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DATA REPORT

SASW Measurements at the NEES Garner Valley Test Site, California

by

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Introduction

Spectral-Analysis-of-Surface-Waves (SASW) measurements were performed at the NEES Garner Valley Test Site by personnel from the University of Texas at Austin. These specialized seismic measurements were conducted by Kenneth H. Stokoe, II, Asli Kurtulus, Farn-Yuh Menq, Christopher Stanton and Nedra Bonal from the University of Texas. The tests were performed on August 19 and 20, 2004. Analysis of the SASW data was performed at the University of Texas at Austin by Asli Kurtulus. The purpose of these tests was to determine shallow shear wave velocity profile close to the instrumented model structure (SFSI experimental structure) and deeper shear wave velocity profiles around the general test area. In total, three shallow (~20 ft) and two deeper (~200 ft) shear wave velocity profiles were evaluated.

This report contains a discussion of the SASW test method that was used at the NEES Garner Valley Test Site. The SASW testing and analysis procedures are described, and results of the measurements are presented.

Overview of the SASW Test Method

The SASW test method is a nondestructive and nonintrusive seismic method. The method utilizes the dispersive nature of Rayleigh-type surface waves propagating through a layered material to determine the shear wave velocity profile into the material (Reference 1). In this context, dispersion arises when surface wave velocity varies with wavelength or frequency. Dispersion in surface wave velocity arises from changing stiffness properties of the soil and rock layers with depth. This phenomenon is illustrated in Figure 1 for a multi-layered solid. A high-frequency surface wave, which propagates with a short wavelength, only stresses material near the exposed surface and thus only samples the properties of the shallow, near-surface material

(Figure 1b). A lower-frequency surface wave, which has a longer wavelength, stresses material to a greater depth and thus samples the properties of the shallower and deeper materials (Figure 1c). Spectral analysis is used to separate the waves by frequency and wavelength to determine the experimental ("field") dispersion curve for the site. An analytical procedure is then used to theoretically match the field dispersion curve with a one-dimensional layered system of varying layer stiffnesses and thicknesses (Reference 2). The one-dimensional shear wave velocity profile that generates a dispersion curve which matches the field dispersion curve is presented as the shear wave velocity profile at the site.

SASW testing involves generating surface waves at one point on the exposed material surface and measuring the motions perpendicular to the surface created by the passage of the surface waves at two or more locations. All measurement points are arranged on the exposed surface along a single radial path from the source. Successively longer spacings between the receivers and between the source and first receiver are typically used to measure progressively longer and longer wavelengths. Testing is performed with several sets of source-receiver spacings, and the totality of all sets of source-receiver spacings is called an SASW array.

Phase plots from surface wave propagation between the receivers are recorded for each receiver spacing. From each phase plot, the phase velocity of the surface wave can be calculated at each frequency from:

$$V_R = f \bullet \frac{360}{\phi} \bullet d \qquad (1)$$

where V_R is the Rayleigh-wave phase velocity in ft/sec or m/s, f is the frequency in Hertz (cycles per sec), ϕ is the phase angle in degrees (at frequency f), and d is the distance between the receivers in the same length units as used to represent V_R. From this calculation, a plot of phase velocity versus frequency, called an individual dispersion curve, is generated. This procedure is repeated for all source-receiver spacings used at the site and typically involves significant overlapping in the dispersion data between adjacent receiver sets. The individual dispersion curves from all receiver spacings are combined into a single, composite dispersion curve called the experimental or field dispersion curve.

Once the composite dispersion curve is generated for the site, an iterative forward modeling procedure is used to create a theoretical dispersion curve to match this experimental curve (Reference 2). The stiffness profile that provides the best match to the experimental dispersion curve is presented as the shear wave velocity, Vs, profile at the site.

Equipment Used at the NEES Garner Valley Test Site

The basic configuration of the source and receivers used in field testing at each array location is illustrated in Figure 2. The vertical component of three-dimensional velocity transducers were used as receivers. All of the velocity transducers were Mark Products Model L-4C transducers which have a natural frequency of 1 Hz.

Two types of sources were used to generate energy over the required frequency ranges. At shorter receiver spacings (5 ft to 20 ft), a sledge hammer was employed as a source. At longer spacings (50 ft to 400 ft), "T-Rex" (the nees @ UTexas mobile tri-axial shaker) was used as the source of the surface wave energy. T-Rex is shown in Figure 3.

The data acquisition system used in these tests was a VXI technology, 48-channel dynamic signal analyzer. The VXI system was used to collect the time records and to perform calculations in the frequency domain so that the relative phase of the cross-power spectrum was reviewed at each receiver spacing. This process also allowed the operator to subjectively evaluate the data being collected in the field to assure consistency with the expected Rayleigh wave propagation in a layered halfspace.

