waves propagate parallel to particle motion away from the receiver.

The trigger geophone is attached to the wooden plank to signal the start time of the impulse and the receiver geophone within the adapter rod signals the arrival of the shear wave down the hole at the known depth. The travel time of the wave is determined as the time difference in the initial responses of the trigger and receiver signals. Several travel time measurements at each depth were made to assure repeatability and reliability of the data. The wave signals at each depth were recorded for later reference by downloading to a printer.

The shear wave velocity determined from this version of the seismic dilatometer is the pseudo-interval velocity. That is, the difference in travel distance at two consecutive test depths is divided by the difference in arrival time for the two depths. Travel times are determined from two separate wave measurements with the same receiver in different vertical locations. Another method to calculate the shear wave velocity is the true-interval method. In order to obtain the true-interval velocity, two receivers located at a set distance apart are used simultaneously. The difference in the initial responses from the two receivers can be measured directly on the oscilloscope from a single impulse. Less test error is associated with the true-interval method because the travel time is determined from a unique wave (Burghnignoli et al. 1991). Additionally, the travel time does not have to be assessed from the more disrupted first arrival. The first arrival of the shear wave is often difficult to choose due to interference from the faster compression wave and other subsurface waves (refracted waves, Love waves, etc.). Using the true-interval method can also eliminate errors associated with the trigger signal. A major drawback of the true-interval method is the added complexity and cost due to the necessity of at least two receiver geophones and coaxial cables as well as a multi-channel oscilloscope. Differences between results using the pseudo- and true-interval velocities were found to be less than 10% by Robertson et al. (1986).

The pseudo-interval velocity is a much more cost effective means to evaluate the shear wave velocity of soils. Only one geophone and cable is added to the test set up and threading process. Also, simple signal conditioners may be used rather than the more complex and expensive multi-channel oscilloscopes required for the true-interval method. However, some errors may be introduced due to trigger delays, interpretation of the first arrival of the shear wave, and variable impulses when utilizing the pseudo-interval method.

3 FIELD TESTS AT OPELIKA, ALABAMA

The geology of the Opelika test site is referred to as the Piedmont province (Figure 2). The Piedmont region is neighbored by the Blue Ridge on the west and Atlantic coastal plain on the east and extends from Pennsylvania southwest into Alabama. The subsurface materials are generally composed of silty to sandy residual soils underlain by partially weathered rock. Residual soils have resulted from the chemical and physical weathering of the underlying parent rock formations which consist of Paleozoic metamorphic and igneous rocks, primarily schists, gneisses, and granites. The weathering process is accelerated in the southeast due to the temperate to warm climate, abundance of rainfall, established vegetation, and lack of glaciation of the region (Sowers and Richardson, 1983). The subsurface profile in the Piedmont region generally consists of an upper zone of completely weathered soil, an intermediate zone made up of saprolite with soil texture, a partially weathered zone with alternate seams of soil and rock, followed by a natural to slightly weathered rock (Martin, 1977). At the Opelika test site, the overlying silty to sandy soils are believed to be derived from schists and gneisses.

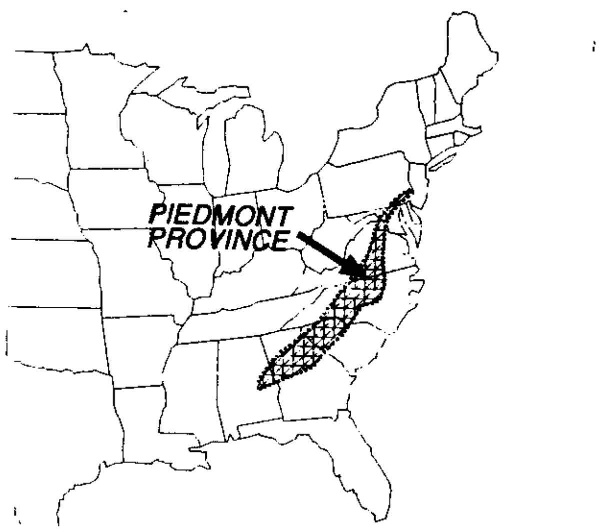

Figure 2. Location of the Piedmont Province.

Three seismic dilatometer soundings were performed at the Opelika test site in August of 1996. A Diedrich D50 drill rig was utilized to push the blade from the surface to test depths of approximately 8 m. The blade was not pushed to further depths because the drill rig was light and could not supply an adequate reaction force or provide sufficient lateral support to prevent buckling instability of the push rods. The dilatometer can generally be pushed to the vicinity of bedrock based on previous experience with larger drill rigs more commonly used for in-situ push tests.

