The Spectral Analysis of Surface Waves Measured at William Street Park, San Jose, California, Using Swept-Sine Harmonic Waves

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INTRODUCTION

William Street Park, San Jose is the location of a blind experiment to assess a variety of invasive and non-invasive techniques for characterizing the shear wave velocity characteristics of the site. In this study, we use an active source approach that employees frequency-controlled harmonic waves to measure the dispersive nature of surface waves in the ground. Three independent inversion algorithms are used to invert shear wave velocities for the upper 30 meters of the soil column. The testing at William Street park indicates that the shear wave velocity in the upper 30 meters is highly variable and that a uniform model ($V_{s,30m}$) or unit-averaged model poorly characterizes the complexity of soil stiffness at this site. The three inverted shear wave velocity profiles indicate that the uppermost 9 meters of the soil has low velocity near the surface (~80 m/s) that monotonically climbs to between 195-225 m/s at a depth of 9 meters. At depths greater than 9 meters, all three profiles indicate that that there is a low shear wave velocity zone to a depth of about 16 meters. The site profile then climbs, with increasing depth, to between 270 m/s and 340 m/s at 30 meters depth. The 30 meter averaged shear wave velocity values for the three inversions models are 210 m/s (WinSASW, University of Texas); 196 m/s (WaveEQ, OYO); and 219 m/s (inverse.m, Georgia Tech). Our preferred profile, presented to the CCOC Workshop organizer prior to workshop is the WaveEQ profile that produced the lowest 30-meter average velocity.

METHODS

Spectral Analysis of Surface Waves (SASW) testing is an inexpensive and efficient means for non-invasively estimating the stiffness properties of the of the ground. Prior to the development of non-invasive surface wave methods, shear waves were measured in cased boreholes or penetration test using a conventional travel-time approach. Unlike surface wave methods, logging cased boreholes and penetration testing are expensive. Furthermore, static penetration tests (e.g. Dilatometer and CPT) often cannot sound to useful depths because of the stiffness or coarse texture of the soil. Surface wave test apparatus is highly portable allowing for measurements in difficult and remote locations

One of the surface wave testing systems of the USGS Coastal and Marine Geology was set up at William Street Park by a crew of 2 people. The apparatus consists of 1-Hz seismometers, low frequency spectrum analyzer, computer-controlled continuous harmonic-wave source (shaker) and amplifier, cables and a small 3kW generator. The shaker-source produces a continuous harmonic-wave that saturates the ground with surface waves of a specific frequency. For a given frequency, the cross power spectra and phase-angle between the outboard and reference seismometers are computed. The test steps through a suite of frequencies, for which, phase computations are made. This method of swept-sine surface wave testing will sweep through a broad range of low frequencies in order capture the surface wave-dispersion characteristics of the ground. This approach is a modification of the traditional random-noise impact SASW test (Stokoe and Nazarian, 1985).

The 1-Hz Kinemetrics receivers we use are designed for capturing vertical motions and cover the frequency range of interest in the active-source surface-wave test. For each source receiver configuration, surface waves are generated by the shaker, controlled by an output waveform from the spectral analyzer. An amplifier boosts the analyzer signal in order to drive the electromechanical motor in the shaker. The receivers measure the waves and a fast Fourier transform (FFT) is performed on each of the four receiver signals. In near-real-time, the linear spectra, cross power spectra, and coherence are computed. The ability to perform near real-time frequency domain calculations and monitor the progress and quality of the test allows us to adjust various aspects of the test to optimize the capture of the phase data. These aspects include the source-wave generation, frequency step-size between each sine-wave burst, number of cycles-per-frequency, total frequency range of all the steps, and receiver spacing.

We adopted common source-midpoint geometry in our array set up (Figure 1). To do this, we placed the harmonic-source at the centerline of the survey with the forward and reverse direction sensor-pairs equidistant from the source for each given array spacing. This configuration allows us to merge the forward and reverse direction dispersion curves if they are similar. In order to build a merged dispersion profile for the site, several different receiver spacings are used to capture the high-, medium-, and low-frequency ranges of the surface wave dispersion. Spacing of the receivers stepped geometrically from 1 meter to 64 meters, i.e. 1, 2, 4, 8, 16, 32, and 64 meters. The two seismometers are separated by a given distance, d, and the source is usually placed at a distance of 2d from the inner seismometer. When the array separation increases to a point where the d:2d spacing becomes impractical, either due to space limitations, cable limits, or the attenuation, the array spacing is changed to d:d. Prior investigations have shown that array spacing ratios between d:d and d:2d are a good compromise in minimizing near field effects and distant-wave attenuation.