V_S Profiles from SASW Testing at the Garner Valley Test Site

A total of three shallow and two deeper shear wave velocity (V_S) profiles was generated at the NEES Garner Valley Test Site. The general locations of the SASW sites, superimposed on an existing illustration of the test site, are shown by the blue lines in Figure 4.

Figures 5 through 9 show the composite experimental dispersion curves that were constructed from the data collected in the field at each SASW array. The theoretical dispersion curves that are fitted to these experimental dispersion curves are also shown in the figures. The two deeper shear wave velocity profiles are presented in Figure 10. The average, shallow shear wave velocity profile determined from the three SASW arrays conducted around the SFSI structure is presented in Figure 11. Tabulated values of shear wave velocity profiles are presented at Tables 1 through 3.

Discussion of V_S Profiles

The two deeper shear wave velocity profiles shown in Figure 10 are well determined. This opinion is based on the small scatter shown in the composite field dispersion curves combined with the close fit between the field and theoretical dispersion curves at each site. At Site 1 (close to the parking lot), the short receiver spacings were located on a poorly constructed gravel road which is the reason for the slightly higher V_s values near the surface and the increased variability. Also, each V_s profile is only presented to a depth of about one-third of the maximum wavelength ($\lambda_{max}/3$) measured in the field.

It is interesting to note in Figure 10 that there is a significant increase (jump) in V_s at an average depth of about 80 ft, with this boundary about 5 ft shallower for the site close to the parking lot.

The average, shallow V_s profile around the SFSI structure is (essentially) constant in the top 10 ft as shown in Figure 11. (In this case, the profile is shown to a depth of $\lambda_{max}/2$ because the profile is constant.) The measured and theoretical curves fit well for Sites 3 and 4. However, significant variability was measured in the field at Site 5. A constant V_s value of 680 fps is still a reasonable average for Site 5, but there is softer material within the depth range of 2 to 4 ft at this site.

References

1. Stokoe, K.H., II, Wright, S.G., Bay, J.A. and J.M. Roesset (1994), "Characterization of Geotechnical Sites by SASW Method," *ISSMFE Technical Committee 10 for XIII ICSMFE*, Geophysical Characteristics of Sites, A.A. Balkema Publishers/Rotterdam & Brookfield, Netherlands, pp. 785-816.

2. Joh, S.-H. (1996), "Advances in Interpretation and Analysis Techniques for Spectral-Analysis-of-Surface-Waves (SASW) Measurements," Ph.D. Dissertation, The University of Texas at Austin.

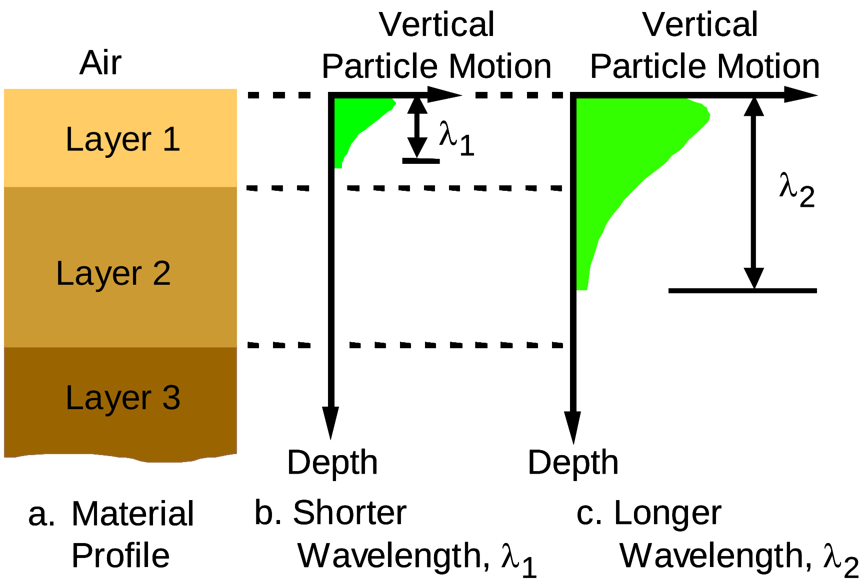

Figure 1 Illustration of surface waves with different wavelengths sampling different materials in a layered system which results in dispersion in wave velocities.

