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COMPARISON OF SHEAR-WAVE VELOCITY PROFILES FROM SASW AND DOWNHOLE SEISMIC TESTS AT A STRONG-MOTION SITE

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SUMMARY

The spectral-analysis-of-surface-waves (SASW) method is a relatively new in-situ method for determining shear-wave velocity profiles. Testing is performed on the ground surface, making it less costly than other methods that require boreholes. The basis of the SASW method is the dispersive characteristic of Rayleigh waves traveling through a layered medium. SASW testing consists of measuring surface-wave velocity at different frequencies to generate the dispersion curve for the site and interpreting it to obtain the corresponding shear-wave velocity profile.

To establish the reliability of this less direct technique, a “blind” evaluation of the SASW method was conducted by researchers at the University of Texas at Austin and the United States Geological Survey. SASW testing was performed at nine strong-motion stations at which borehole seismic measurements were previously made. The SASW data were interpreted independently of the borehole measurements and then systematically compared with the borehole results.

The results for Rinaldi Receiving Station are shown as a typical and uncomplicated example of the sites in the study. Generally, the shear-wave velocity profiles from SASW and downhole testing compare very well, which shows that the method works. Differences are due, in part, to lateral variability in the subsurface, the difference between borehole “point” and SASW “global” measurements, and values of Poisson’s ratio used in SASW modeling. The difference in predicted ground-motion amplification between the V_S profiles from SASW and downhole testing are less than about 5% for most frequencies, which is an inconsequential difference. This study demonstrates that in many situations the SASW method can provide V_S profiles suitable for site response predictions.

INTRODUCTION

In-situ shear-wave velocity profiles are used in a variety of earthquake engineering applications, such as site response studies, liquefaction analyses and soil-structure interaction evaluations. Borehole seismic methods such as the crosshole and downhole method traditionally have been employed to measure shear-wave velocity (V_S) in the field, since they are direct measurements. More recently, the OYO suspension logger has been used for this purpose, particularly in boreholes with depths of 100 m and more. Until now, seismic surface wave methods, involving either Love or Rayleigh waves, have received little attention. Surface wave methods involve more assumptions, unknowns, and numerical simulations than borehole methods. However, surface wave methods offer the advantage of being non-invasive and less costly than borehole methods. The spectral-analysis-of-surface-waves (SASW) method is a relatively new in-situ method that is based on evaluating Rayleigh-wave dispersion at a site from which the V_S profile is evaluated.

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The reliability of the SASW method needs to be established for it to gain widespread use in earthquake engineering. In a joint investigation between the University of Texas at Austin and the U.S. Geological Survey, the SASW method was used to evaluate V_S profiles independently of borehole measurements at several strong-motion recording sites in the 1991 Northridge Earthquake area in Southern California [Brown, 1998]. This study involved 12 sites, as shown in Figure 1. The joint study was undertaken to investigate the applicability and utility of the SASW method in this context.

