Experimental evaluation of the uncertainty of the SASW method

Evaluation expérimentale de l'incertitude de la méthode SASW

K. E. Tuomi & D. R. Hiltunen – *Department of Civil and Environmental Engineering, The Pennsylvania State University, University Park, Pa., USA*

ABSTRACT: Spectral-analysis-of-surface-waves (SASW) testing provides a nondestructive test method for characterization of the variation with depth of the shear modulus (or shear wave velocity) of soils at a test site. While the testing procedure is fairly well developed, little research has been completed to determine the uncertainty associated with the SASW test method. Knowledge of the uncertainty would allow for greater confidence in the test results allowing for greater confidence in design. In this study a large sample of replicate field data was created by conducting multiple SASW tests at test sites in State College, PA and Evanston, IL. From this data, variation in the data collected from a typical SASW test (the phase angle for a given frequency wave) was determined. In addition, the replicate phase angle data were reduced using typical SASW analysis techniques to produce replicate shear wave velocity profiles for the test sites. In this paper it is shown that the uncertainty in phase angle data is small, having coefficients of variation typically less than 7%. Further, the variation appears to be normally distributed. It is shown that the uncertainty in shear wave velocity for a given soil layer can also be small, with coefficients of variation less than 13%. The variation in shear wave velocity does not appear to be normally distributed.

INTRODUCTION

Reliability-based design processes are increasingly popular within the engineering community. Inclusion of uncertainty in design has become more important as the cost of failure has grown and as funds to construct facilities, products, etc. continue to diminish. One of the primary components of reliability-based design is an assessment of the variability of the input parameters, particularly those inputs that significantly affect the design process. The shear modulus of soil, G, is a significant parameter for many geotechnical engineering design problems. Current state-of-practice is that the shear modulus profile for a site be evaluated in situ using investigation techniques based upon seismic wave propagation. Although crosshole and downhole methods are popular, use of the spectral-analysis-of-surface-waves (SASW) method continues to grow as familiarity with the method increases. The non-intrusiveness of the test (no boreholes) typically leads to cost savings when compared with other methodologies. However, like many materials testing techniques, little research and data that describe the uncertainty of results obtained from SASW are available. In addition, current testing practices do not allow for the uncertainty to be assessed. The purpose of this paper is to describe the initial results of a research program to quantify the uncertainty associated with the SASW method.

THE SASW METHOD

The spectral-analysis-of-surface-waves (SASW) method is a testing procedure for determining shear wave velocity (shear modulus) profiles of soil systems in situ. The test is performed from the ground surface without boreholes. Measurements are made at strain levels below 0.001 percent, where elastic properties of soil are considered independent of strain amplitude. Key elements in SASW testing are the generation and measurement of Rayleigh waves. The method has been used to date for a number of applications, including design of foundations for dynamic loads (Woods [1986]), nondestructive pavement evaluation (Hiltunen[1988], Nazarian [1984]), evaluation of soil liquefaction potential (Stokoe and Nazarian [1985]), evaluation of the integrity of a concrete dam (Nazarian [1984]), determination of elastic properties of hard-to-sample soils (e.g., gravelly soils and debris slides, Stokoe et al. [1988]), and as a diagnostic tool for determining effectiveness of soil improvement techniques (Stokoe and Nazarian [1983]). The SASW method has proven to be a valuable tool for determining shear wave velocity profiles. The ability to determine a detailed shear wave velocity profile entirely from surface measurements results in substantial time and cost savings compared to other seismic methods such as crosshole and downhole techniques.

A number of publications in recent years have described in detail the SASW method (Nazarian [1984], Hiltunen [1988]). A schematic of the experimental arrangement for SASW tests is presented in figure 1. Current practice calls for locating two vertical receivers on the ground surface a known distance apart and a wave containing a large range of frequencies is generated in the soil by means of a hammer, vibrator, or other energy source. Testing is usually conducted in both the forward and reverse directions by placing the source on either side of the centerline. Surface waves are detected by the receivers and are recorded using a Fourier spectrum analyzer. The analyzer is used to transform the waveforms from the time to the frequency domain and then to perform necessary spectral analyses. The spectral analysis functions of interest here are the phase of the cross power spectrum and the coherence function. Knowing the distance and relative phase shift between the receivers for each frequency, the velocity of the surface wave (phase velocity) associated with that frequency is calculated. This relationship is known as the dispersion curve. The final step is application of an inversion process that constructs the shear wave velocity profile from the dispersion information.