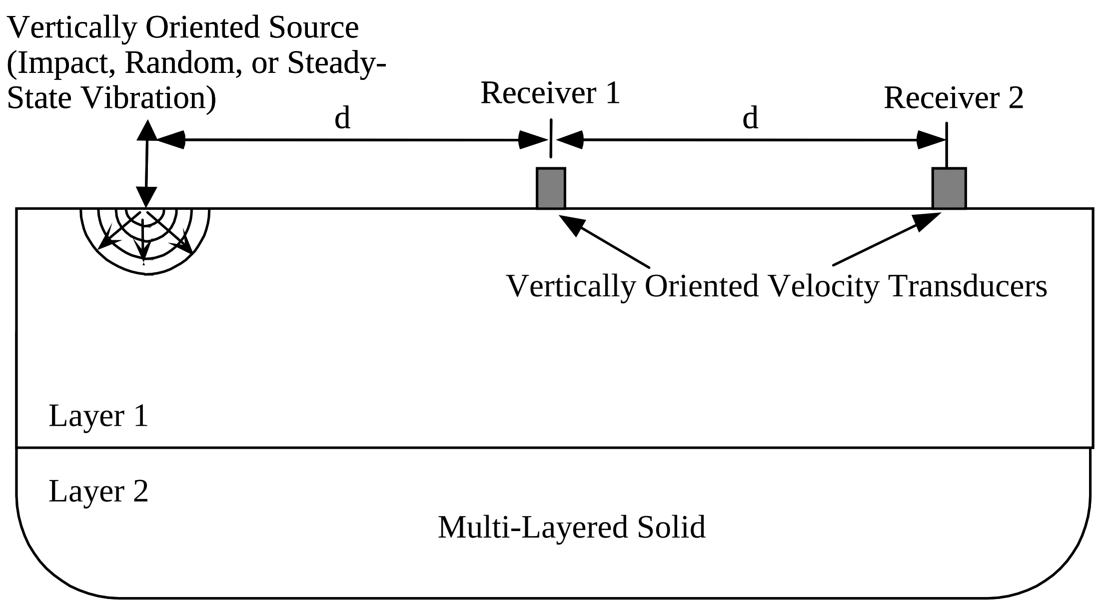

Figure 2 Schematic diagram of the generalized equipment arrangement used in spectral-analysis-of-surface-waves (SASW) testing.

Figure 3 "T-Rex" Tri-axial Vibrator was used as the source of energy for deeper shear wave velocity profiling.

