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PRACTICAL EXPERIENCE USING A SIMPLIFIED PROCEDURE TO MEASURE AVERAGE SHEAR-WAVE VELOCITY TO A DEPTH OF 30 METERS (V_S30)

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SUMMARY

V_S30 is used in the NEHRP Provisions and the 1997 Uniform Building Code to separate sites into classes for earthquake engineering design. V_S30 can also be incorporated into local seismic hazard maps. Surface wave methods have been used to estimate V_S30 for a number of years. These methods are non-destructive, and sample a larger volume of the subsurface as compared to borehole measurements.

During the recent three years the authors have had the opportunity to test a simplified procedure to estimate V_S30 and compare the results to complete surface wave soundings and borehole measurements. Here the authors present the results of these comparisons, practical applications of this method, and the results for engineering practice.

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 1997 Uniform Building Code to separate sites into different classes for engineering design, with the expectation that sites in the same class will respond similarly to a given earthquake. The 2000 International Building Code (IBC) permits a similar approach for site classification, the average shear wave velocity of the upper 100 ft. These site classes are as follows:

Class A – hard rock – $V_S30 > 1500$ m/s (UBC) or $V_S100' > 5{,}000$ f/s (IBC)
Class B – rock – $760 < V_S30 \leq 1500$ m/s (UBC) or $2{,}500 < V_S100' \leq 5{,}000$ f/s (IBC)
Class C – very dense soil and soft rock – $360 < V_S30 \leq 760$ m/s (UBC)
or $1{,}200 < V_S100' \leq 2{,}500$ f/s (IBC)
Class D – stiff soil – $180 < V_S30 \leq 360$ m/s (UBC) or $600 < V_S100' \leq 1{,}200$ f/s (IBC)
Class E – soft soil – $V_S30 < 180$ m/s (UBC) or $V_S100' < 600$ f/s (IBC)
Class F – soils requiring site-specific evaluation

Other applications of V_S imaging include seismic risk or PML studies, seismic hazard zonation, and characterization of seismic instrument sites.

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Traditionally, V_S30 is determined by seismic measurements in boreholes, using the downhole, crosshole, or suspension logging methods. Techniques based on the inversion of surface-wave dispersion data offer the advantage of not requiring boreholes and sampling of a larger volume of soil.

Surface wave techniques such as the spectral-analysis-of-surface-waves (SASW), multi-channel analysis of surface waves (MASW), array microtremor and refraction microtremor techniques are proven, non-destructive seismic methods that can be used to determine the variation of V_S with depth (Stokoe et al., 1994; Brown, 1998; Park et al., 1999; Okada, 2003 and Louie, 2001). The basis of surface wave methods 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. The variation of phase velocity with frequency or wavelength is called dispersion. Surface wave testing consists of collecting surface-wave phase data in the field, generating the dispersion curve, and then using iterative forward or inverse modeling techniques to back-calculate the corresponding V_S profile. From the V_S profile, V_S30 can be calculated.

THEORETICAL BASIS OF V_S30 METHOD

The V_S30 method presented herein is a simplification of other surface wave methods, providing only a single number corresponding to the average shear-wave velocity in the upper 30 m. A method based on the SASW technique was first introduced by Brown et al. (2000a and 2000b) and a similar method based on the passive array microtremor technique was developed independently by Konno and Kataoka (2000).

In the V_S30 method, data acquisition can be less extensive and faster relative to complete surface wave soundings because only a portion of the dispersion curve is needed. The analysis is simple enough that a preliminary interpretation can be made on site. The method is based on the correlation between Rayleigh-wave phase velocity and V_S30, as described below. Like V_S30, Rayleigh-wave phase velocities depend on the material properties averaged over depth. 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 by Leo Brown (Brown et al., 2000a and 2000b) 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. Of the 103 profiles, 33 were obtained by the downhole seismic method, 66 by P-S suspension logging, and four unknown. Fifty of the sites are located in Southern California, 43 in Northern California, and 10 outside of California.

For each V_S, V_P profile, the fundamental-mode Rayleigh-wave dispersion curve was calculated. A constant mass density of 1.92 g/cc for each profile was assumed. Reasonable variations in mass density have a negligible effect on dispersion.

From the 103 profiles, data from 15 profiles were randomly selected and removed from the data set. Simple linear regression was done on the data from the remaining 88 profiles. Correlation was done in the wavelength rather than frequency domain, because wavelength is related more closely to depth of interest. V_S30 is most highly correlated with the Rayleigh-wave phase velocity at a wavelength of 40 m (V_R40). The regression plot and residuals are shown in Figures 1a and 1b respectively. The degree of correlation is high ($r^2 = 0.9864$) and the standard error is 14.5 m/s. Fixing the constant (y-intercept) at 0 had an insignificant effect on the regression. Based on the regression, the predictive equation for V_S30 is:

$$V_S30 = 1.045 * V_R40. \qquad (1)$$

The error bounds are approximately +/-10% of the estimate for a 95% confidence interval. Multiple linear regression does not improve the correlation appreciably.

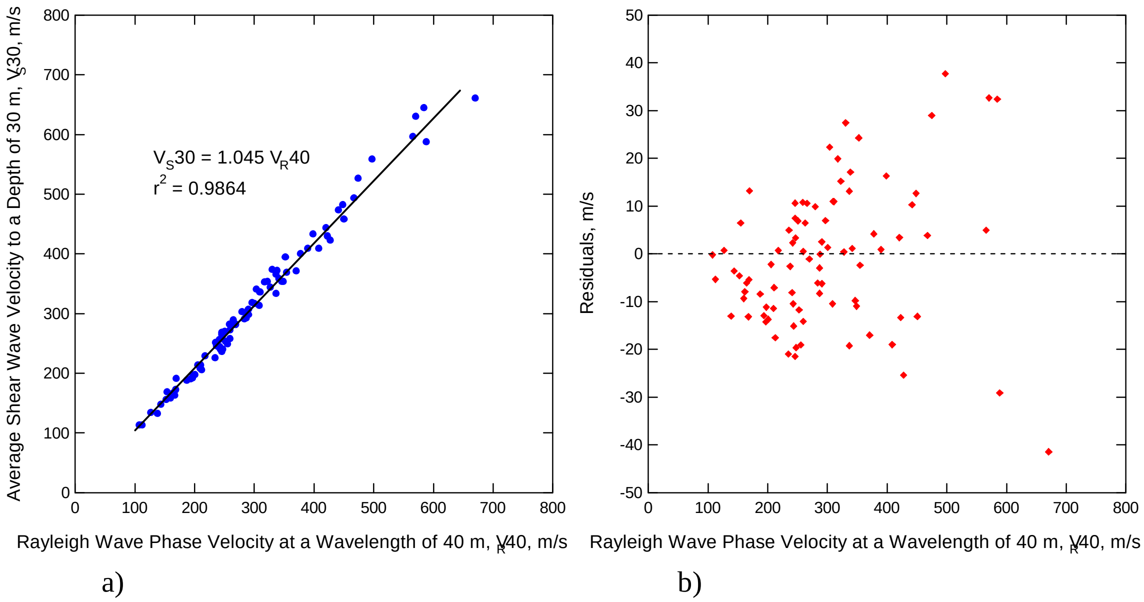

Figure 1. a) V_S30 versus V_R40, with regression line and equations given. b) Residuals.

To evaluate the reliability of the V_S30 regression equation, Brown et al. (2000a, 2000b) applied it to the dispersion curves from the 15 profiles not included in the regression. The predicted values of V_S30 are compared with the actual values in Table 1. Values of V_S30 are predicted within 5% and the site classifications are correct. This comparison assumes perfect data – that fundamental-mode Rayleigh waves are generated in a layered halfspace and that their velocity can be measured accurately.

Table 1. