0677

A SIMPLIFIED PROCEDURE TO MEASURE AVERAGE SHEAR-WAVE VELOCITY TO A DEPTH OF 30 METERS (VS30)

Leo T BROWN[1], John G DIEHL[2] And Robert L NIGBOR[3]

SUMMARY

This paper introduces a preliminary, simplified procedure for estimating the average shear-wave velocity in the upper 30 m (V_S30). V_S30 is used in the *NEHRP Provisions* and the new *1997 Uniform Building Code* to separate sites into different classes for engineering design. Unlike traditional shear-wave velocity measurements made in boreholes, the new method is based on Rayleigh wave propagation and is performed on the ground surface.

Rayleigh waves are dispersive when propagating through a layered medium. The Rayleigh-wave phase velocity varies with frequency or wavelength, depending mainly on the shear-wave velocity over a depth of approximately one wavelength. It is shown that Rayleigh-wave phase velocity at a wavelength of 36 m, V_R36, is highly correlated with V_S30. Fundamental-mode Rayleigh-wave dispersion curves were calculated for 40 seismic velocity profiles and simple linear regression was done to obtain a predictive equation for V_S30. The most practical equation is $V_S30 = 1.076\ V_R36$ (r^2=0.99), with a 95% confidence interval of approximately +/-10%.

Several tests were carried out to evaluate this new V_S30 method. V_S30 was estimated using V_R36 for ten velocity profiles not used in the regression analysis. The differences between actual and predicted values of V_S30 are within the +/-10% error bounds, with all site classes correctly predicted. In addition, surface-wave dispersion data were measured at two sites using a simplified version of the spectral-analysis-of-surface-waves (SASW) method and the estimated V_S30 compared with previously measured V_S30. Generally, the agreement is good, with differences due in part to lateral variability and the inherent differences between downhole and surface wave testing. Although further refinement is necessary, this method promises to be an accurate and cost-efficient way of determining V_S30.

INTRODUCTION

Shear-wave velocity (V_S) has long been known to be an essential parameter for evaluating the dynamic properties of soils. The average shear-wave velocity in the top 30 m, based on travel time from the surface to a depth of 30 m, is known as V_S30. V_S30 is used in the *NEHRP Provisions* [BSSC, 1994] and the new *1997 Uniform Building Code* to separate sites into different classes. The classifications are then used to determine the seismic coefficients for earthquake-resistant design. The expectation is that sites in the same class will respond similarly to a given earthquake. Other applications include seismic risk or PML studies, strength evaluation of existing structures, and characterization of seismic instrument sites.

Traditionally, V_S30 is determined by seismic measurements in boreholes, using the downhole, crosshole, or suspension logging methods. Faster and more cost-effective methods are needed to accurately measure V_S30. Techniques based on the inversion of surface-wave dispersion data offer the advantage of not requiring boreholes.

[1] *GEOVision, Division of Blackhawk Geometrics, 1785 Pomona Road, Suite B, Corona, CA 92880 Email: lbrown@geovision.com*
[2] *GEOVision, Division of Blackhawk Geometrics, 1785 Pomona Road, Suite B, Corona, CA 92880*
[3] *GEOVision, Division of Blackhawk Geometrics, 1785 Pomona Road, Suite B, Corona, CA 92880*

Spectral-analysis-of-surface-waves (SASW) testing is a proven, non-destructive seismic method that is used to determine the variation of shear-wave velocity (V_S with depth [Stokoe et al., 1994; Stokoe et al., 1989; Brown 1998]. The basis of the SASW method is the dispersive characteristic of Rayleigh waves when propagating in a layered medium. The Rayleigh-wave phase velocity primarily depends on the material properties (shear-wave velocity, compression-wave velocity or Poisson's ratio, and mass density) to a depth of one wavelength, as shown in Figure 1. The variation of phase velocity with frequency or wavelength is called the dispersion curve. See Figure 2. 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 corresponding V_S profile. From the V_S profile, V_S30 can be calculated.

