A COMPARISON OF SHEAR WAVE VELOCITIES OBTAINED FROM THE CROSSHOLE SEISMIC, SPECTRAL ANALYSIS OF SURFACE WAVES AND MULTIPLE IMPACTS OF SURFACE WAVES METHODS

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Abstract

Presented herein is the comparison of the shear wave velocity results, with respect to depth, obtained from three separate test methods at a soil test site. The Crosshole Seismic (CS) test was performed utilizing three cased boreholes nominally 10 feet apart. The direct shear wave velocity was obtained from the results of the CS test. The Spectral Analysis of Surface Waves (SASW) test method and Multiple Impact of Surface Waves (MISW) test method were also performed at the same test site for comparison purposes. Neither the SASW nor MISW test methods require the installation of boreholes, thus reducing the cost of the test. SASW and MISW differ slightly from one another in the equipment used, method of data collection, and differ significantly in data processing. This paper includes a comparison and discussion of the test results, as well as backgrounds of each test method.

Introduction

Construction of foundation systems for civil structures often requires detailed information of the site soil properties. Bore logs provide soil samples for soil type classification and laboratory testing to determine strength and consolidation parameters among other properties with respect to depth. A number of soil-boring related in-situ tests have also been correlated with soil strength (e.g. standard penetration test, cone penetration test), however in the interest of accuracy it is certainly advantageous to measure a in-situ soil property directly related to soil modulus. Shear wave velocity (V_s) has become the standard property from which in-situ soil modulus is determined due to its direct relationship with modulus via the soil mass density (which can be assumed with little error or easily measured from soil samples) as well as it's relative ease of measurement, due to the advancement of seismic techniques.

A number of in-situ test methods have been developed to measure V_s with respect to depth; within this paper, three methods, Crosshole Seismic (CS), Spectral Analysis of Surface Waves (SASW), and Multiple Impact of Surface Waves (MISW), will be described and compared. Traditionally, CS testing has been considered the most accurate method in determining V_s, because it is a direct measurement of the wave speed. SASW and MISW however, can be employed much more rapidly and economically because the methods are performed on the ground surface (unlike CS where at least two boreholes are required to perform the testing). Yet, no known research has been performed to directly compare the accuracy of the latter two methods to equivalent CS results. With this objective, all three tests were performed at the same soil site for direct data comparison.

Test Method Background

Crosshole Seismic (CS) Test Method

The Crosshole Seismic (CS) method is designed for determining the variation of in-situ shear and compressional wave velocities of soils and rock with depth. In the CS tests, typically 3 boreholes (2 minimum) are drilled to allow performance of the test per American Society for Testing and Material (ASTM) Standard No. D4428/D4428M. For this site, 3 boreholes were used. The boreholes were nominally 10 feet apart in a straight line. A 3-inch inner diameter PVC casing is then placed in each borehole and is then grouted in place to provide good contact with the surrounding soil (note casing diameter and type may vary). Good casing-to-soil contact is essential to allow sufficient shear wave energy to travel from the source to receiver and be recorded.

If the casings are more than 50 feet in depth it is required by the ASTM standard that the verticality of each hole be measured. This can easily be done with a slope inclinometer or borehole deviation device. The purpose of this measurement is to locate each borehole in 3-dimensional space and thereby obtain borehole-to-borehole straight-line distances for each test depth. These straight-line distances are then used for compressional and shear wave velocity calculations. In this case, due to the depth of the casings, the casing verticality measurement was not performed. Therefore, the spacing between the boreholes used in the data analysis was measured at the ground level.

To start the testing, the electro-mechanical source (EMS) was lowered and seated at the first measurement depth, 3 feet below grade, in one borehole. The two receivers, each a triaxial geophone, were then lowered to the same depth in the adjacent boreholes and coupled to the casing by pumping up an air bladder in each (see Figure 1). The Crosshole Seismic (CS) tests involved firing the solenoid source to generate compressional and shear wave energy. Shear wave energy reversals (polarizations) were measured by firing the EMS in both the upward and downward directions. The CS tests were performed at 5-foot intervals starting at a depth of 3 feet and ending at a depth of 51.5 feet. The data was acquired and recorded with an Olson Instruments Freedom Data PC.