Lift-off (p_0) and expansion (p_1) pressures were measured at 0.3 m intervals. The shear wave velocity (V_s) was calculated based on the responses of the trigger and receiver geophones, as previously described. Figure 3 provides the raw data from the three seismic dilatometer tests performed at the Opelika test site.

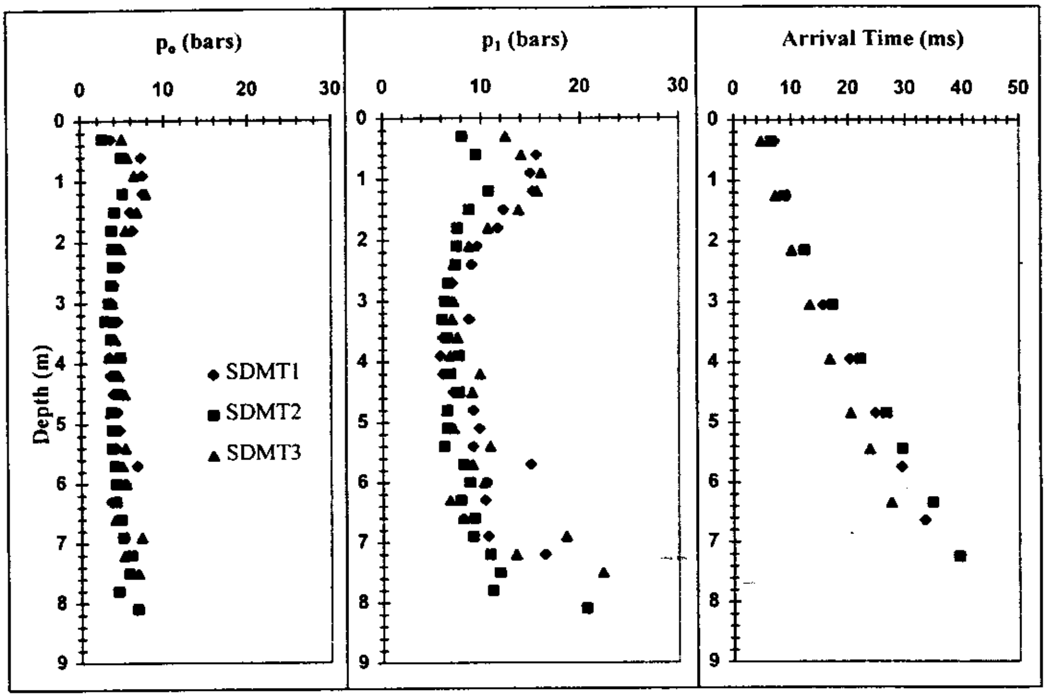

Figure 3. Raw SDMT Data at Opelika, Alabama.

The Opelika test site was advantageous for demonstrating the applicability and validity of the SDMT for in-situ characterization due alternate data collected for cross-comparison. Soil borings, cone penetrometers, and laboratory tests were performed to evaluate the subsurface stratigraphy and strength characteristics for the site. Several tests in addition to the SDMT were performed to evaluate the seismic characteristics of the soils.

The shear wave velocities measured using the seismic dilatometer were compared with results from seismic piezocone tests, a geophysical crosshole test, and a SASW survey. Both the SCPTs and SDMTs were performed in a downhole manner with the source remaining at the surface and a single receiver pushed to various depths in the subsurface. Due to using only one receiver, the velocity calculated is the pseudo-interval. The shear waves for the two direct-push seismic tests were instigated by striking a horizontal plank with a sledge hammer. Therefore, the waves were horizontally-polarized shear waves (SH-waves). Perhaps the most significant advantage of the SCPT and SDMT is that statigraphic and strength information are collected in conjunction to the shear wave velocity measurements in a single sounding.

The crosshole tests consisted of three aligned boreholes cased with plastic pipe and grouted in place. The downhole source and two receivers were lowered into the holes to equal depths and clamped in place using pneumatically inflatable rubber packers. The source produced vertically-polarized shear waves (SV-waves). The shear wave velocities computed from the crosshole tests are the direct-velocities. That is, the velocity is calculated as the measured travel time divided by the measured travel distance for a single impulse. The shear waves are assumed to travel along a horizontal path from the source to the receiver. Crosshole tests are generally considered the bench mark test for shear wave velocity measurements but can sometimes be costly and time consuming due to the laborious procedure of drilling, casing, and grouting the boreholes.

Spectral analysis of surface waves (SASW) is a nonintrusive method of measuring the shear wave velocity profile. Geophones are placed at multiple spacings to evaluate surface waves (Rayleigh waves) with a range of frequencies to decipher the shear wave velocity. A numerical inversion of the data is required for interpretation.