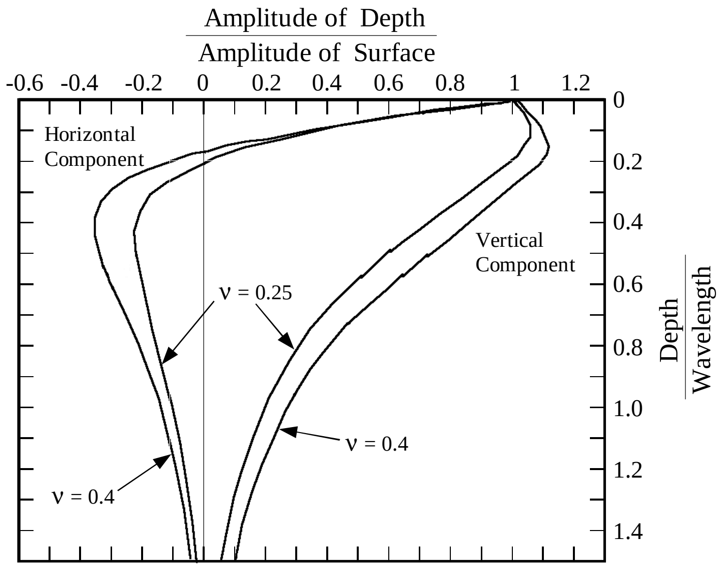


Figure 1. Variation of Rayleigh-wave particle motion with depth for a halfspace with different values of Poisson's ratio, ν, (modified from Woods [1968]).

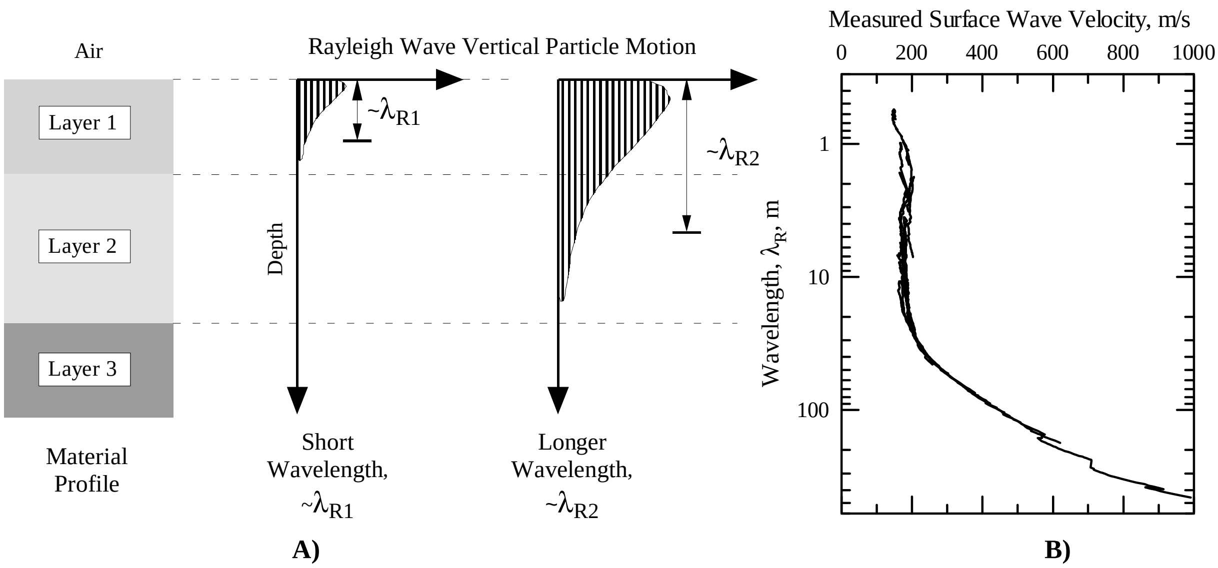


Figure 2. A) The theoretical basis of SASW testing is that Rayleigh waves of different wavelength penetrate to different depths and sample different material. B) The measured Rayleigh-wave dispersion curve is characteristic of the material properties at the site.

BASIS OF V_S30 METHOD

The V_S30 number alone contains much less information about the site than the complete V_S profile or dispersion curve. Therefore, it is probable that V_S30 can be obtained from less dispersion data and computational modeling. Several observations support this. Like V_S30, Rayleigh-wave phase velocities depend on the material properties averaged over depth. Average V_S profiles obtained from theoretical and simplified empirical analysis of dispersion curves both compare well with borehole V_S profiles, although there may be differences in the interval velocities in the different profiles [Brown, 1998].

The new method presented herein is a simplification of the SASW method, providing only a single number corresponding to the average shear-wave velocity in the top 30 m. Data acquisition is less extensive and faster, and the analysis is also simpler, so that a preliminary interpretation can be done on site. The method is based on the correlation between Rayleigh-wave phase velocity and V_S30, as described below. The field procedure consists of measuring only those phase velocities necessary to accurately estimate V_S30 using an empirical predictive equation.

The predictive equation was developed using linear regression on a set of Rayleigh-wave dispersion curves and V_S30 values that were calculated from seismic velocity profiles. Profiles were selected that contained shear- and compression-wave velocity (V_P) data from the surface to a depth of approximately 80 m or more. The requirement for V_S profiles with measured V_P profiles is necessary because the dispersion curve is affected by the V_P profile and V_S30 is not.

Of the 50 profiles selected, 26 are from downhole seismic testing, 20 are layered models interpreted from OYO suspension logging profiles, and 4 are of unknown method. The V_S, V_P profiles were selected from three main sources: the Pacific Engineering and Analysis database, USGS Open-file Report 99-xxx [Gibbs et al., 1999], and the ROSRINE data set [ROSRINE]. Twenty-eight sites are in Southern California, twenty are in Northern California, and two are located outside of California. Thirty profiles are site class D, and ten each belong to site classes E and C. The classification system is shown in Table 1. Since this new V_S30 method is intended for use at soil sites, rock sites were not included in the data set. The cumulative frequency plot of V_S30 for the data set is shown in Figure 3.

Table 1. Site classifications from the *NEHRP Provisions* [BSSC, 1994].

Soil Profile Type	Description	Geotechnical Properties
A	Hard rock	$V_S30 > 1500$ m/s
B	Rock	760 m/s $< V_S30 \leq$ 1500 m/s
C	Very dense soil and soft rock	360 m/s $< V_S30 \leq$ 760 m/s or $N > 50$ or $s_u \geq$ 100 kPa
D	Stiff soil	180 m/s $< V_S30 \leq$ 360 m/s or $15 \leq N \leq 50$, or 50 kPa $\leq s_u \leq$ 100 kPa
E	Soil	$V_S30 <$ 180 m/s or any profile with more than 3 m of soft clay with PI>20, $w \geq 40\%$, and $s_u <$ 25 kPa

For each V_S, V_P profile, the fundamental-mode Rayleigh-wave dispersion curve was calculated using WinSASW, a surface-wave modeling program developed at the University of Texas at Austin [Joh, 1992; Roesset et al., 1991]. Modeling was done in the wavelength rather than frequency domain, because wavelength is related more closely to depth of penetration. Phase velocities were calculated for wavelengths from 1 to 90 m. A constant mass density of 1.92 g/cc for each profile was assumed. This is reasonable because the effect of changes in mass density on phase velocity within the normal density range encountered in geotechnical engineering is small (1-2%), and density data were not available.

From the 50 profiles, data from 10 profiles were randomly selected (2 each from site classes E and C, 6 from site class D) and removed from the data set. Simple linear regression was done on the data from the remaining 40 profiles. V_S30 is most highly correlated with the Rayleigh-wave phase velocity at a wavelength of 36 m (V_R36). The regression plot and residuals are shown in Figures 4a and 4b respectively. The degree of correlation is high ($r^2 = 0.9879$) and the standard error is 13.7 m/s. The constant (y-intercept) was fixed at 0 because the effect on the regression was minimal. Based on the regression, the predictive equation for V_S30 is:

$$V_S30 = 1.076 * V_R36. \quad (1)$$

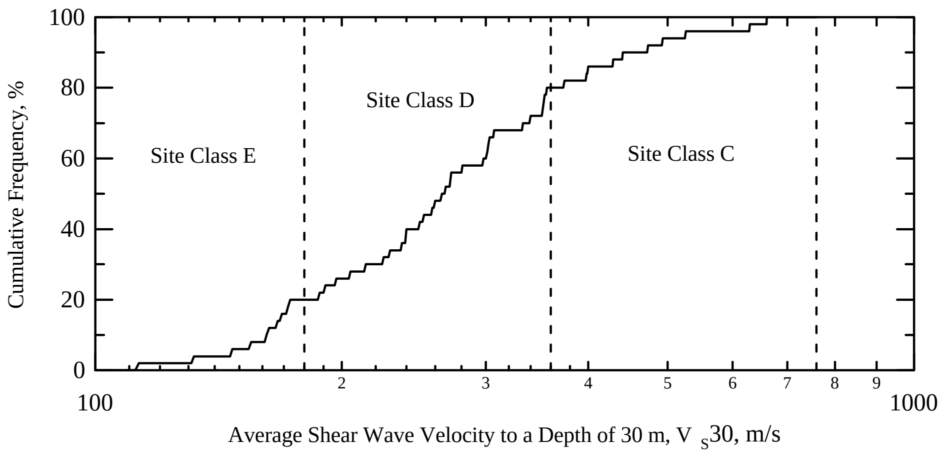


Figure 3. Cumulative frequency plot of V_S30 for the profiles in the data set, with NEHRP site classes shown.

The error bounds are approximately +/-10% of the estimate for a 95% confidence interval. Multiple linear regression does not improve the correlation appreciably. For two variables, the standard error is only reduced to 13 m/s. With sixteen variables (wavelengths from 2 to 80 m), the standard error is 12.4 m/s. Considering the possible sources or error in measuring Rayleigh-wave phase velocities, using only one variable, V_R36, is most practical.

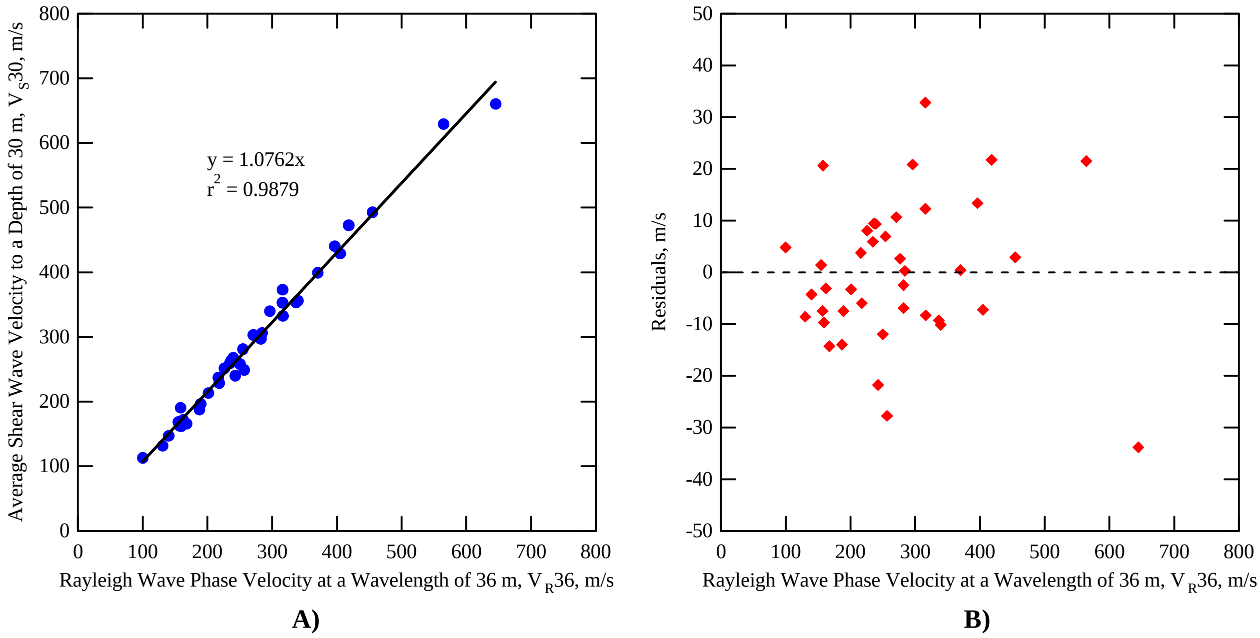


Figure 4. A) Comparison of V_S30 versus V_R36, with regression line and equations given. B) Residuals.

PROCEDURE OF V_S30 METHOD

Because only one point in the dispersion curve, V_R36, is needed to estimate V_S30, the standard SASW testing procedures were modified. The general SASW testing setup is shown in Figure 5 and summarized below [Joh; 1997; Brown, 1998; Brown et al., 1999]. A vertical dynamic load at the surface generates mainly Rayleigh waves, which are monitored by two receivers. A dynamic signal analyzer or PC-based data acquisition system records the ground motions, transforms the time-domain records into the frequency domain, and calculates the cross power spectrum and coherence. After the wrapped phase angle of the cross power spectrum is unwrapped through an interactive process called masking, the dispersion curve is calculated by:

$$V_R = f * d_2/(\Delta\phi/360°), \quad (2)$$

where f is frequency, d_2 is the distance between receivers, and $\Delta\phi$ is the phase difference in degrees.

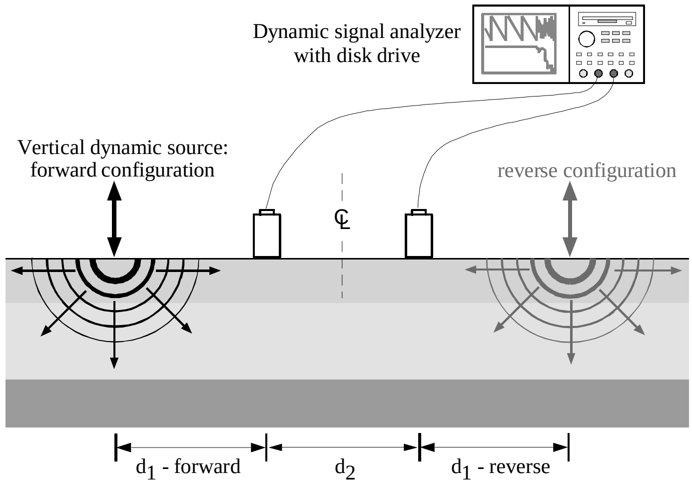


Figure 5. Basic configuration of SASW measurements (Modified from Joh, 1997).

To acquire phase data to generate a dispersion curve over a wide range of wavelengths, practical and theoretical considerations require the use of many receiver spacings. For this new V_S30 method, one or two source-receiver spacings are used. Theoretical studies (and field testing) have shown that the most favorable dispersion curve is obtained when the distance from the source to the first receiver, d_1, is around one to two wavelengths and the distance between receivers, d_2, is equal to d_1 [Sanchez-Salinero 1987; Roesset et al, 1990]. To avoid near-field effects associated with surface waves and body waves, wavelengths are included in the dispersion curve if they are shorter than $2*d_1$. For sites at which the shear-wave velocity profile increases gradually with depth, the measured dispersion curve with this source-receiver geometry is a good approximation of the fundamental-mode Rayleigh-wave dispersion curve [Foinquinos, 1991; Brown, 1998].

Based on these considerations, d_1 and d_2 both equal to 72 m or more would be optimal for measuring V_R36, but site access and signal attenuation make d_1 and d_2 of 36 m more practical. To minimize phase shifts due to differences in receiver coupling and lateral variability, the source location is also reversed (Figure 5). V_R36 is calculated from the phase of the cross power spectrum using Equation 2 (with $\Delta\phi = 360°$ for $d_2 = 36$ m). If spectral calculations are done in real time, a preliminary estimate can be made on site. However, because of noise in the data, the phase data are masked (unwrapped) for a range of wavelengths. The forward- and reverse-source dispersion data are combined and then smoothed through curve fitting before V_R36 is determined. Equation 1 is then used to estimate V_S30.

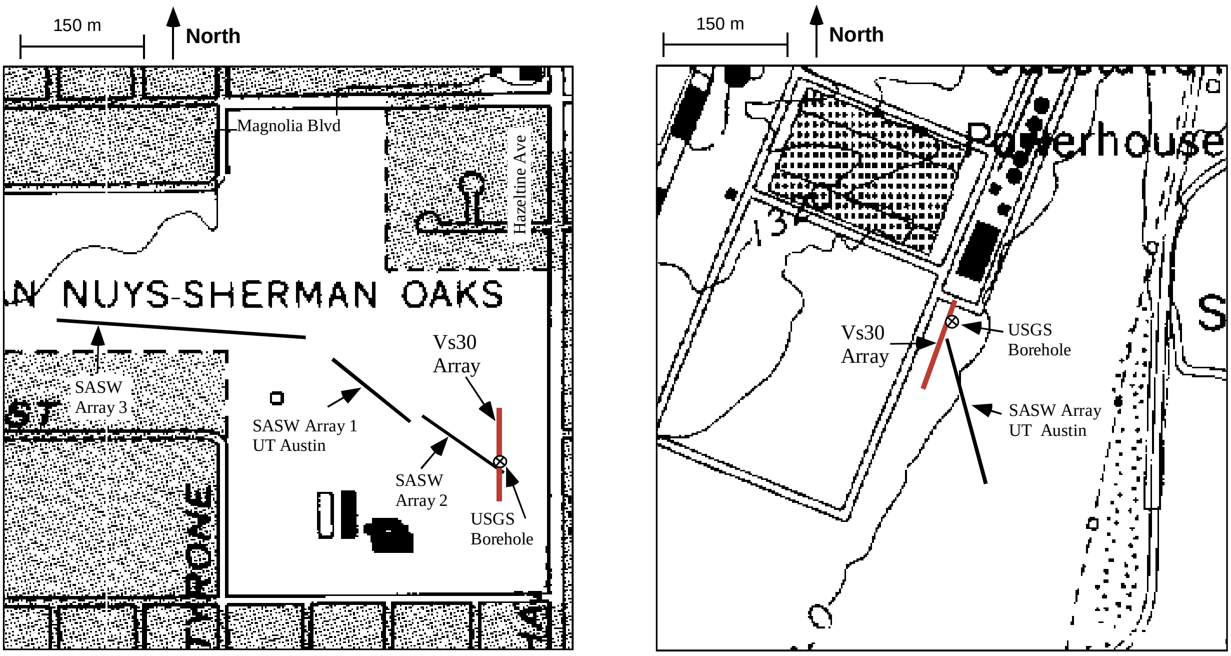
EVALUATION OF V_S30 METHOD

To evaluate the reliability of the regression equation, it was applied to the dispersion curves from the ten profiles not included in the regression. The predicted values of V_S30 are compared with the actual values in Table 2. Values of V_S30 are predicted within 10% and the site classifications are correct.

The 10% error bounds represent ideal conditions, because further uncertainty may be introduced in the field measurements, as discussed in the next section. For this reason, the V_S30 method was tested at two sites at which previous V_S and surface-wave dispersion measurements have been done. The test sites, Sherman Oaks Park (SOP) and Jensen Filtration Plant (JMB), are shown in Figures 6a and 6b, respectively. To minimize the effects of lateral variability in the subsurface, the arrays were located as close as practical to the existing boreholes. A vacuum-assisted 100-lb weight drop was used as the seismic source, and the signals were recorded using Kinemetrics Ranger 1-Hz geophones and a dynamic signal analyzer. The results from the new V_S30 method and existing V_S profiles are summarized in Table 3. The estimation of V_S30 from Equation 1 using V_R36 from previous SASW measurements and the calculated dispersion curve from the downhole profile are also shown for comparison.

Table 2. Comparisons of actual versus predicted values of V_S30, using Equation 1. Error and site classifications are also shown.

Site Name	V_S30	Predicted V_S30	% Error	Actual Site Class	Predicted Site Class
192	172	176	2.0%	E	E
757	155	162	4.2%	E	E
PR2	240	246	2.6%	D	D
191	225	240	6.4%	D	D
695	272	268	-1.3%	D	D
1745	352	334	-5.5%	D	D
269	271	272	0.2%	D	D
PC3	204	218	6.4%	D	D
WVAS	397	397	-0.1%	C	C
JGB	526	501	-5.0%	C	C



A) **B)**

Figure 6. V_S30 testing locations at A) Sherman Oaks Park and B) Jensen Filtration Plant.

At Sherman Oaks Park, there is little lateral variability in the subsurface, as shown by the consistency between the SASW results for the three arrays and the V_S30 array, as shown in columns 1, 3, and 6 of Table 3. The results are most similar between SASW array 2 (270 m/s) and the V_S30 array, which are also the closest spatially (Figure 6a). The V_S30 prediction equation works fairly well here, as shown by the consistency between columns 2 and 5, and between columns 3 and 6 in Table 3. The ~10% difference between V_S30 from the V_S30 method and downhole testing is likely due to the different nature of downhole and surface wave measurements, as discussed in the next section. The results from both methods place Sherman Oaks Park in NEHRP site class D.

Previous borehole and SASW measurements have shown that there is considerable lateral variability at the Jensen Filtration Plant site [Brown, 1998]. As expected from the location of the V_S30 array (Figure 6b), the results for the V_S30 method (column 1 of Table 3) are in between those from the SASW array (column 3) and the downhole measurements (column 2). V_S30 from suspension logging (column 4) is higher than that from the V_S30 method and lower than V_S30 from the USGS downhole V_S profile. A range is given for V_S30 from suspension logging because of the uncertainty in the data in the top 9 m. For the velocity profiles at this site, the V_S30 predictive equation imparts an error of approximately -5% to -10%, as shown by the comparison between columns 2 and 5, and columns 3 and 6. The difference between the V_S30 method and downhole results at Jensen Filtration Plant is due to a combination of lateral variability, error in the predictive equation, and the inherent differences between downhole and surface wave testing. Based on suspension logging, SASW testing, and the V_S30 method, the site belongs to NEHRP site class D, whereas the downhole results classify it in site class C.

Table 3. Comparison of results from the new V_S30 method (1) and previous V_S, V_R measurements. The downhole data (2) are from Gibbs et al. [1999], the SASW data (3) are from Brown [1998], and the OYO suspension logging data (4) are from ROSRINE [1996]. Equation 1 is applied to the calculated dispersion curve for the downhole profile (5) and the measured dispersion curve from previous SASW testing (6).

Data Source/ V_S30 (m/s) Site	New V_S30 Method (1)	Downhole V_S Profile (2)	SASW Testing V_S Profile(s) (3)	OYO Suspension Logging V_S Profile (4)	Calculated V_R36 from Downhole V_S, V_P Profiles * 1.076 (5)	V_R36 from SASW Testing * 1.076 (6)
SOP	272	302	275, 270, 291	-	304	281, 268, 296
JMB	323	373	300	345-353	340	284

DISCUSSION

Because the predictive equation was developed using theoretical fundamental-mode Rayleigh-wave dispersion curves and values of V_S30, there is more uncertainty in the V_S30 prediction than in the error bounds for Equation 1. There is uncertainty in measuring Rayleigh-wave phase velocities in the field. Theoretically, a vertical impact on a halfspace generates both body waves and Rayleigh waves, with 67% of the impact energy imparted to the Rayleigh waves, 26% to shear waves, and 7% to compression waves [Miller and Pursey, 1955]. The recorded phase data in the V_S30 method is affected by refracted and reflected body wave energy, and possible higher modes of surface wave propagation.

At many sites, shear wave velocity increases gradually with depth due to sediment age, cementation, overburden pressure, etc., and the effect of non-fundamental-mode Rayleigh wave energy on the dispersion curve is minimal. Common exceptions to this situation include engineered fill over soft sediments, asphalt/concrete and compacted base material over softer sediments, and soft soil on shallow bedrock. The existing models used to calculate the dispersion curves assume that the subsurface is horizontally layered, laterally invariant, and isotropic. At sites that are in gross violation of these assumptions in the V_S30 method, traditional SASW testing or another method should be used to calculate V_S30.

Downhole seismic testing is a direct measure of V_S30. However, the first wave arrivals in the seismic record represent the fastest travel path for seismic energy from the surface to a depth in the borehole. If the subsurface is non-homogeneous, the material sampled by downhole testing may have a higher velocity than the much larger volume of soil sampled by surface-wave measurements. Lateral variability in the subsurface may contribute further to the difference between the results of surface wave and borehole methods. However, the results from the V_S30 method may represent the properties of the entire site better than a single borehole measurement. Because the V_S30 field procedure is relatively fast, data can also be collected at several locations on site to assess the lateral variability.

The boundaries for the NEHRP/UBC site classifications are differences in V_S30 of a factor of two (Table 1). Although the relative error between predicted and actual V_S30 was not larger than 12% for any of the 40 sites in the regression, 5 sites were misclassified. If the +/-10% estimate range overlaps several classes, further testing may be necessary to determine site class with certainty. It is anticipated, however, that the V_S30 method will be applied at sites where there are no shear-wave velocity data, and borehole seismic testing would be cost-prohibitive.

CONCLUSIONS AND RECOMMENDATIONS

The new V_S30 method is a promising, cost-efficient alternative to traditional borehole methods used to measure V_S30. For purposes of site classification, the accuracy of the V_S30 method is more than adequate in most situations. The correlation of Rayleigh-wave phase velocities with V_S30 is robust, although improvements to the preliminary V_S30 method should be made before its general use.

Several options exist to overcome many of the assumptions in the preliminary V_S30 method. Data processing and filtering techniques could be used to isolate the fundamental-mode Rayleigh-dispersion curve from the data [Park et al., 1999]. Such techniques require multiple-receiver arrays. Alternatively, the source and receiver locations could be incorporated into a model used to generate the "dispersion curves" based on full stress-wave propagation [Roesset et al., 1991], which could then be correlated with V_S30. Practical field testing using different receiver spacings would also be needed to validate this more sophisticated model.

Additional field testing is necessary to gauge the reliability of the V_S30 method in its present form. More V_S, V_p profiles should be incorporated into the database to make sure that it is representative of site conditions likely to be encountered. Profiles should be included that fill in the data range in site class C, although the linear relationship appears to hold over site classes E, D, and C. The geographic distribution of profiles should also be more diverse if the method is to be applied generally.

REFERENCES

Brown, L.T., 1998, "Comparison of V_S profiles from SASW and borehole measurements at strong-motion sites in Southern California", Master's thesis, University of Texas at Austin.

Brown, L.T., Boore, D.M. and K.H. Stokoe, II, 1999, "Comparison of shear-wave velocity profiles from SASW and downhole seismic tests at a strong-motion site", *Proceedings, 12th World Conference on Earthquake Engineering*, Auckland, New Zealand.

BSSC, 1994, *NEHRP Recommended provisions for the development of seismic regulations for new buildings, part I: Provisions*, Building Seismic Safety Council, Federal Emergency Management Agency, Washington D.C.

Foinquinos, M.R., 1991, "Analytical study and inversion for the spectral-analysis-of-surface-waves method", Master's thesis, University of Texas at Austin.

Gibbs, J.F, Tinsley, J.C, Boore, D.M. and W.B. Joyner, 1999, "Seismic velocities and geological conditions at twelve sites subjected to strong ground motion in the 1994 Northridge, California, Earthquake: An update", *U.S. Geological Survey Open-File Report 99-xxx* (in press).

Joh, S.-H., 1992, *User's guide to WinSASW, a program for data reduction and analysis of SASW measurements*, University of Texas at Austin.

Joh, S.-H., 1997, "Advances in interpretation and analysis techniques for spectral-analysis-of-surface-waves (SASW) measurements", Ph.D. Dissertation, University of Texas at Austin.

Miller, G.F. and Pursey, H., 1955, "On the partitioning of energy between elastic waves in a semi-infinite solid", *Proceedings of the Royal Society of London, Series A* 233:55-69.

Park., C.B., Miller, R.D. and J. Xia, 1999, "Multichannel analysis of surface waves", *Geophysics*, Vol. 64 No. 3, p. 800-808.

Roesset, J.M., Chang, D.-W., and Stokoe, K.H., II, 1991, "Comparison of 2-D and 3-D models for analysis of surface wave tests", *Proceedings of the Fifth International Conference on Soil Dynamics and Earthquake Engineering*, pp. 111-126.

Roesset, J.M., Chang, D.-W., Stokoe, K.H., II and M. Aouad, 1990, "Modulus and thickness of the pavement surface layer from SASW tests", *Transportation Research Record* 1260:53-63.

ROSRINE Web site: http://rccg03.usc.edu/rosrine.

Sanchez-Salinero, I., 1987, "Analytical investigation of seismic methods used for engineering applications", Ph.D. dissertation, University of Texas at Austin.

Stokoe, K.H.,II, Rix, G.L. and S. Nazarian, 1989, "In situ seismic testing with surface waves" *Proceedings, 12th International Conference on Soil Mechanics and Foundation Engineering, Vol 1*, Rio de Janeiro, Brazil, pp. 330-334.

Stokoe, K.H.,II, Wright, S.G., Bay, J.A. and J.A. Roesset, 1994, "Characterization of geotechnical sites by SASW method", *Geophysical Characterization of Sites*, Technical committee for XIII ICSMFE, A.A. Balkema Publisher, Rotterdam, Netherlands, pp. 785-816.

Woods, R.D., 1968, "Screening of surface waves in soils", *Journal of Soil Mechanics and Foundations Division., Proc. ASCE*, 94 (SM4):951-979.