The shear and compressional wave velocities were calculated using the following equations from the source to receiver and receiver to receiver boreholes:

$$V_S = SR/t_s$$
$$V_P = SR/t_p$$

where V_S is the shear wave velocity, SR is the distance between the source and receiver boreholes or between the two receiver boreholes, t_s is the travel time of shear waves, V_P is the compressional wave velocity, and t_p is the travel time of the compressional wave. Calculation of shear and compressional wave velocities between the receiver boreholes is equal to the distance between the boreholes divided by the wave travel arrival time differences. The shear modulus (G) and the constrained modulus (M) can then be calculated by:

$$G = \varrho * V_s^2$$
$$M = \varrho * V_p^2$$

where ϱ is the mass density (unit weight divided by gravity). For this investigation computations of G, E or M were made based on an assumed soil density of 120 pounds/cubic foot (pcf).

Poisson's ratio (ν) and Young's modulus (E) can also be calculated from CS test data by employing the relationships shown below:

$\nu = [0.5 * (V_p/V_s)^2 - 1] / [(V_p/V_s)^2 - 1]$
$E = 2G(1+\nu)$

However, for the purpose of this paper data presentation is limited to shear wave velocities.

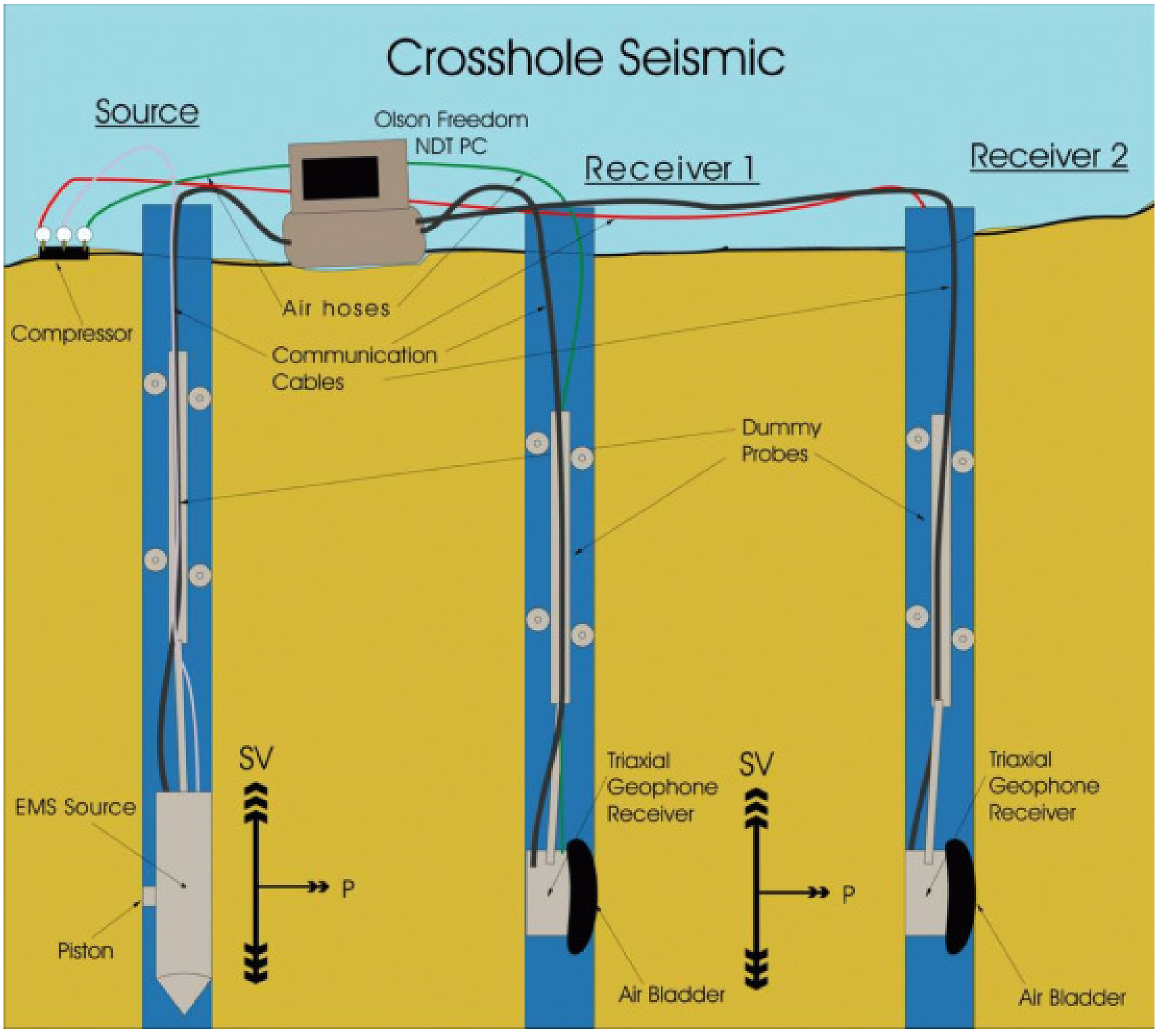

Figure 1: Crosshole Seismic experimental set-up.

Spectral Analysis of Surface Waves (SASW) Test Method

The SASW method uses the dispersive characteristics of surface waves to determine the variation of the surface wave velocity (stiffness) of layered systems with depth (Heisey et al. 1982). Shear wave velocity profiles can be determined from the experimental dispersion curves (surface wave velocity versus wavelength) obtained from SASW measurements through a process called forward modeling (an iterative inversion process to match experimental and theoretical results). The SASW method can be performed on any material provided an accessible surface is available for receiver mounting and impacting.

The extent of the accessible surface limits the investigation depth. As a rule of thumb, if one is interested in material properties to a depth of D, then the accessible surface should extend in a line of receivers to a distance equal to 0.5D or more. Generally, high frequency or short wavelength waves penetrate through shallow depths, and low frequency or long wavelength waves penetrate through deeper depths. A typical SASW test on a soil site comprises of two receivers (typically geophones) and an excitation source (typically a sledge hammer or large drop weight). The receivers are placed at a set distance apart (d), the soil surface