4 INTERPRETATION OF RESULTS

Stratigraphic information gathered from the dilatometer tests agree relatively well with laboratory tests and other in-situ tests performed at the site. The visual classification from the boring logs generally identified the upper two meters as a

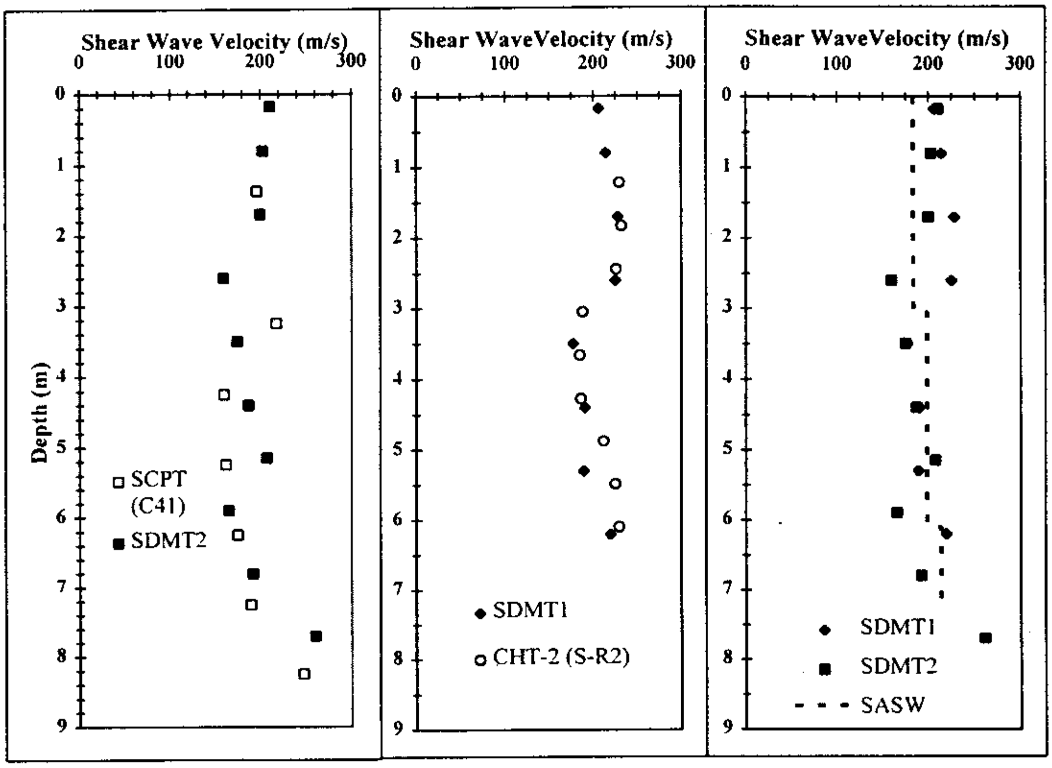

Figure 4. SDMT Shear Wave Velocity compared with SCPT, CHT, and SASW.

very stiff clay and silt with an average blow count (N) value of 13 blows/0.3 m. The material index values from the dilatometer indicated this region to be composed of silty sand to silt. Laboratory analyses of samples retrieved from depths of less than 3 m generally indicated a silty fine sand material, agreeing with the classification from the dilatometer. Laboratory tests and boring log information denote the soil in the 2 to 7 m zone to be primarily composed of a silty sand. The dilatometer classification and laboratory analyses registered the material in this zone as a sandy silt.

Seismic dilatometers SDMT1 and SDMT2 were performed approximately 1.5 m away from two seismic piezocones tests. The SDMTs were placed very close to seismic piezocone soundings in an attempt to decrease the impact of soil variability on the measured shear wave velocities of the two tests. These tests were also relatively close to the crosshole and SASW tests.

Figure 4 presents a comparison of the shear wave velocity profiles determined using the seismic dilatometer with the profiles from the seismic piezocone penetrometer, crosshole test, and SASW test. Shear wave velocity measurements from seismic dilatometer tests agree well with results from the other seismic tests performed at the site. Because the seismic cone and the seismic dilatometer are both downhole tests with a single receiver measuring horizontally polarized shear waves (SH-waves), the velocity profiles are expected to compare favorably.

Shear wave velocities measured by the SDMT compare favorably with neighboring crosshole results displaying a similar trend and values. However, the measurement from the crosshole test are not expected to display an exact agreement with the SDMT due to differing test setups (downhole measurements with a single receiver versus crosshole measurements with two receivers) and measuring waves that propagate in different directions.

The SASW measurements agree well with the SDMT results as seen in Figure 4. In a more non-homogenous material, the velocity measurements from downhole tests and SASW would most likely not agree as well due to the averaging mechanisms of SASW and analyzing larger volumes of the material. Additionally, SASW evaluates a different wave form than the SDMT test.