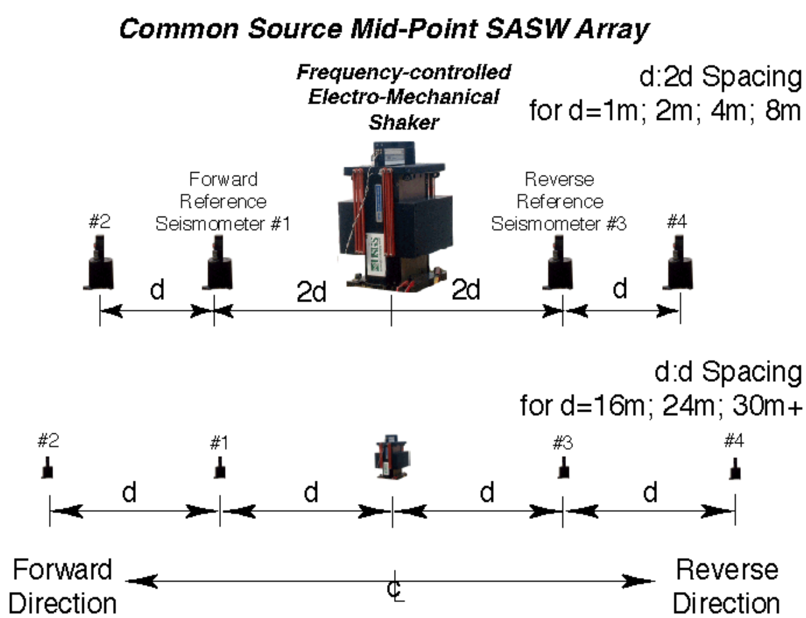


Figure 1. Configuration of the USGS-surface wave testing system, composed of 1-Hz sensors and a 100 kg electro-mechanical shaker. The shaker apparatus allows for frequency-controlled swept-sine analysis. Array separation changes from d:2d to d:d as forward and reverse sensors are configured for large array separations.

Rayleigh wave wavelengths (λ) are computed by relating the seismometer spacing (δ) and the phase angle (θ, in radians determeined from the cross-power spectra) between the seismometers:

$$\lambda = 2\pi\delta/\theta \qquad (1)$$

The Rayleigh wave surface wave velocity is computed as the product of the frequency and its associated wavelength:

$$V_r = \lambda f \qquad (2)$$

The grouped and average dispersion curves for the William Street site are presented in Figure 2 for a frequency range of 2-88 Hertz.