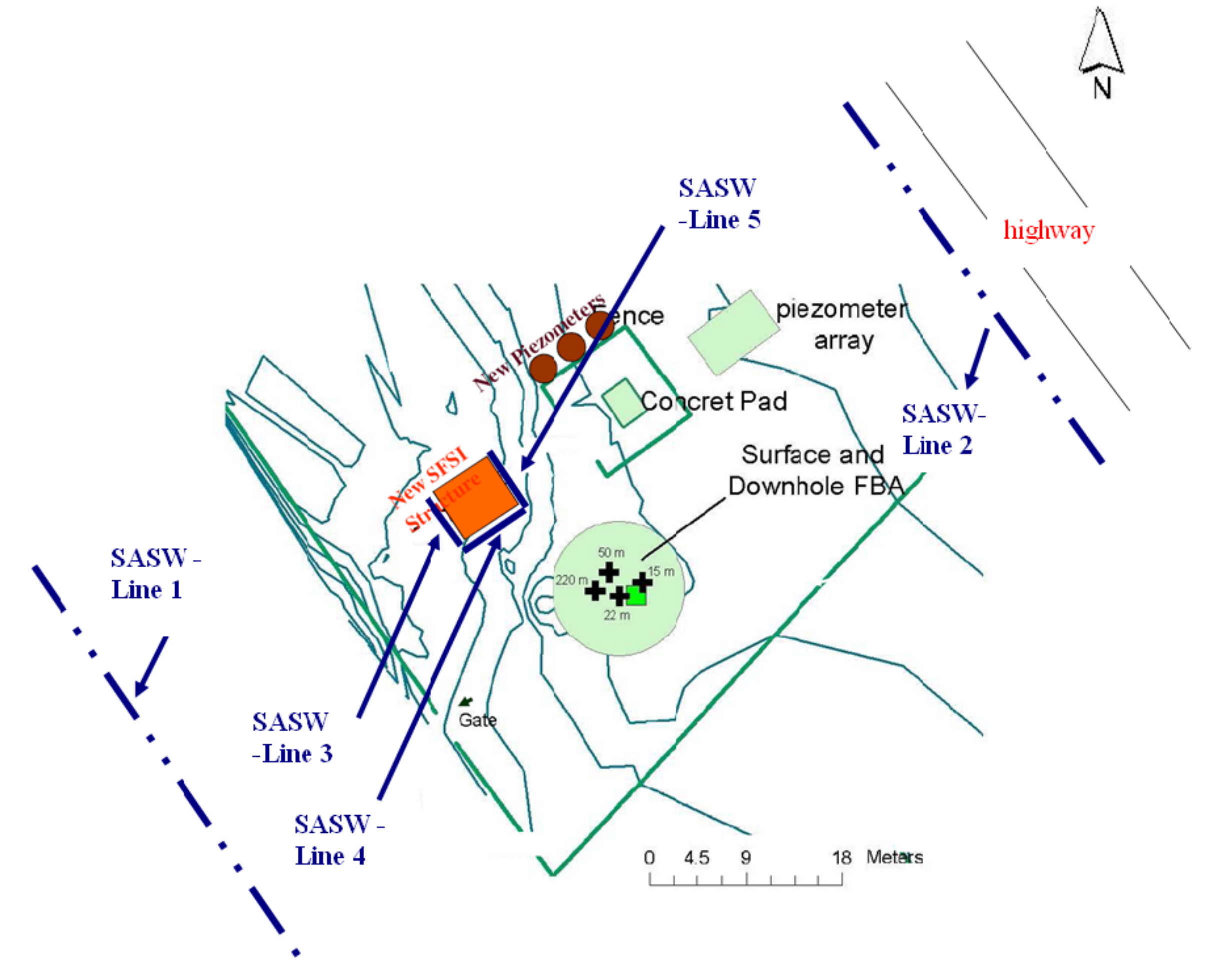

Figure 4 General locations of the SASW arrays tested at Garner Valley Test Site. Lengths of the lines representing arrays are not to the scale and locations of SASW Lines 1 and 2 are approximate.

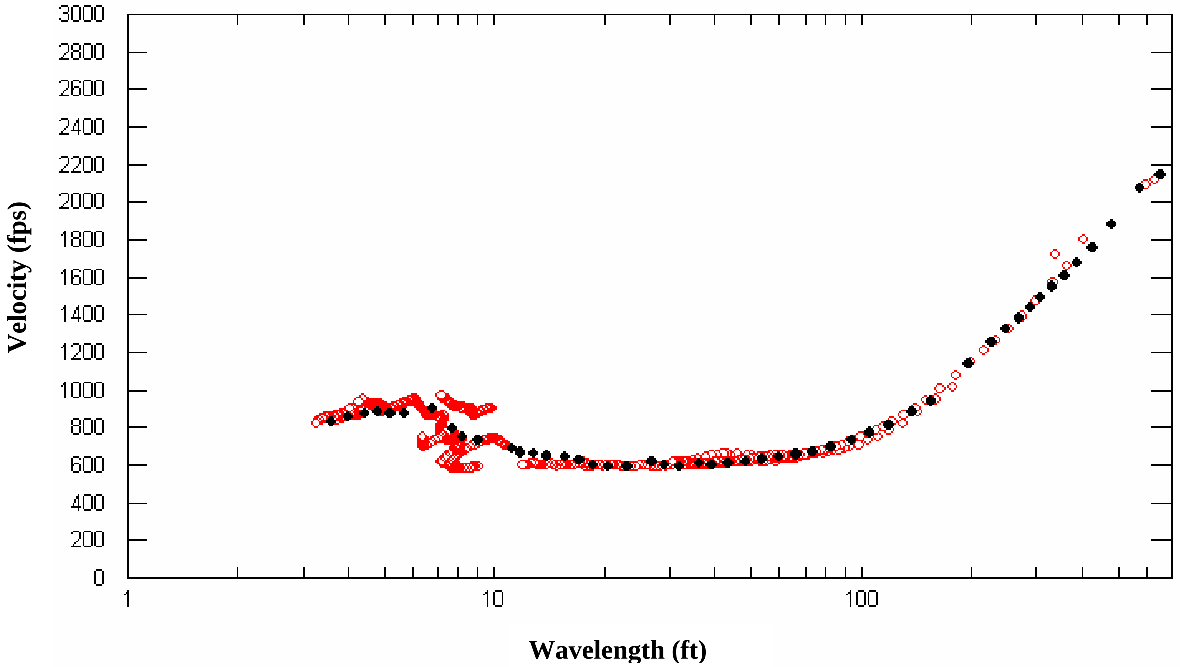

Figure 5 Theoretical dispersion curve fit to the composite experimental dispersion curve at SASW-Line 1 (close to parking lot). Hollow red data points represent the composite experimental curve, and the solid black data points represent the theoretical dispersion curve.