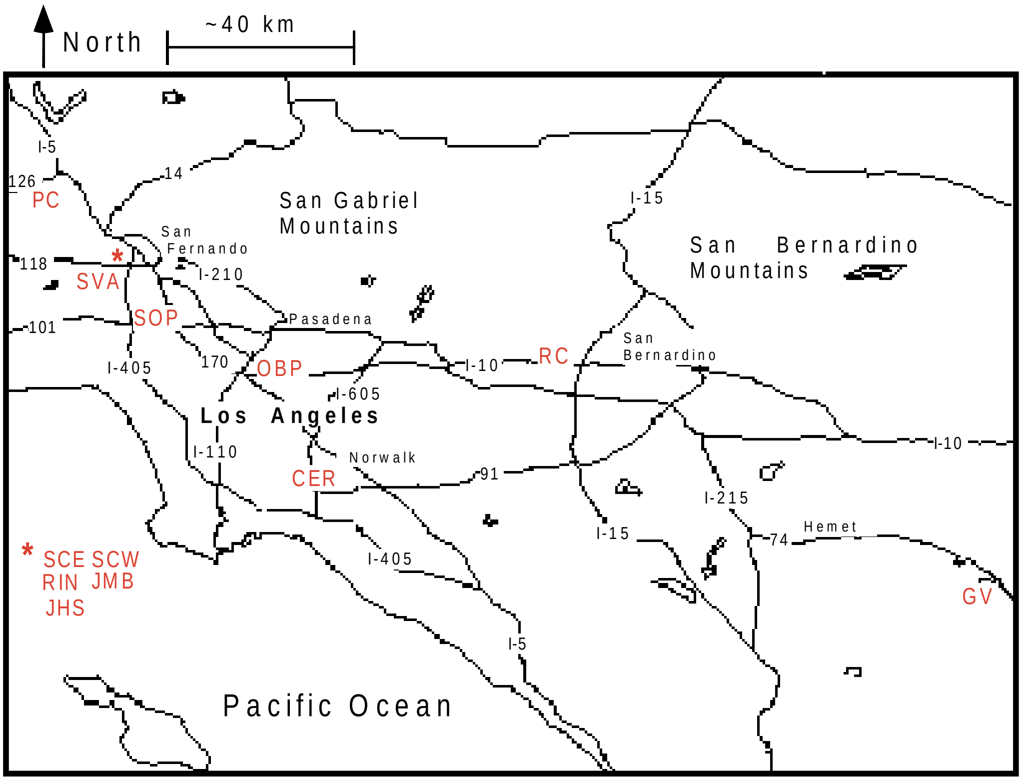


Figure 1. Site map of Los Angeles region showing the locations of SASW testing sites in this study. Rinaldi Receiving Station (RIN) is located near San Fernando.

The SASW method, described below, was used to collect surface wave dispersion data at each of the 12 sites shown in Figure 1. These data were interpreted using several theoretical models and an empirical analysis to produce V_S profiles to depths of up to 100 m at most sites. The profiles were then compared with independent borehole results, in terms of shear-wave velocity, average shear-wave velocity, and approximate predicted site response. To illustrate the results, the seismic measurements at the Rinaldi Receiving Station in Los Angeles, California, are presented.

OVERVIEW OF SASW METHOD

Spectral-analysis-of-surface-waves (SASW) testing, initially developed at the University of Texas at Austin, is an in-situ seismic method for determining shear-wave velocity profiles [Stokoe et al., 1994; Nazarian and Stokoe, 1994; Stokoe et al., 1989]. It is non-invasive and non-destructive, with all testing performed on the ground surface at strain levels in the soil in the elastic range (< 0.001%). From the modeled shear-wave velocity (V_S) profile, a small-strain shear modulus, G_{max}, profile can be determined using an estimated material density, ρ, as:

$$G_{max} = \rho * V_S^2. \tag{1}$$

The basis of the SASW method is the dispersive characteristic of Rayleigh waves when propagating in a layered medium. The phase velocity, V_R, depends primarily on the material properties (shear-wave velocity, mass density, and Poisson's ratio or compression-wave velocity) over a depth of approximately one wavelength. Waves of different wavelengths, λ, (or frequencies, f) sample different depths as illustrated in Figure 2. As a result of the variance in the shear stiffness of the layers, waves with different wavelengths travel at different phase velocities; hence, dispersion. A surface-wave dispersion curve, or dispersion curve for short, is the variation of V_R with λ or f. SASW testing consists of collecting surface-wave phase data in the field, generating the dispersion curve, and then using iterative modeling to back-calculate the shear stiffness profile.