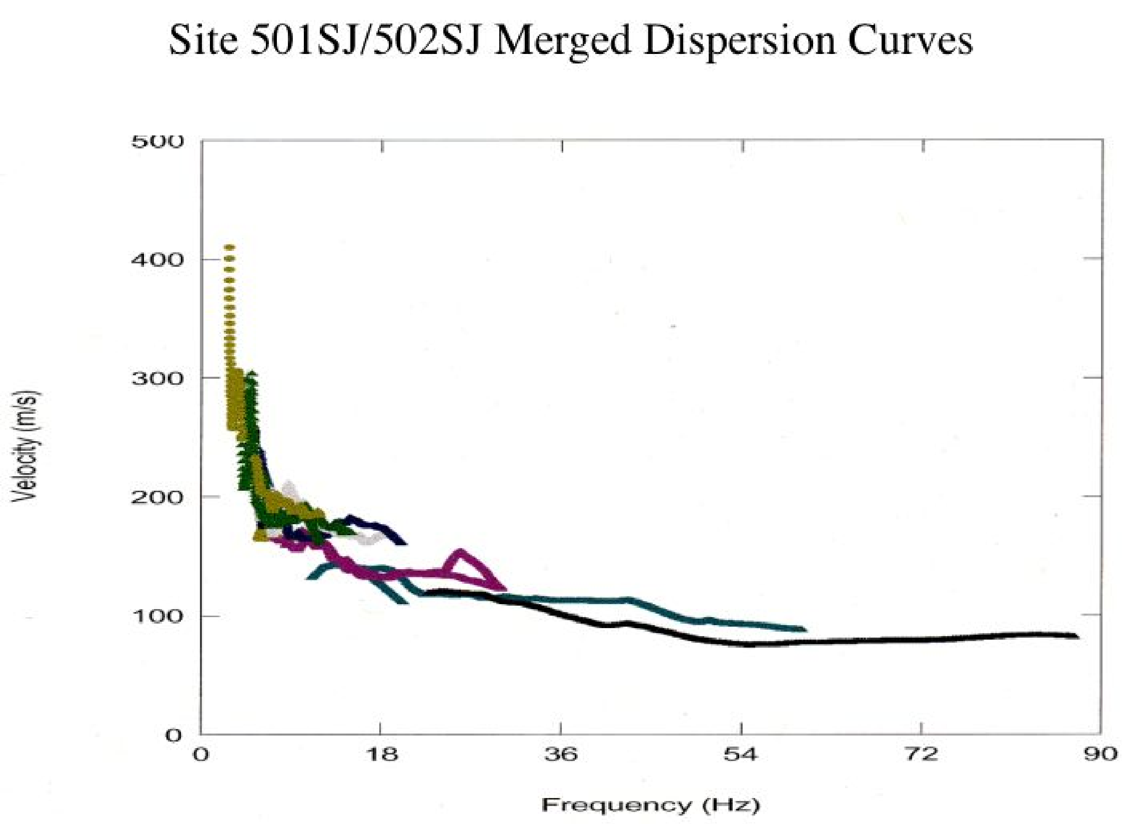
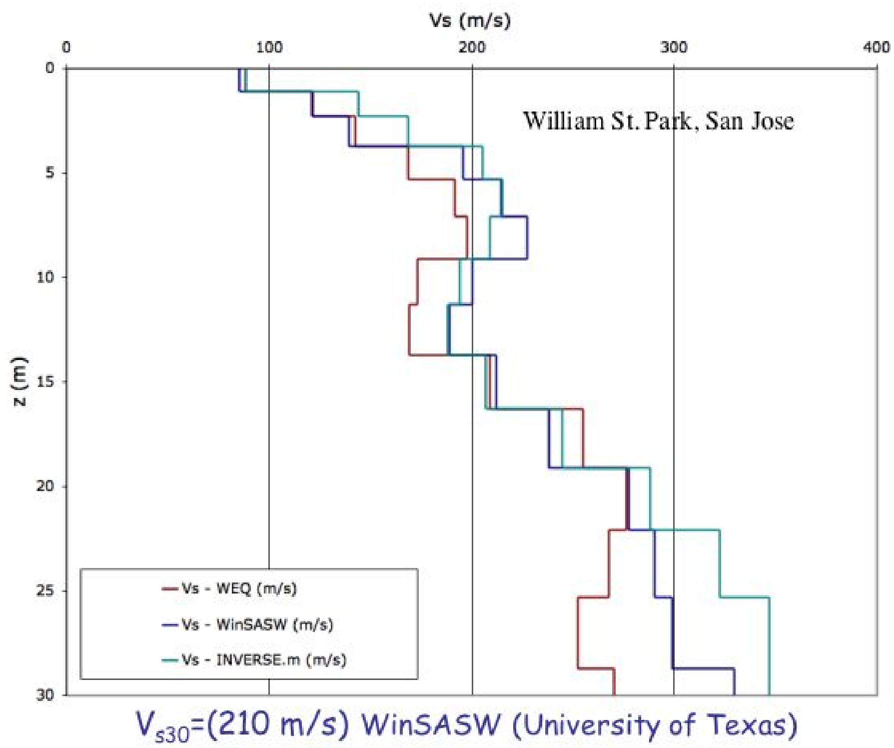


Figure 2. Dispersion curves for individual array spacing at William Street Park combined for the forward and reverse direction arrays.

We invert shear wave velocity profiles using three independent inversion codes. The Poisson ratio used in the inversions is 0.33 above the water table and 0.48 below the water table. The water table depth was estimated by observing the water depth in Coyote Creek adjacent to the test site. The inversion process is used to estimate the soil stiffness model whose computed *theoretical*-dispersion curve is a best-fit with the experimental dispersion data collected in the field. The term "best-fit" is intended to indicate the minimum non-linear least squares regression of the theoretical and experimental residuals. Two inversions algorithms, WaveEq of OYO Corp. (see Hayashi, this report; Hayashi and Kayen, 2003) and inverse.m of Georgia Tech (see Rix, this report; Lai and Rix, 1998), use an automated-numerical approach that employs a constrained least squares fit of the theoretical and experimental dispersion curves. The third algorithm, WinSASW of the University of Texas at Austin (see Stokoe, this report; Joh, 1996), solves for a theoretical dispersion curve through manual trial and error. Estimated shear wave velocity profiles from the three inversions for the William Street site are presented in Figure 3 to 30-meters depth.



V_{s30}=(210 m/s) WinSASW (University of Texas)
V_{s30}=(197 m/s) WaveEQ (OYO Corp)
V_{s30}=(219 m/s) inverse.m (Matlab, GaTech)

Figure 3. Shear wave velocity profiles to 30 meters at William Street park computed from three inversion algorithms. The three profiles classify the site as 'D' (IBC, 2003) and indicate similar heterogeneity of the soil column.