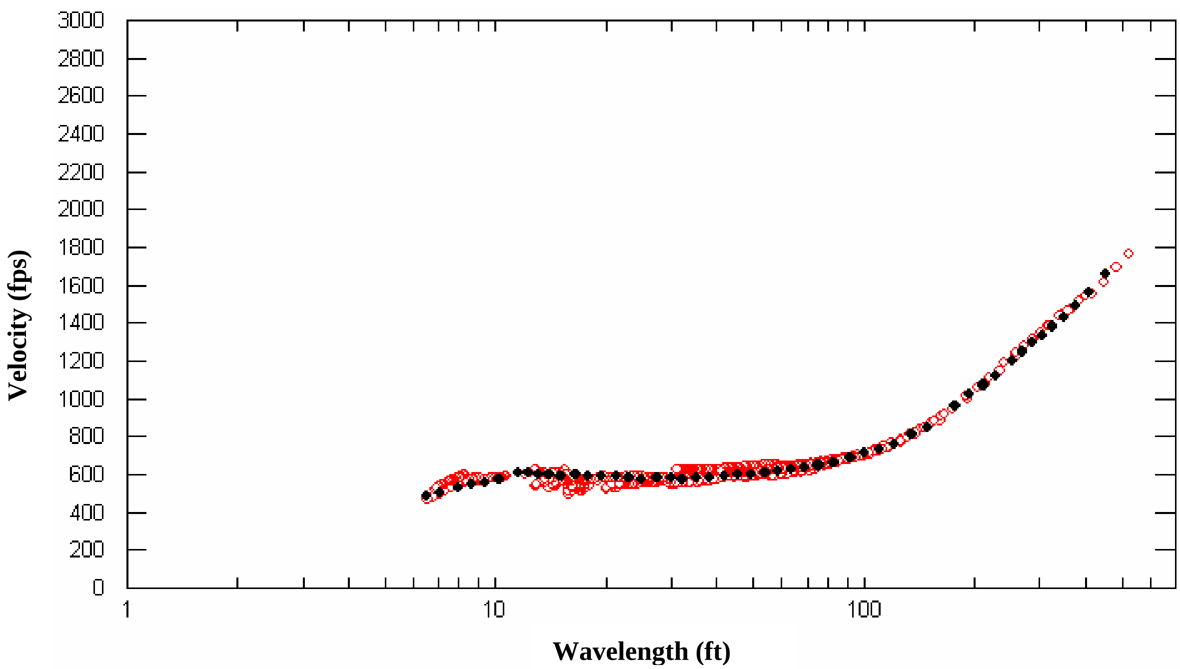

Figure 6 Theoretical dispersion curve fit to the composite experimental dispersion curve at SASW-Line 2 (close to highway). Hollow red data points represent the composite experimental curve, and the solid black data points represent the theoretical dispersion curve.

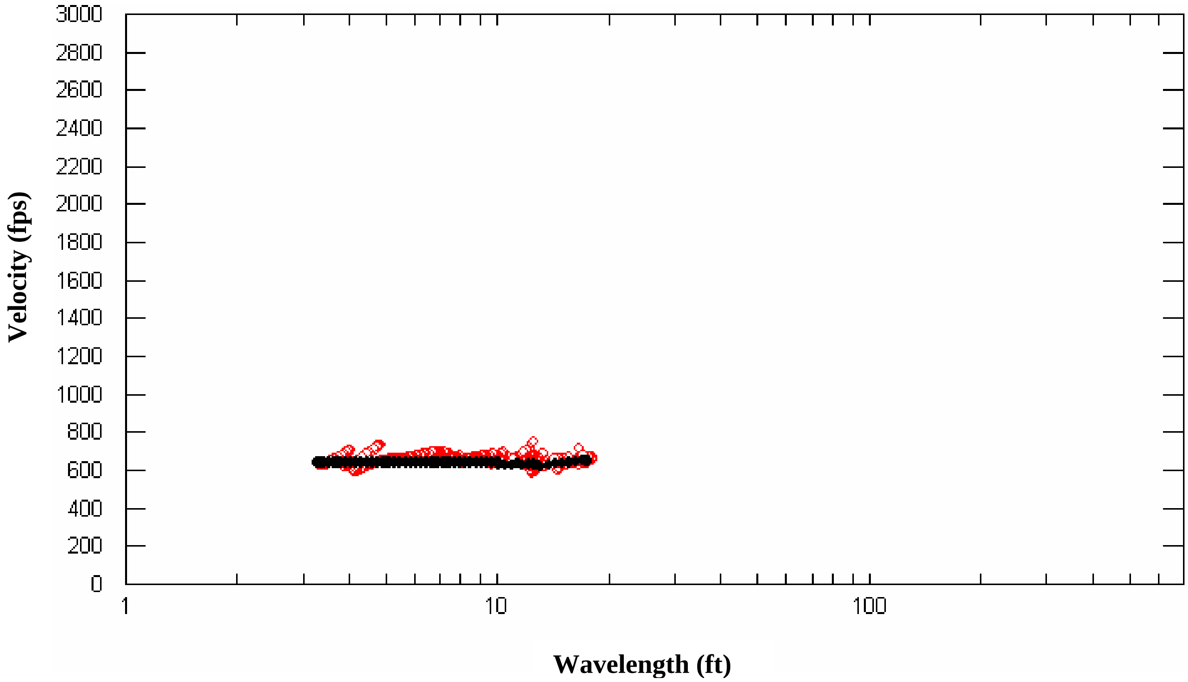

Figure 7 Theoretical dispersion curve fit to the composite experimental dispersion curve at SASW-Line 3 (around SFSI structure). Hollow red data points represent the composite experimental curve, and the solid black data points represent the theoretical dispersion curve.