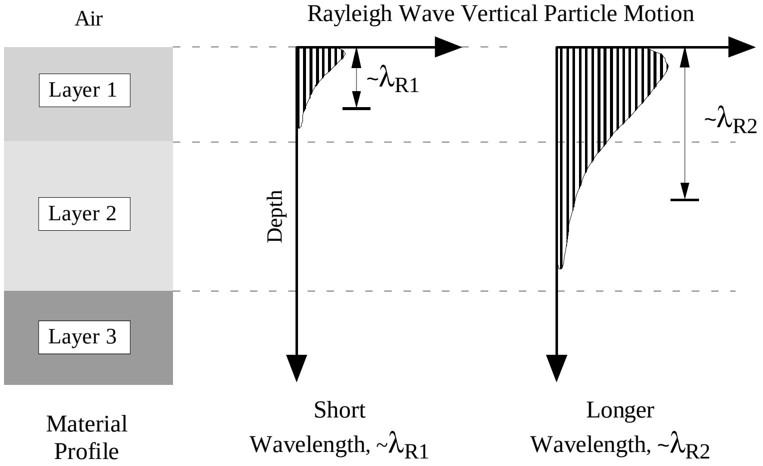


Figure 2. The theoretical basis of SASW testing is that Rayleigh waves of different wavelengths penetrate to different depths and sample different material.

A detailed description of the SASW field procedure is given in Brown [1998] and Joh [1997]. A vertical dynamic load is used to generate horizontally propagating Rayleigh waves. For this investigation, a Vibroseis truck, commonly used for seismic exploration in the oil industry, was used to generate the long wavelengths. Various hand-held hammers were used for the short wavelengths. The ground motions were monitored by two vertical receivers (70% critically damped 1-Hz geophones), and recorded by the data acquisition system (in this study, a dynamic signal analyzer). A schematic of this is shown in Figure 3. To minimize phase shifts due to differences in receiver coupling and subsurface variability, the source location is reversed. Theoretical as well as practical considerations, such as attenuation, necessitate the use of several receiver spacings to generate the dispersion curve over the wavelength range required to evaluate the stiffness profile to a depth of 100 m. As an example, interreceiver spacings of 1.8, 3.6, 7.6, 15.2, 30.5, 61, and 122 m were employed at the Rinaldi Receiving Station. The distance from the source to the first receiver was nominally the same as the interreceiver distance.

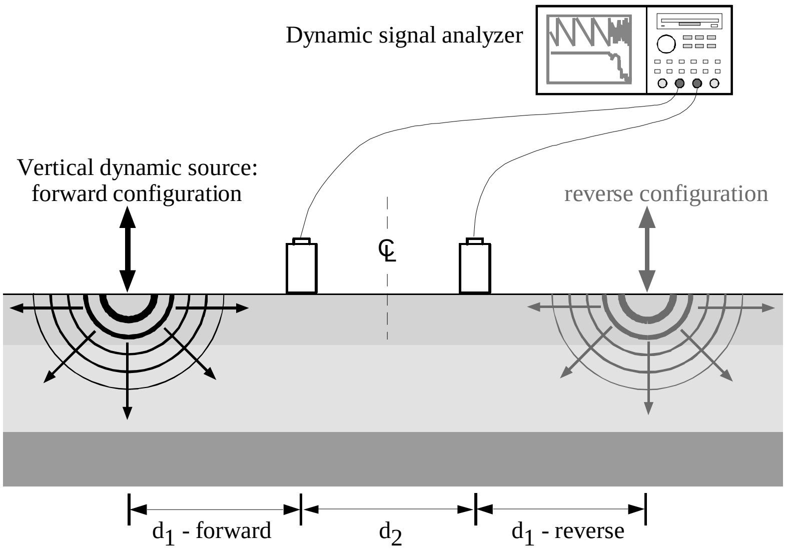


Figure 3. Basic configuration of SASW measurements (modified from Joh, 1997).

The dynamic signal analyzer performs the spectral calculations necessary to generate the dispersion curve from the recorded ground motions. After the time-domain motions from the two receivers are converted to frequency-domain records using the Fast Fourier Transform, the cross power spectrum and coherence are calculated.