is excited with the source at a distance of d from one of the receivers so that the source and two receivers are in a straight line. Several impacts are recorded and averaged to improve accuracy. The distance d determines how deep into the ground the test method will be able to resolve data for. Typically, multiple spacings (e.g. 2 ft, 4 ft, 8 ft, 16 ft, etc) are required to develop an accurate shear wave velocity profile with depth. The known distance between receivers and the measured phase difference between the surface waves at the two receivers are used to determine the shear wave velocity profile. Data was acquired and recorded with an Olson Instruments Freedom Data PC.

Similar to CS testing, the shear wave velocity profiles determined in SASW testing can easily lead to direct calculation of soil parameters such as modulus and poisson's ratio. The parameters determined from seismic measurements (SASW measurements) represent the material behavior at small shearing strains, i.e. strains less than 0.001 percent. Thus, moduli calculated from compression, shear or surface wave velocities represent the maximum moduli of materials because of their low strain levels. It should be noted that the measurement of the surface wave velocity, also called Rayleigh wave velocity, is actually performed in the SASW test. Surface wave velocity (V_R) in a homogeneous half-space is related to shear wave velocity by (the exact equation is given in numerous geophysical textbooks):

$$V_R \sim 0.9\ Vs$$

Multiple Impacts of Surface Waves (MISW) Test Method

SASW and MISW differ slightly from one another in the equipment used, method of data collection, and differ significantly in data processing. MISW is a data acquisition technique used to obtain a multichannel equivalent record of seismic data using only one receiver (Ryden et al. 2004). After data acquistion the multichannel equivalent record is treated as a true multichannel record and the Multichannel Analysis of Surface Waves (MASW) (Park et al. 1998; Park et al. 1999) is used for further analysis.

In the MISW data acquisition technique a receiver (typically a geophone) is set in the ground. The source is then used to excite the ground surface at a distance, d, away from the receiver. Several impacts are recorded and averaged to improve accuracy. The distance, d, is then increased and the processes is repeated. This process can be repeated as necessary to increase d and thus the depth to which shear wave velocities can later be calculated.

Data Analysis and Results

Example Data and Analyis

Example data from the CS test performed on-site is displayed in Figure 2.