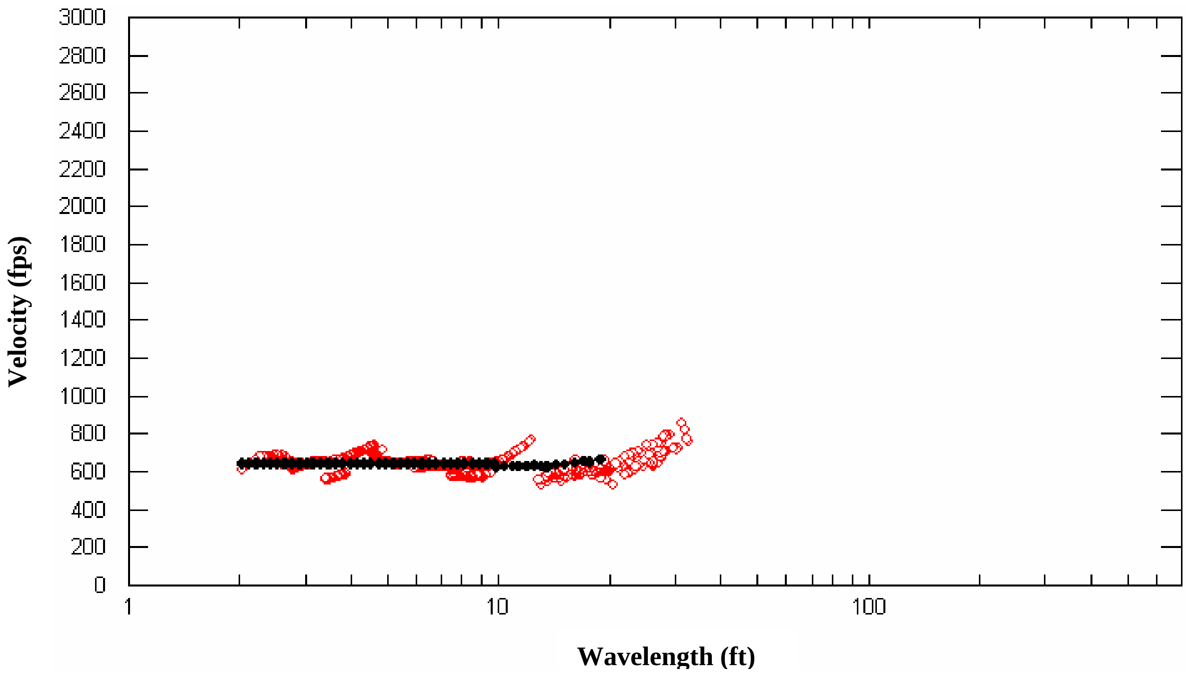

Figure 8 Theoretical dispersion curve fit to the composite experimental dispersion curve at SASW-Line 4 (around SFSI structure). Hollow red data points represent the composite experimental curve, and the solid black data points represent the theoretical dispersion curve.