Velocity profiles from each test method are shown together in Figure 5. The general shear wave velocity trend for the upper 8 meters is around 200 m/s. The difference between the shear wave velocity measured using the SDMT and other test methods was generally less than 25 m/s and

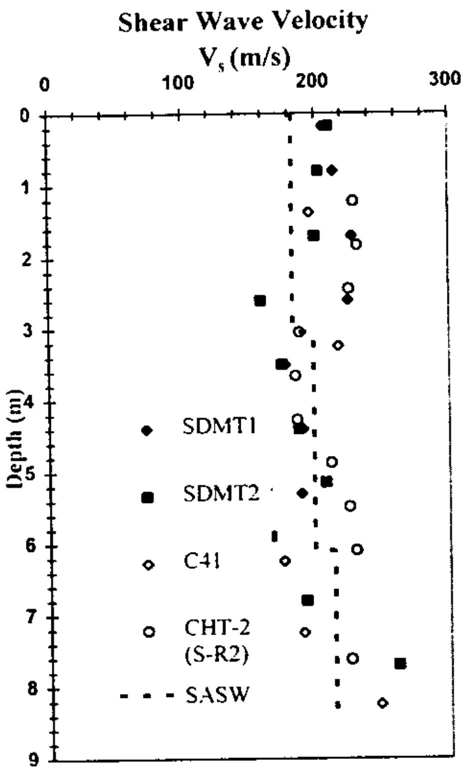

Figure 5. Comparison of Measured Shear Wave Velocities at Opelika, Alabama.

never more than 75 m/s. Considering soil variability, error introduced by averaging mechanism of pseudo-interval method, resolution limitations of electronics, operator judgment of picking the first arrival, and different operators for each test, the velocity profiles for the Opelika test site display acceptable agreement. The validity of the downhole measurements of the seismic dilatometer test for evaluating the shear wave velocity of soils is confirmed by the correspondence with existing geophysical tests such as the seismic piezocone, the crosshole test, and SASW.

5 APPLICATIONS OF THE SDMT

The seismic flat dilatometer test provides a simple and cost effective means for stratigraphic delineation and assessing soil stiffness and strength parameters for low-, intermediate-, and high strain conditions. The conventional flat dilatometer test provides an evaluation of the undrained shear strength (s_u) in clays and the effective friction (ϕ') angle in sands. With the addition of a velocity transducer, downhole geophysical measurements can be performed to directly measure the shear wave velocity (V_s). Shear wave velocity of soil is a nondestructive property that is useful for solving problems involving earthquake engineering, dynamically-loaded foundations, assessment of liquefaction susceptibility, and for determining the small-strain shear modulus (G_{max}) of the soil. In addition to dynamics applications, the stiffness of soils at low strain levels is also relevant to monotonic deformation problems, such as foundation settlement (Burland, 1989).

6 CONCLUSIONS

A seismic dilatometer apparatus was constructed and field tested at a residual silty sand site in Opelika, Alabama. Conventional dilatometer data compared well with material classification and strength parameters from field and laboratory tests. Validity of downhole shear wave velocity profiles was confirmed by comparison with existing in-situ tests such as seismic piezocone tests, crosshole arrays, and SASW surveys.

7 REFERENCES

Burghignoli, A., Cavalera, L. and Chieppa, V., (1991). "Geotechnical Characterization of Fucino Clay," *Proceedings*, 10th European Conference on Soil Mechanics and Foundation Engineering, Vol. I, Firenze, pp. 27-40.

Burland, J.B., (1989). "Small is Beautiful: The Stiffness of Soils at Small Strains," *Canadian Geotechnical Journal*, Vol. 26, No. 4, pp. 499-516.

Kates, G. (1996). "Development and Implementation of a Seismic Flat Dilatometer Test for Small- and High- Strain Soil Properties," MS Thesis, Georgia Institute of Technology, Department of Civil and Environmental Engineering.

Lutenegger, A.J., (1988). "Current Status of the Marchetti Dilatometer Test," *Proceedings*, ISOPT 1, Orlando, Vol. 1, Balkema, Rotterdam, pp. 137-155.

Martin, R.E., (1977). "Estimating Foundation Settlements in Residual Soils," *Journal of Geotechnical Engineering*, Vol. 103, No. GT3, pp. 197-212.

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*, Vol. 112, No. 8, pp. 791-803.

Schmertmann, J.H., (1986). "Suggested Method for Performing the Flat Dilatometer Test," *Geotechnical Testing Journal*, Vol. 9, No. 2, pp. 93-101.

Sowers, G.F. and Richardson, T.L., (1983). "Residual Soils of the Piedmont and Blue Ridge," *Transportation Research Record*, No. 919, pp. 10-16.