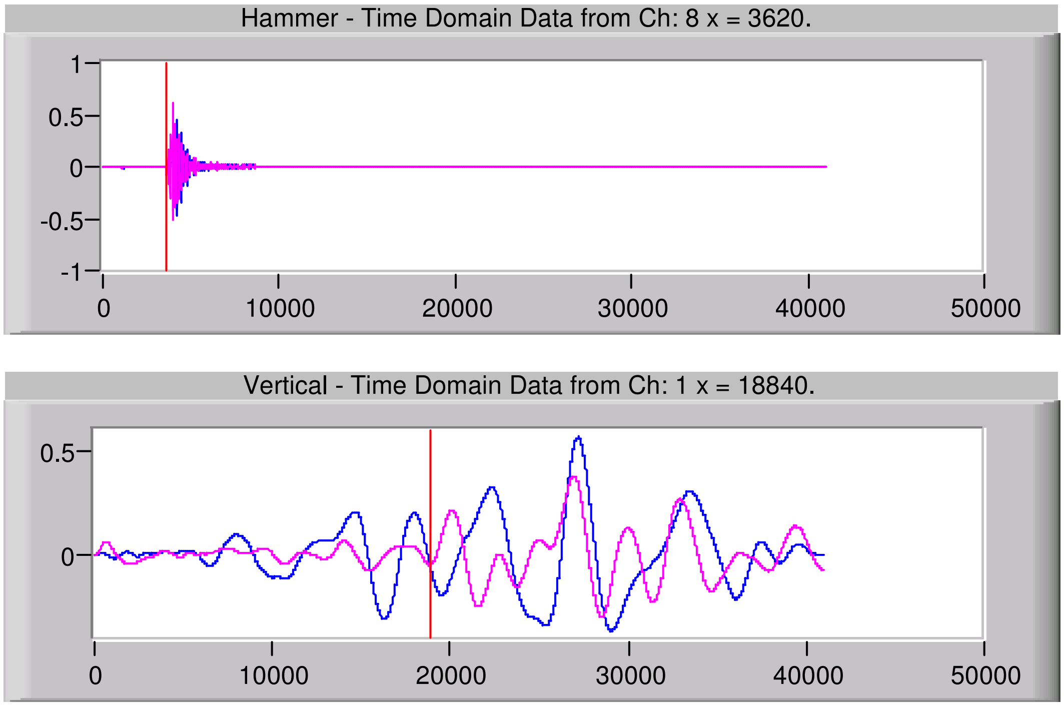

Figure 2: a. CS trigger data. b. CS up and down shear wave data (x-axis in microseconds, y-axis in output voltage). The vertical red lines mark the trigger time and the shear wave arrival time respectively.

The upper plot displays the time history of the trigger embedded in the EMS; the trigger occurs at 3620 microseconds. The lower plot displays the time history data of both an upward impact (magenta) and a downward impact (blue). The shear wave arrival time corresponds with the time where the polarized waves become 180 degrees out of phase, which is marked by the vertical red line and in this instance occurs at 18840 microseconds. The shear wave velocity is then calculated by subtracting the trigger time from the shear wave arrival time and dividing by the distance from the source to the receiver.

Example SASW data and basic processing is presented in Figure 3.