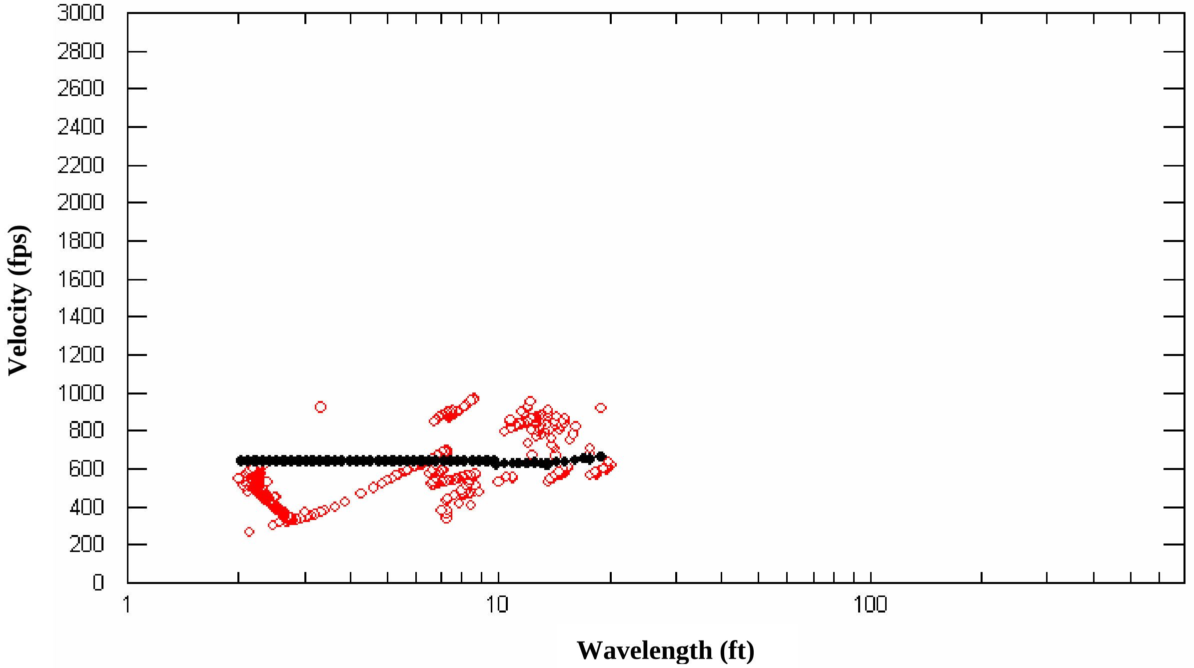

Figure 9 Theoretical dispersion curve fit to the composite experimental dispersion curve at SASW-Line 5 (around SFSI structure). Hollow red data points represent the composite experimental curve, and the solid black data points represent the theoretical dispersion curve.

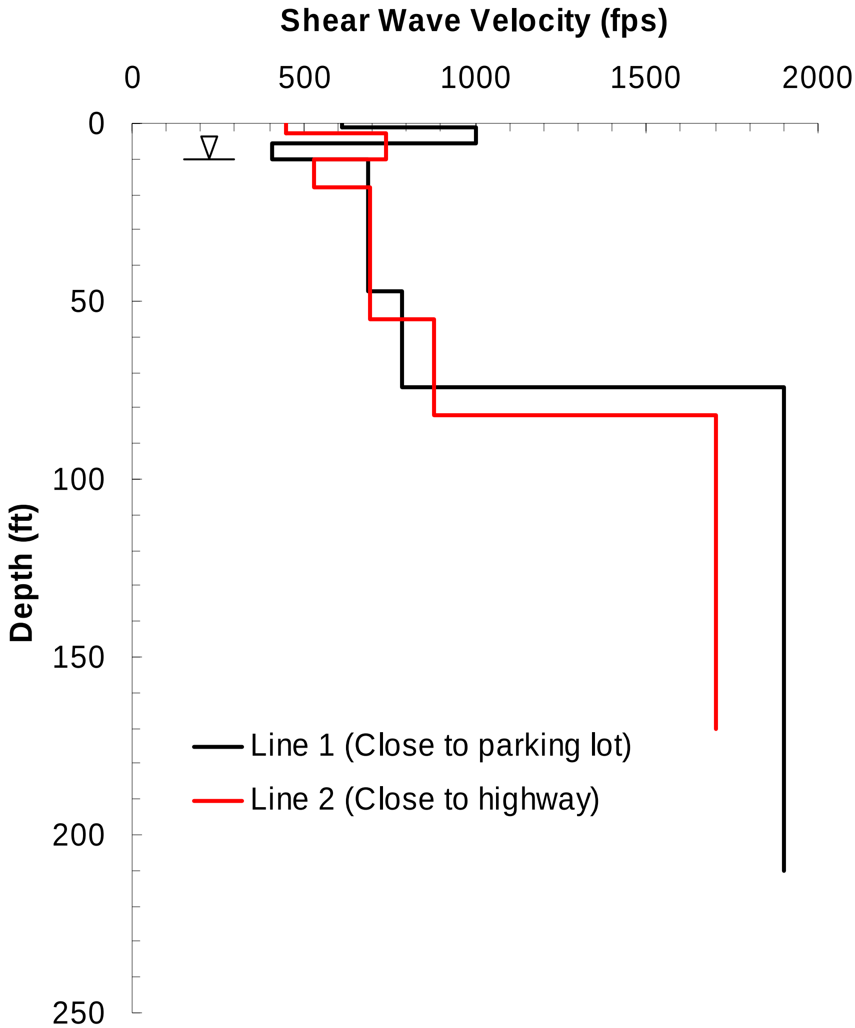

Figure 10 Deeper shear wave velocity profiles determined from SASW testing at the Garner Valley Test Site.

