Multiple Impact Surface Waves (MISW) – Improved Accuracy for Pavement System Thicknesses and Moduli vs. Spectral Analysis of Surface Waves (SASW)

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ABSTRACT

This paper includes a comparison and discussion of the surface wave test results, as well as backgrounds of the MISW and SASW methods. The older Spectral Analysis of Surface Waves (SASW) and newer Multiple Impact of Surface Waves (MISW) test methods were performed at the same forensic investigation project on a concrete pavement underlain by a cement treated base, for comparison purposes. The older SASW and newer MISW methods differ only slightly from one another in the equipment used and method of data collection, but involve significantly different data processing. The SASW method greatly overestimates Young's moduli of less stiff base materials immediately below the much stiffer asphalt or concrete pavement layer. In contrast the MISW method is able to estimate the properties of these less stiff base materials immediately below the much stiffer pavement layers by accounting for higher order wave modes during the inversion process.

INTRODUCTION

As mechanistic-empirical design methods are increasingly used in pavement design, there is an increasing need to measure Young's elastic moduli in situ. Measurement of each individual pavement layer during the construction process has been possible using the Spectral Analysis of Surface Waves (SASW) method since its research and development by Dr. Kenneth H. Stokoe, II and his students at the University of Texas at Austin beginning in the late 1970's (1). Many different surface wave methods have been developed for pavement and geotechnical site investigations including: SASW, frequency wave number (f-k) spectrum, multi-channel analysis of surface waves (MASW) and continuous surface waves (CSW). These methods and others were reviewed in detail in 2004 by Stokoe, Joh and Woods (2).

Also in 2004, Ryden and Lowe (3) reported a study on guided waves in a layered half-space with large velocity contrasts where a decreasing velocity with depth is presented. They found by calculating multiple mode dispersion curves in the complex wave number domain and taking into consideration the attenuation caused by leakage into the underlying half-space, that they could better resolve the thicknesses and moduli of layered pavement systems with improved matching of the experimental and theoretical phase velocity vs. frequency dispersion curves. This method is called Multiple Impact Surface Waves (MISW) herein. In particular, the lower moduli base and subgrade layers immediately below stiff pavement layers are resolved far better with the MISW approach than with the SASW and other surface wave approaches.

This paper describes the SASW and MISW test methods, data collection procedures and detailed results of a case history in which both methods were performed on a layered concrete pavement system project site. A total of 15 separate test areas were investigated utilizing both test methods. In addition to the nondestructive surface wave testing, borings were performed at 6 of the test site locations. The borings provide additional insight and validation of the surface wave test method comparison results.

COLLECTION OF SASW AND MISW FIELD DATA

In SASW tests, two receivers are placed on the surface, and a hammer is used to generate the acoustic energy (see Fig. 1). During data collection with short receiver spacings accelerometers are preferable to sample the shallow layers (high frequencies) while for longer receiver spacings (lower frequencies) geophones are typically used in sampling the deep materials. The source and receiver signals were recorded by an Olson Instruments Freedom Data PC Spectral Analysis of Surface Waves System and stored for further analysis. Two profiles, a forward profile and a reverse profile, are typically obtained in SASW measurements where the accessible surface is struck by a hammer in line with the two receivers from opposite ends.

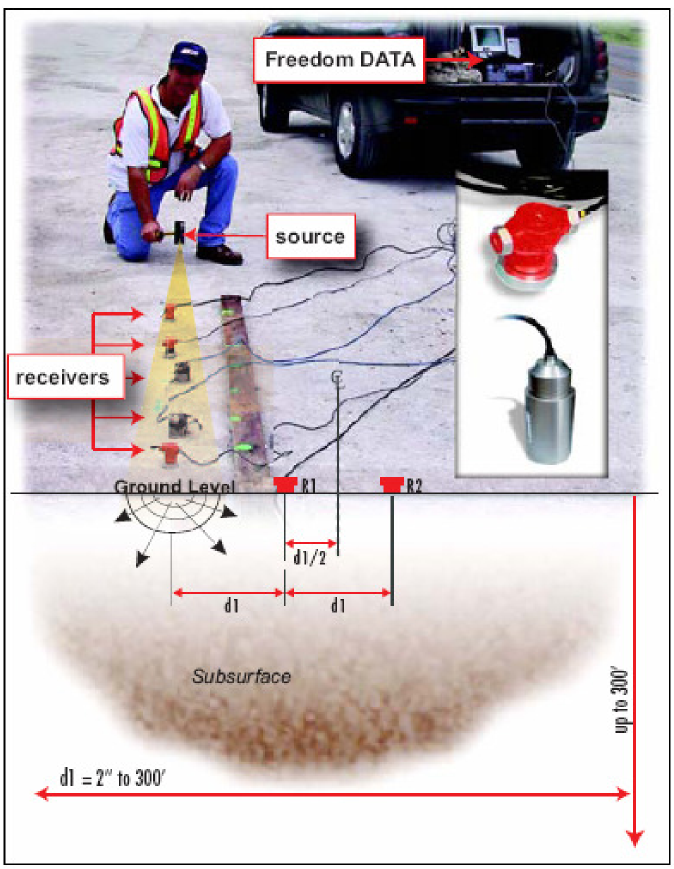

Figure 1. SASW testing with geophone receivers and an impact hammer source.

The MISW method and process flow chart is illustrated in Fig. 2. The same data acquisition unit was used for MISW testing. During MISW tests the generated surface waves were measured with a seismic accelerometer fixed at zero offset. Hammer impacts were generated from 0.20 to 5.00 m offset in 0.20 m increments. All recorded signals were then compiled to make an equivalent multi-channel record which can be transformed to a phase velocity spectrum similar to the MASW transformation technique (4).

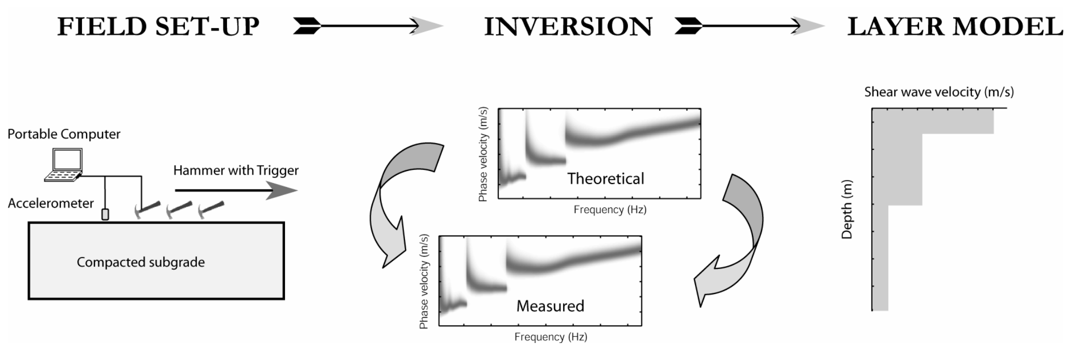

Figure 2. MISW process schematic showing data acquisition, processing and shear wave velocity profile output.

SASW and MISW Surface Wave Methods

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 (1). Figure 3 below shows typical surface wave data (in this case with an exponential window applied) in the top two plots, the coherence between the two receivers in the middle plot and the resulting phase versus frequency plot at the bottom.

Accounting for the known receiver spacing the phase versus frequency information is used to develop an experimental dispersion curve, which plots phase velocity versus wavelength. Shear wave velocity profiles can be determined from the experimental dispersion curves 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.

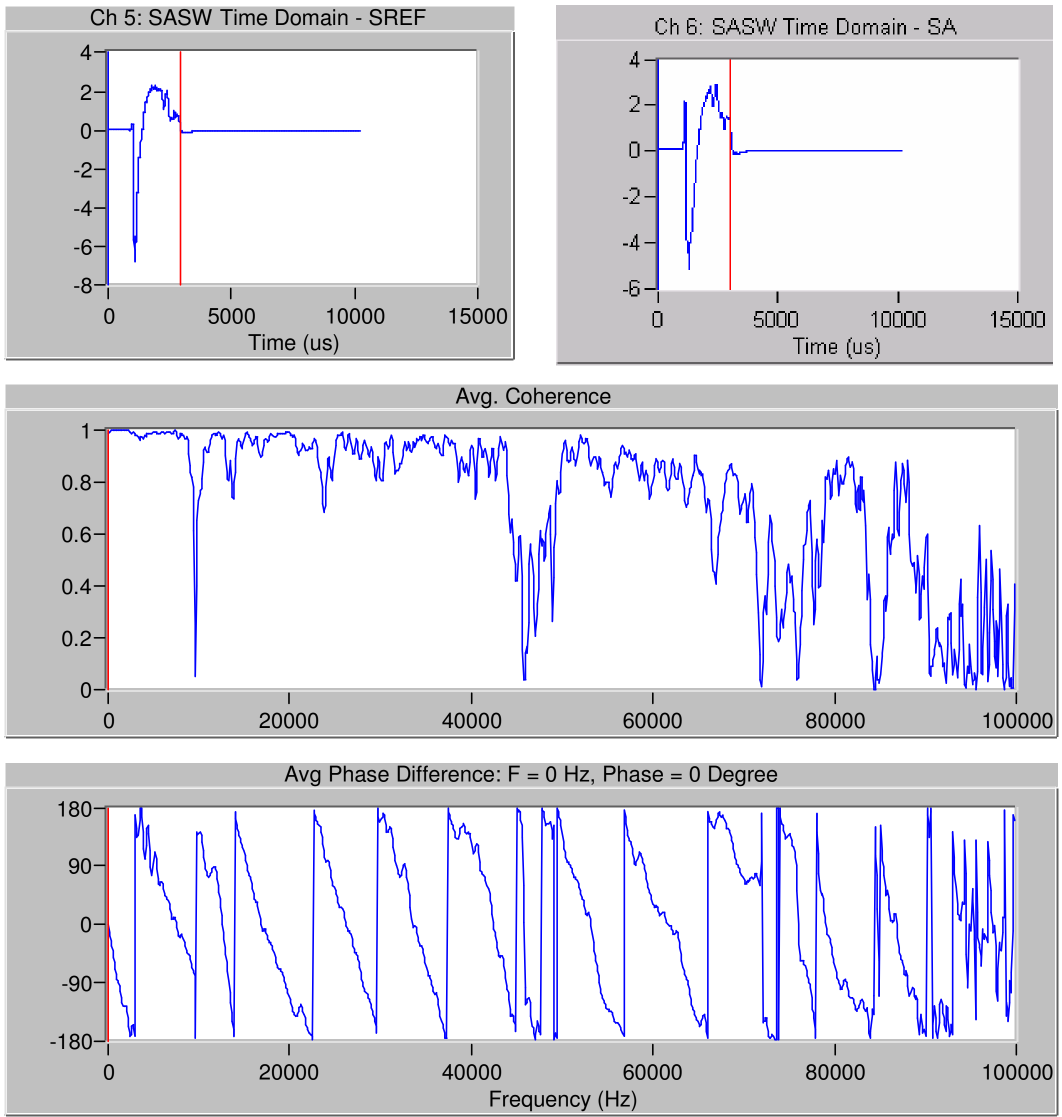

Figure 3. Example SASW data plot: time domain data of geophone (top plot), coherence for data quality (middle plot), and phase transfer function between geophones (bottom plot).

The MISW test method utilizes many of the same principles and equations as the SASW method (3). The data collection of both methods is also similar. Fig. 4 shows typical data from MISW testing and the resulting dispersion image. The differences between the two methods are predominantly in the data analysis. All of the data taken during MISW testing is analyzed together to create a dispersion image or phase velocity spectrum. As is generally seen in the MISW phase velocity spectrum for pavements, the phase velocity increases as a function of frequency. This apparent increase in the dispersive trend at higher frequencies is built-up by interference of higher modes of surface waves and it is reported that the data can be more accurately evaluated by taking this effect into account. This effect can be accounted for by modeling to match the dispersion image rather than the fundamental mode dispersion curve primarily analyzed in SASW.

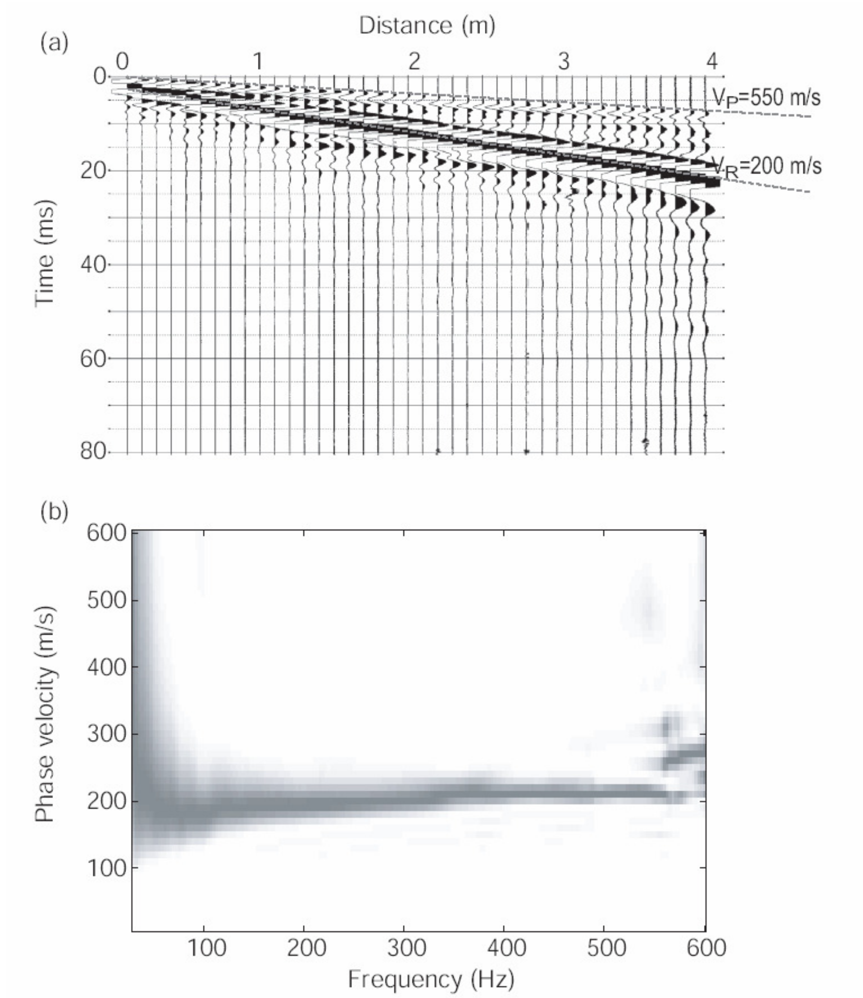

Figure 4. Example MISW data plot: time domain data of receiver (top plot) from left to right each trace from increasing impact to receiver distance, and the dispersion curve image showing phase versus frequency (bottom plot) – note this example data is from a separate project on natural soils to illustrate simple, single layer data.

SASW and MISW Theoretical Modeling Data Processing

For both SASW and MISW, in order to determine the shear wave velocity profile from the "apparent" velocities of the dispersion curve, analytical modeling is necessary. The analytical modeling used herein is a forward modeling process that is iterative and involves assuming a shear wave velocity profile and constructing a theoretical dispersion curve or dispersion image. The experimental (field) and theoretical curves are compared, and the assumed theoretical shear wave velocity profile is adjusted until the two curves or images match.

For SASW modeling the interactive computer software WINSASW (developed by Dr. Sung Ho Joh during his Ph.D. research at the Univesity of Texas at

Austin) was used to compute and iteratively match a theoretical dispersion curve, based upon an assumed shear wave velocity and layer thickness profile, to the field measured dispersion curve. These algorithms have produced reasonable accuracy when comparing velocities determined with the SASW and seismic crosshole methods on soil sites. A SASW result with a good match between the measured and experimental data and the resulting shear wave velocity profile is presented in Fig. 5 for one of the concrete pavement test sites.

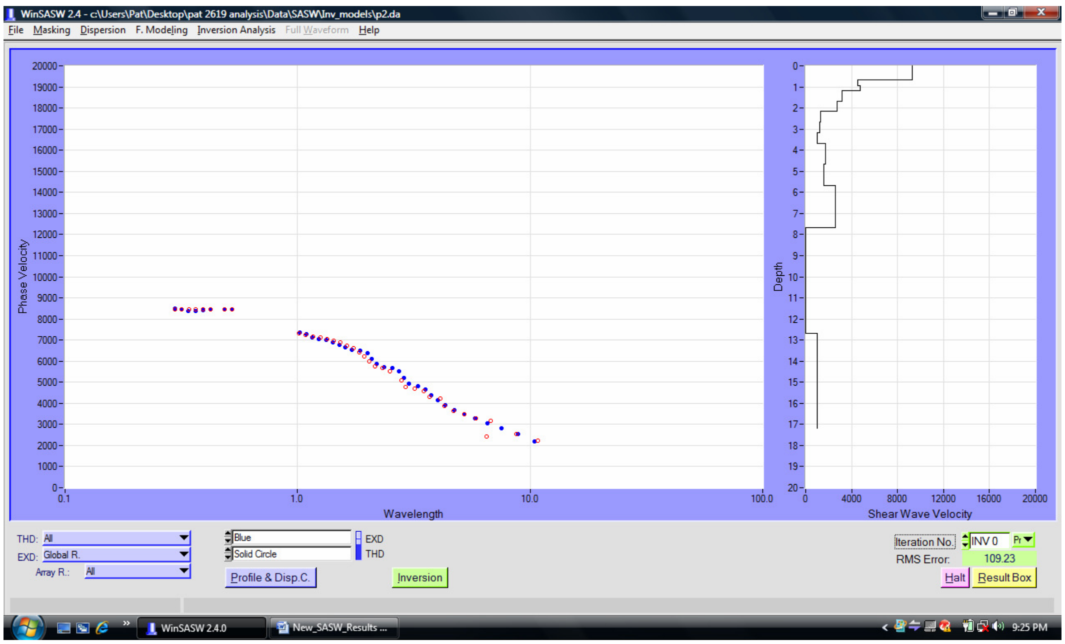

Figure 5. SASW dispersion curve plot for Concrete Pavement Site (phase velocity vs. wavelength on left with good match of experimental data – open circles and theoretical match – solid circles) and Theoretical Shear Wave Velocity vs. Depth on the right.

For MISW modeling, SeisNDT, a program developed by Dr. Nils Ryden (3), was used for data collection, analysis, and theoretical modeling. The modeling program iteratively adjusts multiple parameters in order to match the experimental dispersion velocity spectrum image. This technique and analysis algorithms have been shown to accurately determine the layer thicknesses and moduli of pavement and soil systems. A MISW result from the same concrete pavement site as tested with the SASW method is presented in Fig. 6 below. The surface wave data is plotted in the left plot as impact point offset from the accelerometer receiver versus time while the phase velocity spectrum of the experimental data is plotted as amplitude normalized and not normalized in the two right hand plots.

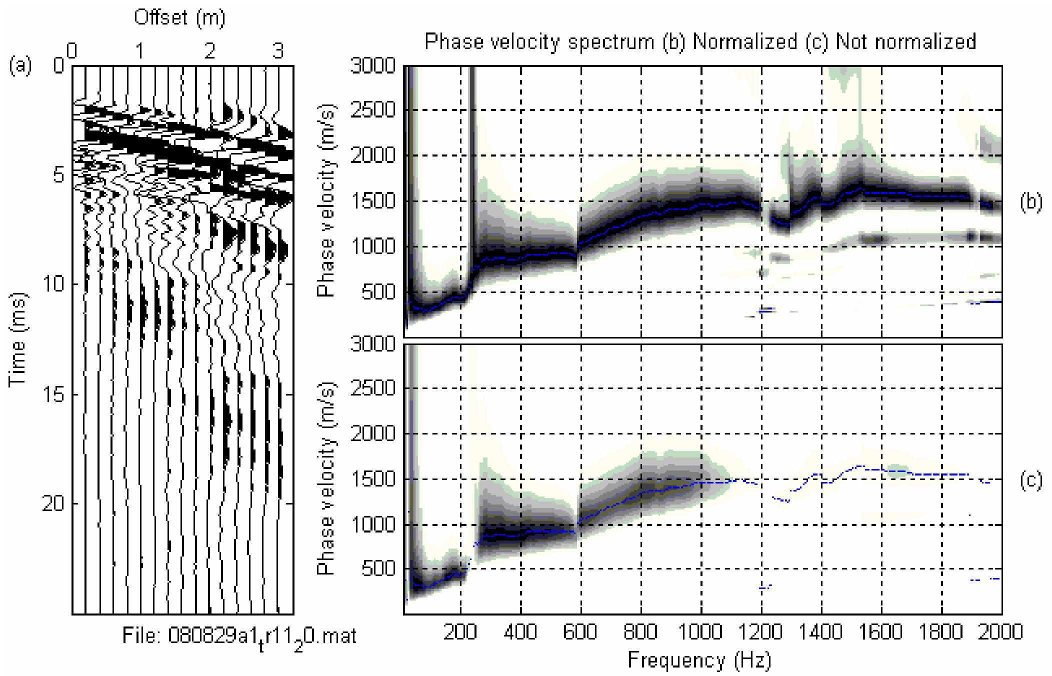

Figure 6. Example MISW results from Concrete Pavement Site with time domain data in left plot and Phase Velocity Spectrum in right plots.

The matching of the experimental phase velocity spectrum with the theoretical phase velocity spectrum is presented in Fig. 7 with the top plot being the measured phase velocity spectrum, the second plot being the best fit theoretical velocity spectrum and the third plot comparing the mismatch between the experimental and theoretical results. The bottom plot on the left is the shear wave velocity profile versus depth while the layer data in terms of thicknesses, shear and compressional wave velocities and Poisson's ratios are summarized in the lower right.

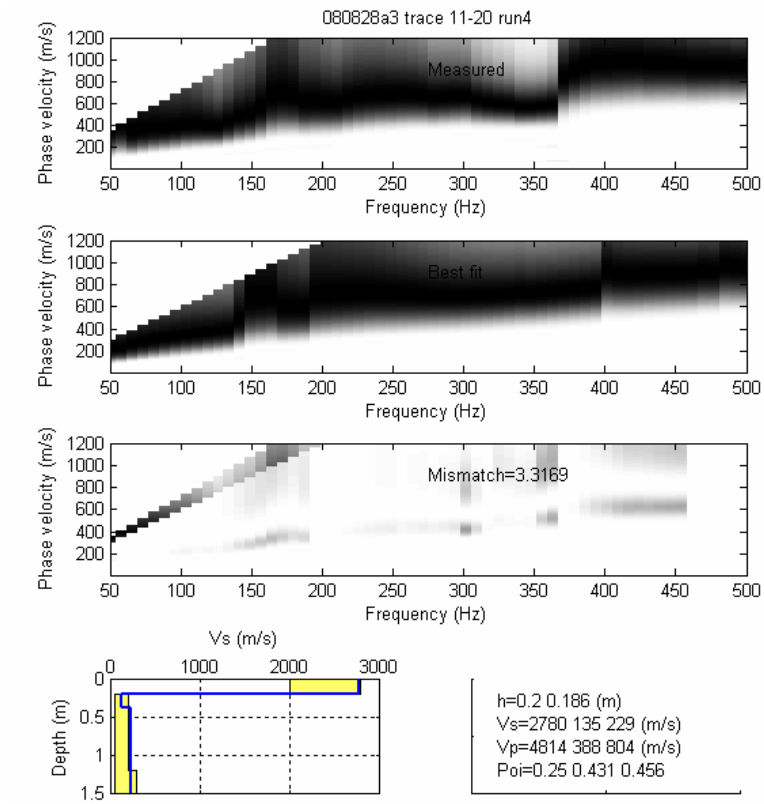

Figure 7. MISW Matching of Phase Velocity Spectrum for Experimental (top) and Theoretical Best-fit (2nd plot), and Mismatch (3rd plot) with MISW Theoretical Shear Wave Velocity Profile vs. Depth (left-bottom) and Layer Information (right-bottom).

TEST SITE BORING INFORMATION

A total of 6 soil borings were performed at the concrete pavement test site corresponding to 6 of the 15 total tested locations. The borings provide physical samples with which to compare our nondestructive test results. Generally, all six borings produced similar pavement layer system profiles. Four of the six borings consisted of an 200 – 225 mm thick pavement layer underlain by a 300 – 400 mm thick cement treated clay layer, followed by a 1.0 – 1.5 m thick stiff, sandy clay layer. One boring did not have a cement treated clay layer, while another boring had a 0.5 m thick clayey sand layer instead of the cement treated clay layer.

It would stand to reason that the cement treated clay layer would be stronger than the sandy clay layer directly beneath it, however samples from both of these layers in three borings were subject to unconfined compressive strength tests. In all three cases the sandy clay layer produced higher values than the cement treated clay layer. The unconfined compressive strengths ranged from 0.14 – 0.27 MPa for the cement treaded clay layer and ranged from 0.20 to 0.40 MPa for the sandy clay layer. The boring logs also show the same trend in data from a pocket penetration test that was performed in-situ in all borings. It is important to note that shear wave velocities of cement treated soils are typically on the order of 500 to 1,500 m/sec

COMPARISON OF SASW AND MISW RESULTS

The direct comparisons, from a typical test site, of the theoretically best fit shear wave velocity profiles from the SASW and MISW testing are presented in Figure 8. Review of this figure indicate that the SASW method predicted significantly higher shear wave velocity profiles for the cement treated clay base layer immediately below the concrete than the MISW method. Generally, both methods predicted similar shear wave values for the pavement layer and tended to converge at depths greater than 1 meter.

Further examination of Figure 8 indicates that the shear wave velocity of the cement-treated base was quite high below the concrete in the SASW results (700 - 1200 m/s). However, the MISW results predicted a much slower velocity (~100 m/s). As noted above, the unconfined compressive strength tests performed on samples of the cement-treated base revealed comparatively low strengths at the pavement site. This finding is in agreement with the MISW results as the cement-treated base was found to have similar strengths to the underlying natural clayey, sandy subgrade soils that had not been treated.

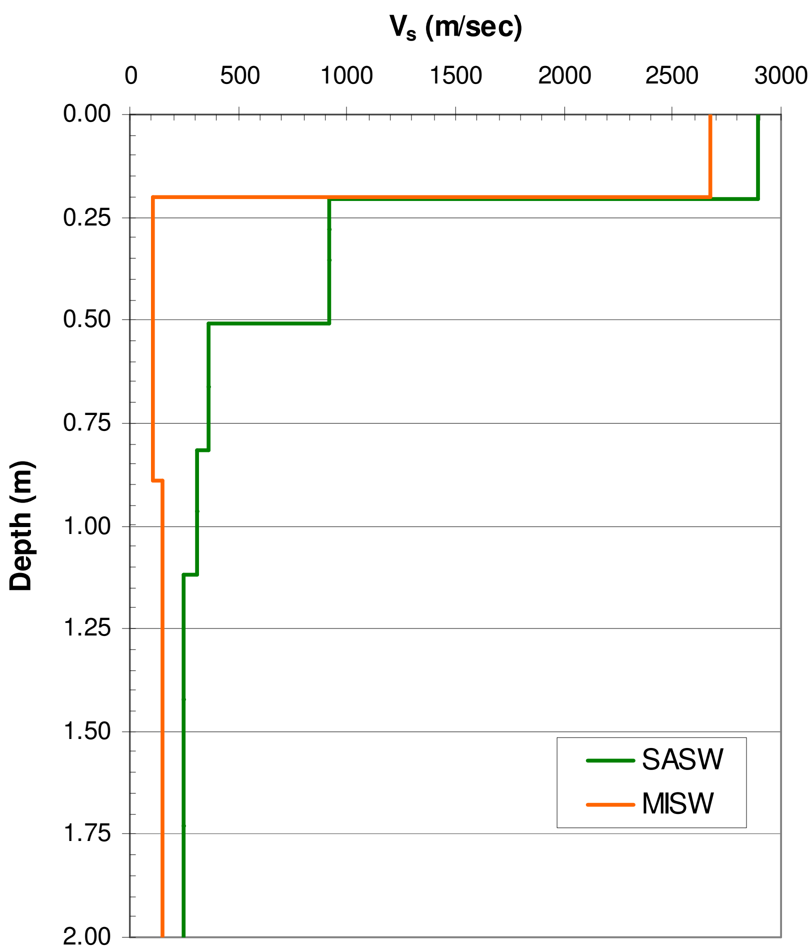

Figure 8. Comparison of SASW and MISW shear wave velocity profiles with depth. Example data from 1 of 9 similar sites.

The results from the MISW testing indicate that the subbase layer has a shear wave velocity ranging from 100 – 200 m/sec. Based on experience this is considered a soft to average stiffness subgrade layer. According to our modeling the uppermost soil layer ranged in thickness from 4 inches to nearly 3 feet. The second soil layer beneath the concrete pavement has similar properties and typically shows a slight increase in shear wave velocity but is still considered a soft to average stiffness layer. These results are well supported by the boring logs, pocket penetration tests performed in-situ at the time of the boring, as well as unconfined compression tests performed on soil samples.

CONCLUSIONS

The base materials immediately beneath the concrete pavement are described as cement-treated clay in 4 of the 6 boring logs. The average shear wave velocity calculated for this layer was approximately 150 m/sec, however cement-treated soils typically have shear wave velocities at least 3 times greater than what was measured. It is also important to note that shear wave velocity squared is linearly related to modulus, therefore the factor of 3 difference in shear wave velocity would correspond to a factor of 9 difference in modulus. If the soil base layer was indeed intended to be cement stabilized (as it appeared in the boring logs), than the strength assumed in the design of the pavement is likely significantly greater than the current strength of the base. This reduced modulus and base strength will lead to the pavement system failing long before its intended design life. This case history illustrates the importance of such a measurement in a pavement rehabilitation project.

The MISW method can thus be used to determine shear wave velocity profiles from which Young's moduli and layer thicknesses can be accurately calculated for use in mechanistic-empirical pavement design. Additionally, the MISW method can be applied for Quality Assurance/Quality Control (QA/QC) purposes during construction and in pavement monitoring and rehabilitation projects to provide accurate layer thickness and moduli data of a layered pavement system.

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