The phase of the cross power spectrum, ϕ_w (f), represents the phase differences between the two receivers as the wavetrain propagates past them. It ranges from $-\pi$ to π in a wrapped form and must be unwrapped through an interactive process called masking. Phase jumps are specified, near-field data (wavelengths longer than twice the interreceiver distance), and low-coherence data are removed. The experimental dispersion curve is calculated from the unwrapped phase angle and the distance between receivers by:

$V_R = f * d_2/(\Delta\phi/360°)$,
(2)
where V_R is Rayleigh-wave phase velocity, f is frequency, d_2 is the distance between receivers, and $\Delta\phi$ is the phase difference in degrees. Since the composite dispersion curve from all receiver spacings contains thousands of data points that may have considerable scatter, an average (compact) dispersion curve is calculated.

WinSASW, a program developed at the University of Texas at Austin, is used to reduce and interpret the dispersion curve [Joh, 1992]. Through iterative forward modeling, a shear-wave velocity profile is found whose theoretical dispersion curve is a close fit to the field data. The final model profile is assumed to represent actual site conditions. Several options exist for forward modeling: a formulation that takes into account only fundamental-mode Rayleigh- wave motion (called the 2-D solution), and those that include all stress waves and incorporate receiver geometry (3-D solution) [Roesset et al., 1991].

An empirical relationship, referred to as the Lambda/3 approximation, can be applied to the dispersion data to obtain a highly smoothed variation of the shear-wave velocity with depth. This interpretational method was used in the steady-state Rayleigh wave method, the predecessor to the SASW method. It is given by:

$V_S = 1.1 * V_R$ at $z = \lambda/3$
(3)
where V_S is the assumed shear-wave velocity versus depth, z, and V_R is the phase velocity for a given Rayleigh-wave wavelength, λ.

SASW TESTING RESULTS AT RINALDI RECEIVING STATION

The location of SASW measurement at Rinaldi Receiving Station is shown in Figure 4. The composite and compact dispersion curves for Rinaldi Receiving Station and the match between the theoretical and compacted dispersion curves are shown in Figures 5a and 5b, respectively.

Interpretation (fitting) of the dispersion curve was blind; that is, no lithology or borehole velocity data were used in the modeling. The fundamental-mode Rayleigh-wave (2-D) solution and the full stress-wave solution with idealized receiver geometry (3-D global solution) were used to match the dispersion curves. For the 3-D global solution, a wavelength-dependent receiver spacing is assumed. The two receivers were assumed to be at two and four wavelengths from the receiver (2λ-4λ). The V_S profiles from the 2-D and 3-D global SASW solutions are shown in Figure 6a. Also shown are V_S profiles from the Lambda/3 approximation, OYO suspension logging [ROSRINE, 1996], and USGS downhole measurements [Gibbs et al., 1999]. The average V_S ($V_{S,ave}$) profiles are shown in Figure 6b. They are calculated from travel time, tt, from the surface to a given depth, z, by:

$V_{S,ave} = z/tt(z)$,
(4)
$tt(z) = \Sigma\ (h_i/V_{S,i})$,
(5)
where h_i is layer thickness and $V_{S,i}$ is the layer shear-wave velocity.

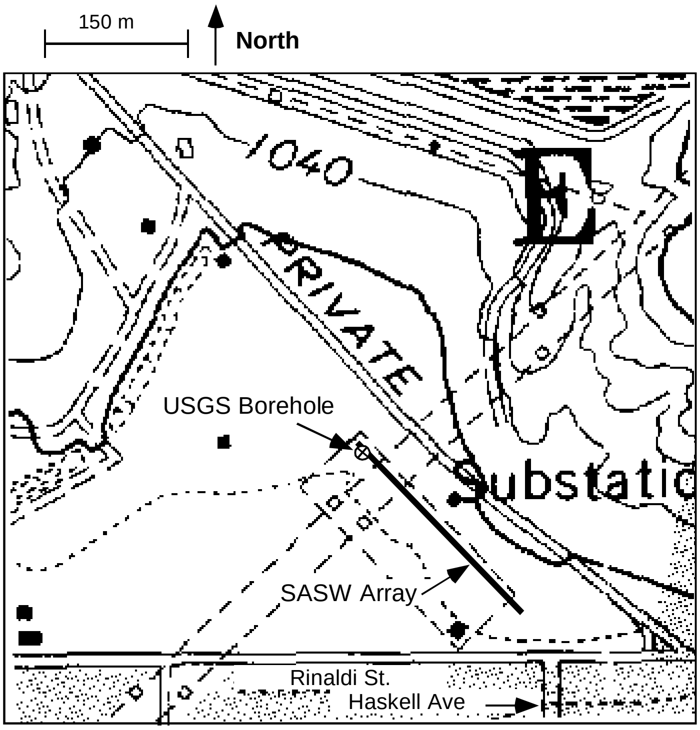
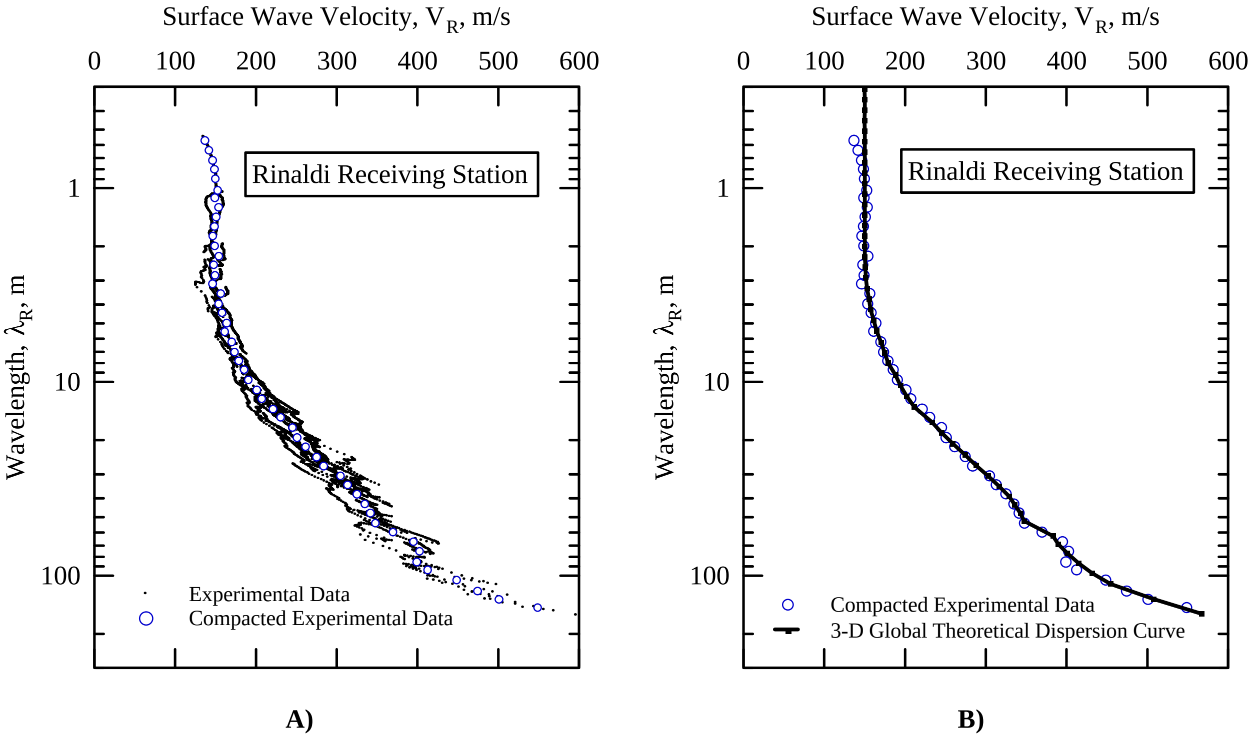
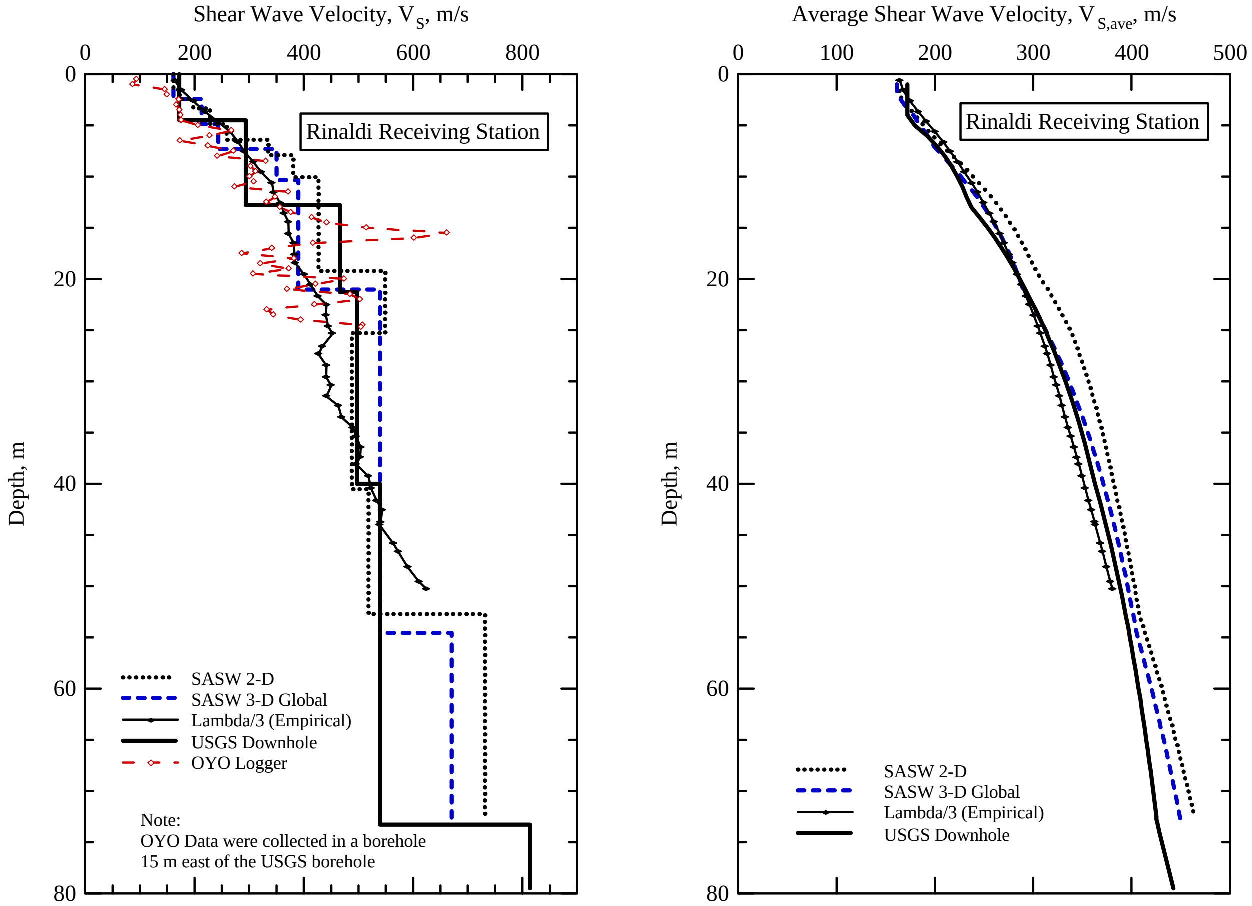


Figure 4. Site map for Rinaldi Receiving Station, showing approximate testing locations.



A) **B)**

Figure 5. A) Comparison of composite experimental and compacted dispersion curves for Rinaldi Receiving Station. B) Fit between compacted experimental and theoretical dispersion curves.



A) **B)**

Figure 6. A) Comparison of V_S profiles from SASW 2-D and 3-D solutions, Lambda/3 approximation, USGS downhole testing, and OYO suspension logging. B) Comparison of average V_S profiles from SASW 2-D and 3-D solutions, Lambda/3 approximation, and USGS downhole testing.

To estimate the differences between different V_S profiles in a manner relevant to earthquake site response, the quarter-wavelength amplification ratio was calculated. It is comparable to the ratio of the smoothed theoretical amplifications predicted by two different profiles [Boore and Brown, 1998]. The downhole V_S profile is used as the reference profile. For vertically propagating shear waves from a given source depth and velocity, assuming the different V_S profiles have the same density profile, the quarter-wavelength amplification ratio reduces to:

$$A_{SASW}(f) / A_{DH}(f)= [V_{S,ave,DH}(f) / V_{S,ave,SASW}(f)]^{0.5},$$
(6)

where A(f) is the frequency-dependent quarter-wavelength amplification approximation for SASW or downhole (DH) V_S profiles. Details on the quarter-wavelength amplification approximation are described by Boore and Joyner [1997]. The ratio is calculated at the same frequencies, based on travel time:

$$f(z) = 1/[4*tt(z)]$$
(7)

The frequencies are determined by the first mode of vibration of a system composed of a layer of thickness z and constant velocity equal to $V_{S,ave}$, over a halfspace. The quarter-wavelength amplification ratios for Rinaldi Receiving Station are shown in Figure 7.

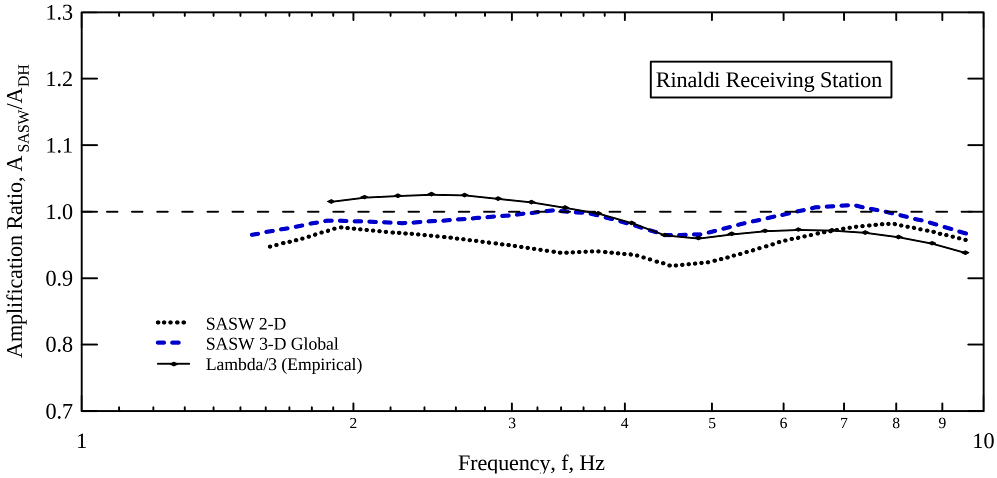


Figure 7. Amplification ratios versus frequency, assuming a quarter-wavelength approximation for earthquake site response, for Rinaldi Receiving Station. The USGS downhole profile is the reference profile.