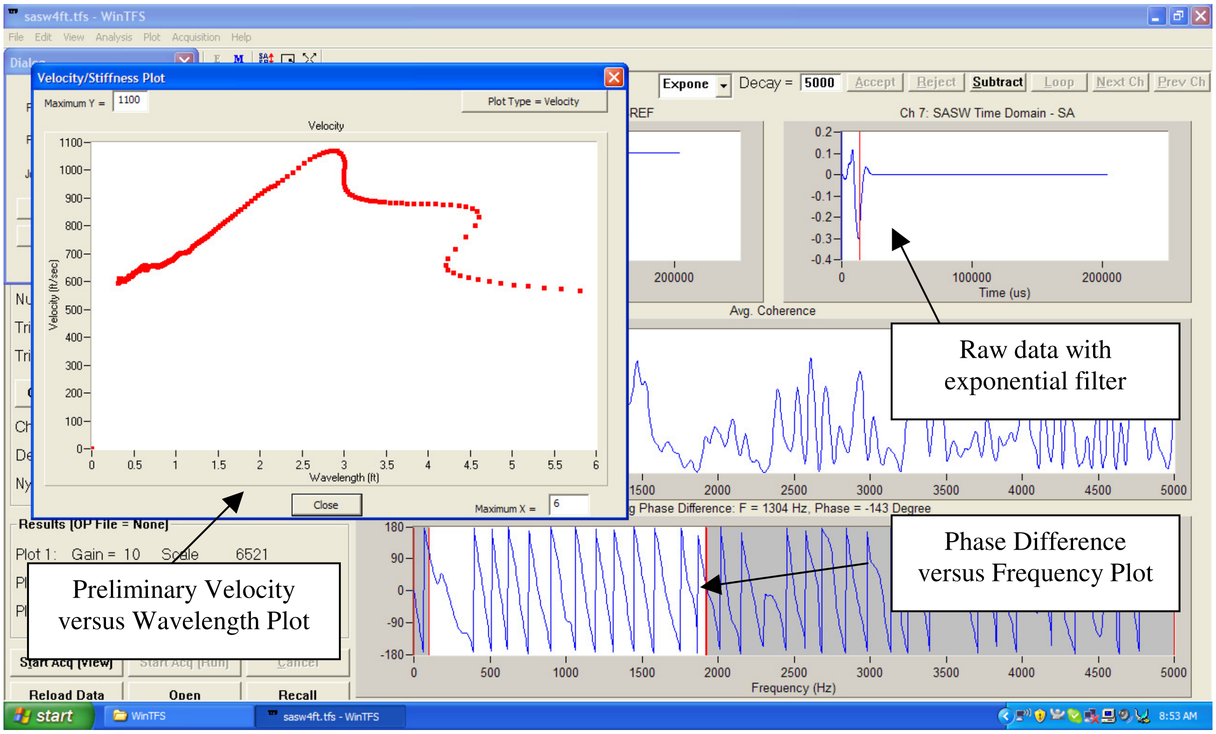

Figure 3: SASW raw data with exponential filter, phase difference plot with respect to frequency and prilimary velocity versus wavelength (depth) plot.

Example MISW data is displayed in Figure 4.

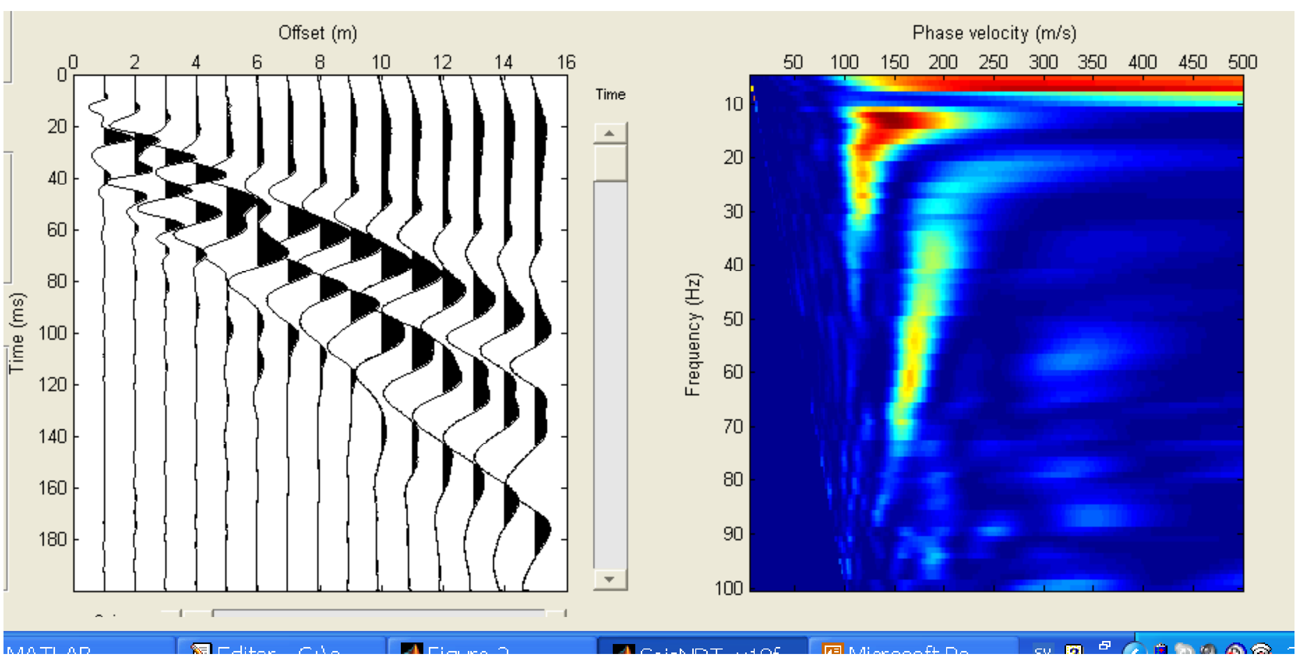

Figure 4: MISW raw data and resulting phase velocity spectrum.

The plot on the left shows the time history data from a MISW test at the site. Each vertical line represents an average of 5 impacts at a particular offset distance from the receiver; the offset distance is show on the x-axis. Notice how the wave arrival time becomes greater as the offset distance increases. The plot on the right shows the calculated experimental phase velocity spectrum of the MISW data. The experimental phase velocity spectrum shows multiple modes of dispersion curves separated by clear jumps in phase velocity at certain frequencies. To avoid mode number identification (and thus the risk of interpreting a wrong mode number) the complete phase velocity spectrum is used to invert for a shear wave velocity with depth profile (Ryden and Park 2006).

A comparison of the experimental and theoretically fitted phase velocity spectrum from the MISW test method is presented in Figure 5. The best matching theoretical phase velocity spectrum corresponds to the layer model shown in Figure 6.

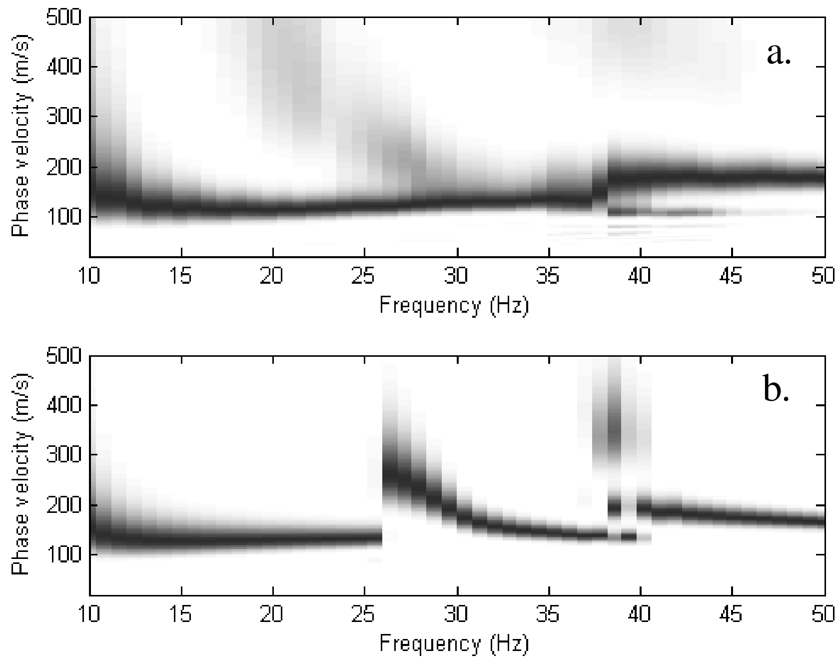

Figure 5: a. Experimental MISW phase diagram. b. Three-layer model phase velocity spectrum.

Shear Wave Velocity Data Comparison and Discussion

The resultant shear wave velocity profiles with respect to depth for the CS and MISW test methods are displayed for comparison in Figure 6.

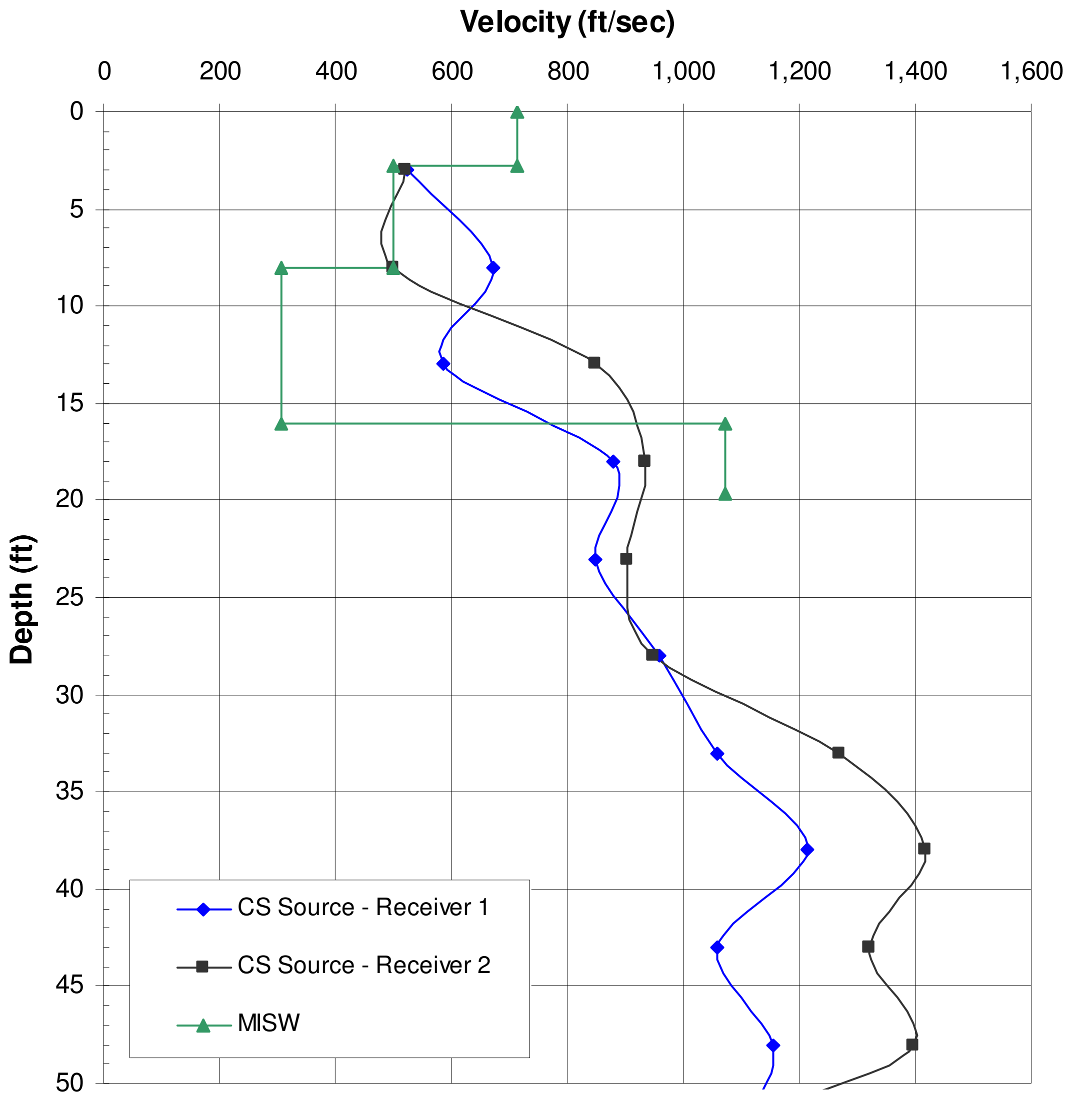

Figure 6: Shear wave velocity profile comparison.

As seen in Figure 6 MISW and CS correspond reasonably well with one another. Although the CS test was performed to a depth of 51.5 feet the MISW test method only produced good data to a depth of approximately 20 feet due to extremely soft top soil conditions. The SASW data was also severely effected by the top soil conditions and produced poor data at most of the test spacings.

Conclusions

The comparision suggests that the MISW method may produce results similar to the results from the CS test. Due to the quality of the SASW data no conclusions can be drawn at this time. Further research is needed at a variety of soil sites to develop better comparisons of the three test methods. The CS method was the least effected by the extremely soft six inches of topsoil, this is certainly an advantage.

References

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