RESULTS

The testing at William Street park indicates that the shear wave velocity in the upper 30 meters is highly variable and that a uniform model ($V_{s,30m}$) or unit-averaged model poorly characterizes the complexity of the soil stiffness. The three inverted shear wave velocity profiles indicate that the uppermost 4 meters of the soil has low velocities, 80 and 200 m/s that monotonically climb to around 195-225 m/s at a depth of 9 meters. Below 9 meters, all three profiles indicate that the shear wave velocity falls below 210 m/s to a depth of about 16 meters and then climbs with increasing depth to between 270 m/s and 340 m/s at 30 meters depth. The 30 meter averaged shear wave velocity values for the inversions are 210 m/s (WinSASW, University of Texas); 196 m/s (WaveEQ, OYO); and 219 m/s (inverse.m, Georgia Tech). Our preferred profile, stated prior to the CCOC Workshop is the WaveEQ profile.

REFERENCES

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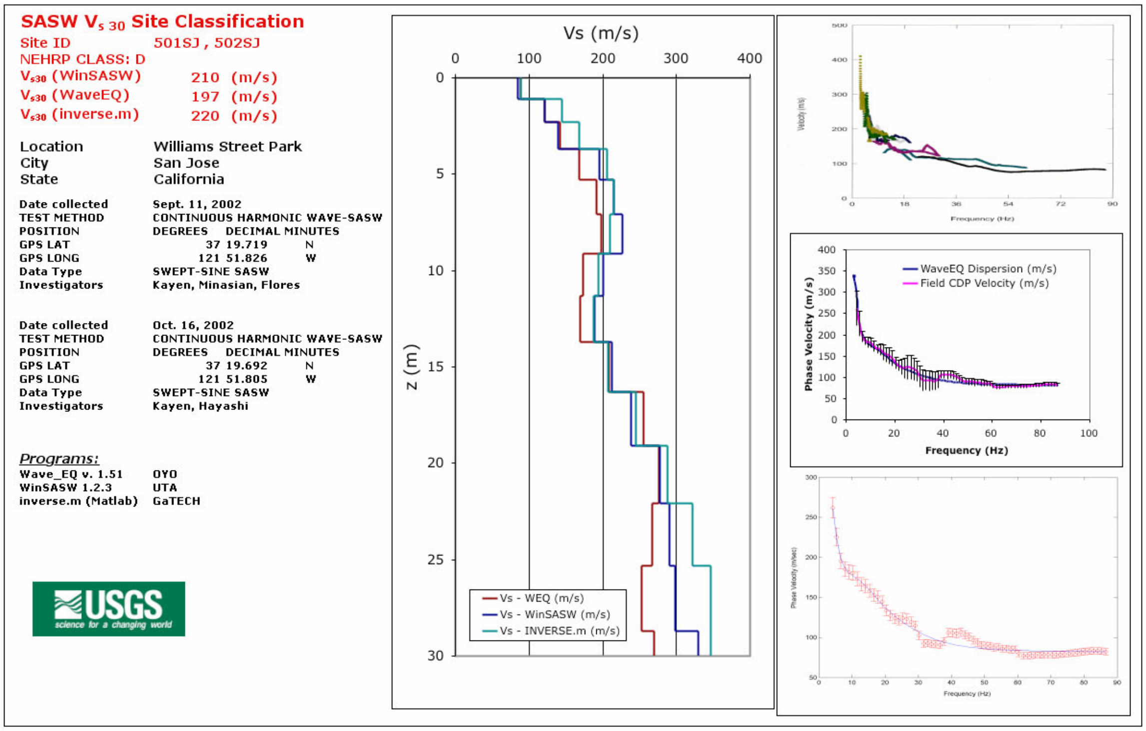
Appendix A.


SASW $V_{s\ 30}$ Site Classification
Site ID 501SJ , 502SJ
NEHRP CLASS: D
V_{s30} (WinSASW) 210 (m/s)
V_{s30} (WaveEQ) 197 (m/s)
V_{s30} (inverse.m) 220 (m/s)
Location Williams Street Park
City San Jose
State California
Date collected Sept. 11, 2002
TEST METHOD CONTINUOUS HARMONIC WAVE-SASW
POSITION DEGREES DECIMAL MINUTES
GPS LAT 37 19.719 N
GPS LONG 121 51.826 W
Data Type SWEPT-SINE SASW
Investigators Kayen, Minasian, Flores
Date collected Oct. 16, 2002
TEST METHOD CONTINUOUS HARMONIC WAVE-SASW
POSITION DEGREES DECIMAL MINUTES
GPS LAT 37 19.692 N
GPS LONG 121 51.805 W
Data Type SWEPT-SINE SASW
Investigators Kayen, Hayashi
Programs:
Wave_EQ v. 1.51 OYO
WinSASW 1.2.3 UTA
inverse.m (Matlab) GaTECH
USGS
science for a changing world
Vs (m/s)
z (m)
Vs - WEQ (m/s)
Vs - WinSASW (m/s)
Vs - INVERSE.m (m/s)
WaveEQ Dispersion (m/s)
Field CDP Velocity (m/s)
Phase Velocity (m/s)
Frequency (Hz)