DISCUSSION

Even though there is considerable scatter in the SASW dispersion data, there is good general agreement to a depth of around 50 m between the shear-wave velocity profiles from SASW testing and the USGS downhole seismic testing (Figure 6). The V_S profile from the 2-D solution is similar to that of the 3-D solution, with the velocities usually slightly higher. The OYO suspension logging data also exhibit a lot of variability, but is consistent with the other data, except near the surface, where the values are below the others. Since the suspension logging was done in a shallower borehole 15 m east of the USGS borehole, some difference is expected. The V_S profile from the empirical Lambda/3 approximation compares well with the other profiles.

Part of the difference between the V_S profiles from downhole and SASW testing is due to the different layer interfaces. Layer intervals for the downhole profile were selected based on observed travel times and the borehole lithology log, whereas no site information was used in the SASW analysis. Lateral variability may also contribute to differences in shear-wave velocity. The downhole profile is a point measurement of the subsurface properties, whereas SASW measurements are averaged along a horizontal distance extending approximately 240 m southeast from the USGS borehole (Figure 4). In many geologic environments, there may be significant changes in the subsurface over this distance, and these can be reflected in the SASW measurements.

The main reason for the difference in shear-wave velocity between the SASW and downhole V_S profiles is the value of Poisson's ratio used in the SASW models. A constant value of Poisson's ratio of 0.25 was used to calculate the compression-wave velocities from the shear-wave velocities in the theoretical models. If no other data are available, this is a reasonable assumption for unsaturated soils and rock. Since the water table is around 6 m at Rinaldi Receiving Station, the compression-wave velocities below that depth are much higher than in the SASW models. Since increasing the compression-wave velocities increases the Rayleigh-wave velocities, the effect of using a low value of Poisson's ratio is that the shear-wave velocities in the model are higher to compensate. The error in the shear-wave velocity is around 10% to 20% based on a sensitivity study [Brown, 1998]. The error in the predicted site response is much less and is only for lower frequencies, which are sensitive to the velocities at greater depths.

The average shear-wave velocity profiles largely remove the effect of layer interfaces. All of the profiles are fairly close, except the V_S profile from the 2-D solution, which is higher at depths greater than 10 m (Figure 6). For site response, the difference in absolute shear-wave velocity is not as important as that in average shear-wave velocity. The amplification ratios for the SASW 3-D global and Lambda/3 profiles are both within 5%, showing that the travel times through these SASW models are consistent with the downhole data (Figure 7). The amplification ratios for the 2-D model are still within 10%.

Because of the general trend of increasing shear-wave velocity with depth, all SASW interpretational methods performed fairly well. The full stress-wave solutions are expected to be more accurate than the fundamental-mode Rayleigh-wave solution if there are large velocity contrasts or velocity inversions in the profiles.

CONCLUSIONS

The SASW method offers the potential of evaluating shear-wave velocity profiles quickly and cost effectively. The comparison of V_S profiles from downhole seismic and SASW testing at Rinaldi Receiving Station is generally good. This study demonstrates that in many situations the SASW method can provide V_S profiles suitable for site response predictions. Details of the layering are less important than the average depth-dependence of the velocity. The difference in predicted ground-motion amplification between the V_S profiles from SASW and downhole testing are less than about 5% for most frequencies, which is an inconsequential difference.

SASW measurements are inherently different from borehole measurements since they average over a much larger area. Lateral variations and non-homogeneities in the subsurface may cause differences in the V_S profiles from the two methods, with the interesting point being that both sets of measurements correctly represent the material that has been sampled. Background information such as the approximate stratigraphy and depth to the groundwater table should be used in the SASW analysis for greater accuracy. At sites where there is a gradual increase in shear stiffness with depth, the fundamental-mode Rayleigh-wave dispersion model is a good approximation of the SASW experiment. At more complicated sites, surface-wave dispersion models that take into account receiver geometry, body-wave energy, and higher modes of Rayleigh-wave propagation will generally improve the solution.

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