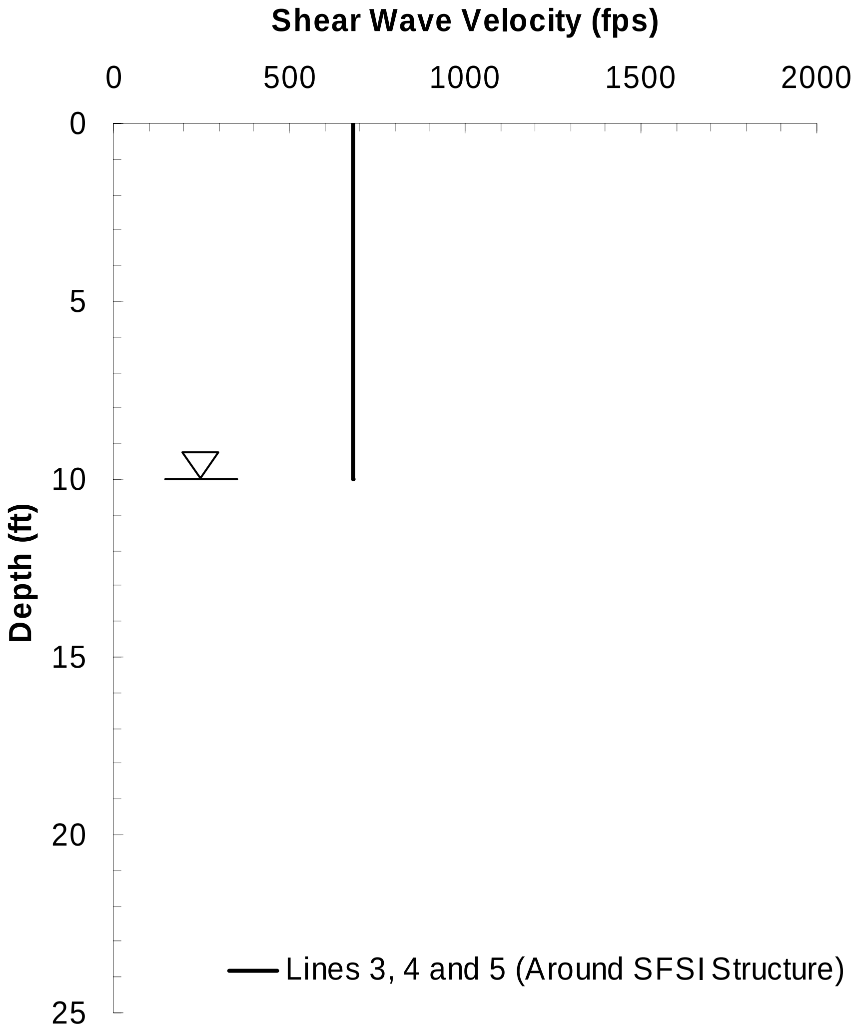

Figure 11 Shallow shear wave velocity profiles around SFSI structure determined from SASW testing at the Garner Valley Test Site.

Table 1. Tabulated values of wave velocity profile from SASW testing at the Garner Valley Test Site; SASW- Line 1 (close to parking lot).

Depth to Top of Layer (ft)	**Layer Thickness (ft)**	**Compression Wave Velocity* (fps)**	**Shear Wave Velocity (fps)**	**Assumed Poisson's Ratio**	**Assumed Total Unit Weight (pcf)**
0	1	1141	610	0.30	110
1	4.5	1871	1000	0.30	110
5.5	4.5	767	410	0.30	110
10	37	5000	690	0.49	125
47	27	5000	790	0.49	125
74	halfspace	5000	1900	0.42	125

*Based on the shear wave velocity and assumed value of Poisson's ratio above the water table. Below the water table, V_p was assumed equal to 5000 fps.

Table 2. Tabulated values of wave velocity profile from SASW testing at the Garner Valley Test Site; SASW- Line 2 (close to highway).

Depth to Top of Layer (ft)	**Layer Thickness (ft)**	**Assumed Compression Wave Velocity (fps)**	**Shear Wave Velocity (fps)**	**Assumed Poisson's Ratio**	**Assumed Total Unit Weight (pcf)**
0	3	841.9	450	0.30	110
3	7	1384.4	740	0.30	110
10	8	5000	530	0.49	125
18	37	5000	695	0.49	125
55	27	5000	880	0.48	125
82	halfspace	5000	1700	0.43	125

*Based on the shear wave velocity and assumed value of Poisson's ratio above the water table. Below the water table, V_p was assumed equal to 5000 fps.

Table 3. Tabulated values of wave velocity profile from SASW testing at the Garner Valley Test Site; SASW- Lines 3, 4 and 5 (around SFSI structure).

Depth to Top of Layer (ft)	**Layer Thickness (ft)**	**Assumed Compression Wave Velocity (fps)**	**Shear Wave Velocity (fps)**	**Assumed Poisson's Ratio**	**Assumed Total Unit Weight (pcf)**
0	10	1272.2	680	0.30	110
10	10	5000	680	0.49	125
20	halfspace	5000	1000	0.48	125

*Based on the shear wave velocity and assumed value of Poisson's ratio above the water table. Below the water table, V_p was assumed equal to 5000 fps.