Numerous investigations have been reported in which the reliability of the SASW method has been assessed. However, most reliability assessments have concentrated on accuracy (bias) of the test results, typically by comparing results from SASW with results from other established testing methods such as the crosshole technique. Few investigations have reported on the other significant aspect of reliability: the uncertainty or precision of the results. Error bands, confidence intervals, or other assessments of precision are not typically reported because of the significant time and effort needed to generate the error band, as seen in this study.

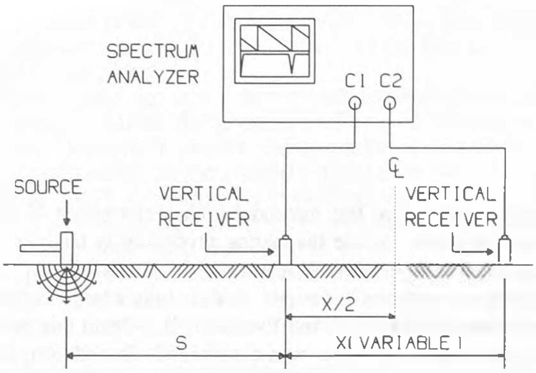

Figure 1. Schematic of SASW Test (after Nazarian [1984])

RELIABILITY ANALYSIS

To collect the data necessary for this study SASW testing was conducted following standard test practice at two sites: the Pennsylvania Transportation Institute Test Track (PSTT) at The Pennsylvania State University in State College, PA and at Northwestern University (NWU) in Evanston, IL. At each of these sites two sites were selected for testing and designated Site 1 and Site 2 creating a total of four individual test sites. At each of these four sites 30 replicate cross power spectrum data for various receiver spacings were collected. Characteristic statistics were computed to provide an indication of the variation in the collected phase angle data. Shear wave velocity profiles for the test sites were determined by creating a dispersion curve from the average phase angle data of the 30 replicate tests per receiver spacing and then inverting this dispersion curve to find an estimate of the shear wave velocity profile for that site. Using these shear wave velocity profiles as starting points, the dispersion curves created by each individual replicate at each of the test sites were then inverted and 30 separate estimates of the shear wave velocity profile were produced for each test site. Characteristic statistics calculated for the shear wave velocities provide an indication of the precision of the test method.

The PSTT test site is characterized by gently undulating terrain with a typical soil profile consisting of approximately 1.3 m of Hagerstown silt loam overlying a fractured limestone valley bottom. Hagerstown silt loam is a well-drained reddish soil created from weathered limestone and dolomite often found in limestone valleys (USDA [1968]). The NWU test site is located along the Lake Michigan waterfront of the campus of Northwestern University. The site is located on part of the sand filled area constructed in 1966 to increase the area of the campus. A typical soil profile for the NWU site consists of 6.4 m of fine sand fill followed by a soft to medium clay layer to a depth of 16.2 m followed by a stiff clay layer. The water table is typically at a depth of 3.6 m.

The SASW testing for the PSTT sites was conducted along two lines which ran east-west at the top and bottom of a small rise. Site 1 was at the top of the rise and Site 2 was at the bottom. The testing at the NWU sites was conducted along a line running east-west, Site 1, and then perpendicular to that along a north-south line, Site 2. Following the SASW test configuration illustrated in figure 1, a fixed centerline was designated at each test site. Tests were conducted at several receiver spacings (X). At each receiver spacing the source was located a distance from the near receiver (S) equal to the receiver spacing. The receivers were Mark Products Model L-4C geophones and the recording device was a Hewlett Packard Model 3567A Dynamic Signal Analyzer. The impacts necessary for the SASW testing were created by 36-N and 89-N sledgehammers. Typically the 36-N sledgehammer was used for the shorter receiver spacings and the 89-N sledgehammer for the longer receiver spacings.

Tables 1 and 2 list characteristic statistics of replicate phase angle data collected at a PSTT and a NWU site. Mean phase angles for selected frequencies associated with each receiver spacing are shown along with the standard deviation, coefficient of variation (COV), and the minimum and maximum phase angles. Variation of the test data is also shown in figure 2 where the average phase angle data for a receiver spacing at PSTT is shown banded by three standard deviations. It is apparent from these tables and the figure that the phase angle data collected in a typical SASW test is small, having coefficients of variation typically less than 7%. Data points in figure 2 where the width of the error bands suddenly increase represent those points in the data where the phase angle shows irregular behavior. This increase in the uncertainty of the phase angle data supports the concept of removing irregular data points, which is typically done in SASW analysis. In general, it is apparent in tables 1 and 2 that the COV of the phase angle data for a given receiver spacing decreases with increasing frequency. This can be attributed to the fact that high frequency waves travel nearer to the ground surface and are more reliably measured in a surface test.

Table 1. Characteristic Statistics of Phase Angle Data for PSTT2

Receiver Spacing (m)	Freq. (Hz)	Avg. (deg)	Std. Dev. (deg)	Coeff. of Var. (%)	Min. (deg)	Max. (deg)
1.8	60	149.2	8.2	5.5	132.2	166.1
	90	459.0	4.8	1.0	448.6	470.4
	120	676.2	8.7	1.3	643.6	691.3
2.4	60	199.7	12.7	6.4	168.1	216.5
	80	495.0	10.1	2.0	458.5	508.3
	100	651.7	12.2	1.9	609.8	671.5

Table 2. Characteristic Statistics of Phase Angle Data for NWU1

Receiver Spacing (m)	Freq. (Hz)	Avg. (deg)	Std. Dev. (deg)	Coeff. ofVar. (%)	Min. (deg)	Max. (deg)
2.4 F	25	146.5	2.64	1.8	139.5	152.8
	75	345.9	13.4	3.9	329.9	377.0
	125	658.2	8.77	1.3	656.6	680.9
	175	919.7	15.5	1.7	892.1	954.7
3.6 F	20	178.6	5.26	2.9	170.3	190.8
	60	453.3	2.97	0.6	448.6	458.8
	100	799.3	2.51	0.3	794.3	808.9
4.8 F	20	209.3	7.68	3.6	191.8	226.9
	60	632.2	2.92	0.4	626.7	644.2
	100	1014	2.64	0.2	1011	1024

For some of the receiver spacings for the NWU data the COV of the phase angle increases somewhat at the highest frequencies. At the highest frequencies collected there is potential for energy losses which can cause a deterioration of the quality of the phase angle data. Higher frequency waves travel through a greater number of cycles before reaching the receivers. This leads to energy losses due to damping which may provide a less reliable signal. The variation in the phase angle data was also found to have a normal distribution by plotting samples of select frequencies on a normal probability plot as seen in figure 3. The phase angle data at a given frequency consistently plot in a straight line, indicating a normal distribution.

From the average phase angle data for each test site an average dispersion relationship was created. Using this data as input, an SASW inversion routine was used to determine a shear wave velocity profile for each of the four test sites. Using this shear wave velocity profile as a starting point, each individual dispersion curve of the 30 phase angle replicates was inverted to create a separate shear wave velocity profile per site. Characteristic statistics of the shear wave velocity profiles are shown in tables 3 and 4 for the PSTT and NWU sites. While typical SASW test procedure involves modification of the system layering until a suitable model is found, for comparison of the 30 replicate tests the model fitting was limited to the layers defined by inversion of the dispersion curve created from the average phase angle data. The variation in the shear wave velocity profiles for a PSTT and a NWU site, banded by three standard deviations, are plotted in figures 4 and 5. In all of the site profiles, a thin top layer that has a higher or similar uncertainty than successive layers is apparent. These thin upper layers may exist due to compaction or desiccation of the surface of the test sites. The larger uncertainty of this top layer may exist because of the difficulty in obtaining high frequency data in a SASW test. Frequencies that would be necessary to resolve such a thin layer at the surface are higher than those typically successfully collected at a soils test site. While the collected data leads the inversion procedure to attempt to resolve this thin layer there is insufficient data to reliably determine the shear wave velocity. Another possible reason for the larger COV of the top layer for the PSTT sites is the difficulty in modeling a higher shear wave velocity layer over a slower layer. This difficulty in modeling may increase the COV of the top layer of the PSTT site and also for the second layer of the NWU site. In the PSTT site the uncertainty of the shear wave velocity is seen to increase with depth after the top layer. This is consistent with the increase in COV of the phase angle data at lower frequencies noted earlier since lower frequency waves travel at larger depths. The NWU site does not show this increase in uncertainty with depth. However, the NWU site shows the same difficulties that the PSTT site shows in that there is a thin upper layer and the second layer is at a higher velocity than the half-space potentially increasing the uncertainty. It is of interest to note the trend of an increasing COV, or uncertainty, with increasing shear wave velocity. This observation would indicate a possible relationship between higher shear wave velocity and larger uncertainty. Testing samples of the shear wave velocity on a normal probability plot indicates that the shear wave velocities are not normally distributed as shown for example in figure 6. In comparison with the phase angle data (figure 3), shear wave velocities for a given layer do not plot in a straight line.

CONCLUSIONS

Based upon the data presented and discussed herein, the following conclusions are appropriate:

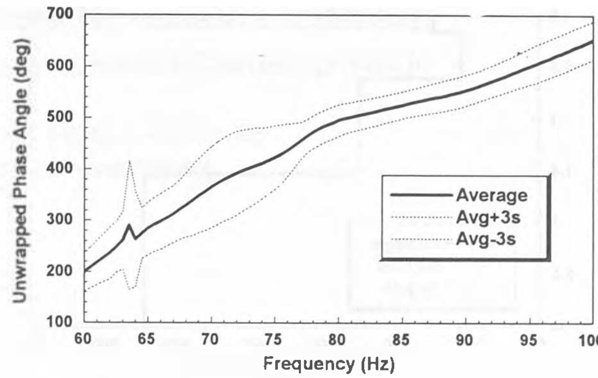

Figure 2. Avg. Phase Angle Banded by 3 Std. Deviations

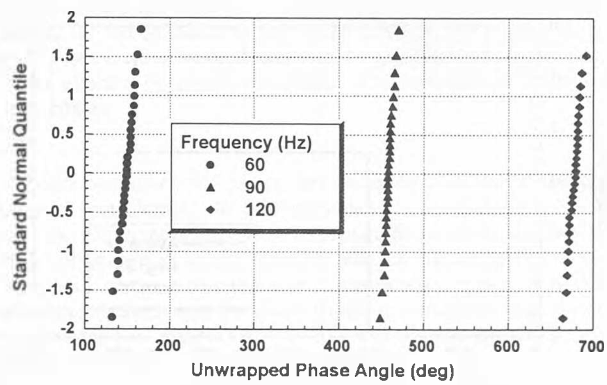

Figure 3. Normal Probability Plot for Phase Angle (PSTT2)

Table 3. Characteristic Statistics of Shear Velocity Profiles for PSTT2

Layer Thickness (m)	Avg. (m/s)	Standard Dev. (m/s)	Coeff. of Var. (%)	Min. (m/s)	Max. (m/s)
0.15	146	11.9	8.1	128	183
0.46	108	2.9	2.7	98	112
0.91	247	8.3	3.3	239	275
Half-Space	544	31.4	5.6	479	586

Table 4. Characteristic Statistics of Shear Velocity Profiles for NWU1

Layer Thickness (m)	Avg. (m/s)	Standard Dev. (m/s)	Coeff. of Var. (%)	Min. (m/s)	Max. (m/s)
0.61	132.4	1.95	1.5	129.1	135.7
2.43	215.7	6.55	3.0	202.4	229.1
Half-space	160.8	0.99	0.6	159.3	162.8

- There is low uncertainty in the phase angle data collected in replicate tests using standard SASW test procedures. The coefficient of variation for the phase angles is typically less than 7% and samples appear to be normally distributed.

- The increase in uncertainty observed at frequencies where irregular behavior occurs in the phase angle data supports the removal of these points from SASW data analysis as is done in current practice.

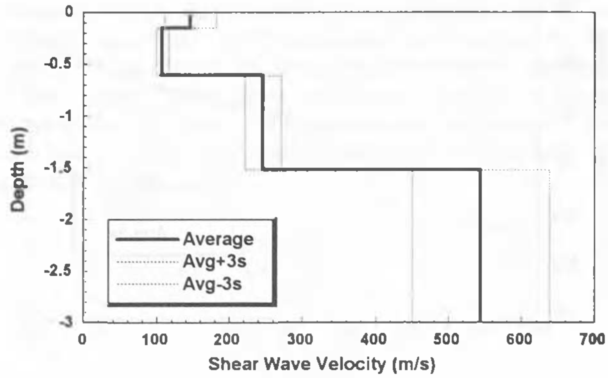

Figure 4. Shear Wave Velocity Profile for PSTT2

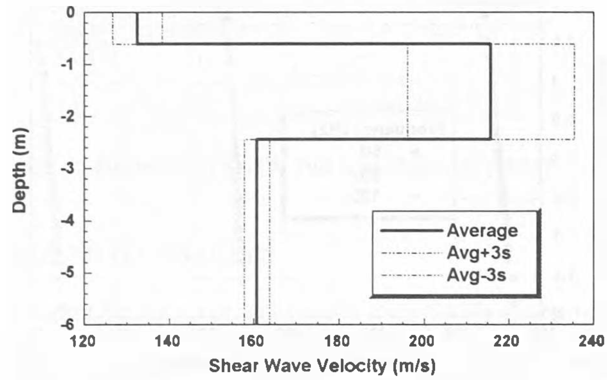

Figure 5. Shear Wave Velocity Profile for NWU1

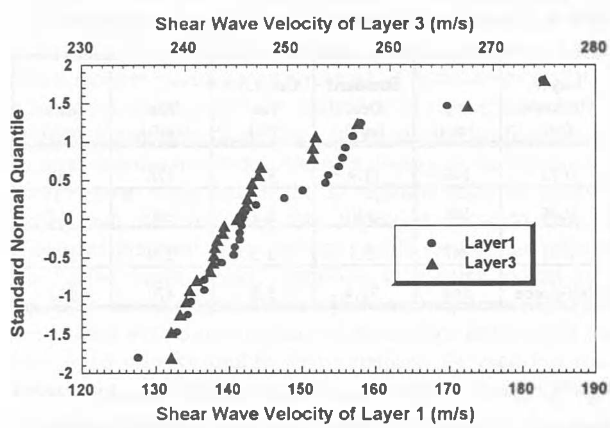

Figure 6. Normal Probability Plot for Shear Velocity (PSTT2)

- There is low uncertainty in the shear wave velocity profile produced by the inversion process used in SASW data analysis. Individual layer velocities exhibit coefficients of variation of 13% or less. Variation in shear wave velocity within a particular layer does not appear to be normally distributed.

- The presence of a thin, less reliable layer at the surface of the test site indicates a lack of sufficient data to reliably resolve this layer using SASW inversion.

ACKNOWLEDGMENTS

The authors would like to acknowledge the following parties:

- Office of the Dean of Engineering, College of Engineering, at the Pennsylvania State University for fellowship support for Ms.Tuomi.

- Department of Civil and Environmental Engineering at the Pennsylvania State University for support of this research and for providing assistantship support for Ms.Tuomi.

- Dr. Steven F. Arnold of the Department of Statistics at the Pennsylvania State University for technical advice and encouragement during conduct of this work.

REFERENCES

Hiltunen, D. R. (1988), "Experimental Evaluation of Variables Affecting the Testing of Pavements by the Spectral Analysis of Surface Waves Method," *Technical Report GL-88-12,* U.S.A.E. Waterways Experiment Station, Vicksburg, MS, August, 303 pp.

Nazarian, S. (1984), "In Situ Determination of Elastic Moduli of Soil Deposits and Pavement Systems by Spectral-Analysis-of-Surface-Waves Method," Ph.D. Dissertation, University of Texas at Austin, 453 pp.

Stokoe, K. H. II and Nazarian, S. (1983), "Effectiveness of Ground Improvement from Spectral Analysis of Surface Waves," *Proceedings of the Eighth European Conference on Soil Mechanics and Foundation Engineering*, Helsinki, Finland, May.

Stokoe, K. H. II and Nazarian, S. (1985), "Use of Rayleigh Waves in Liquefaction Studies," *Measurement and Use of Shear Wave Velocity for Evaluating Dynamic Soil Properties*, ASCE, pp. 1-17.

Stokoe, K. H. II, Nazarian, S., Rix, G. J., Sanchez-Salinero, I., Sheu, J. C., and Mok, Y. J. (1988), "In Situ Seismic Testing of Hard-to-Sample Soils by Surface Wave Method," *Earthquake Engineering and Soil Dynamics II--Recent Advances in Ground Motion Evaluation*, Geotechnical Special Publ. No. 20, ASCE, pp. 264-278.

Tuomi, K. E. and Hiltunen, D. R. (1996), "Reliability of the SASW Method for the Determination of the Shear Modulus of Soils," Paper Accepted for ASCE Specialty Conference: Uncertainty in the Geological Environment: From Theory to Practice, Madison, WI, August 1-3.

United States Department of Agriculture (USDA) Soil Conservation Service (1968), *Soil Survey Interpretations for Centre County, Pennsylvania*, United States Department of Agriculture, p. 161.

Woods, R. D. (1986), "In Situ Tests for Foundation Vibrations," *Use of In Situ Tests in Geotechnical Engineering*, Geotechnical Special Publication No. 6, ASCE, pp. 336-375.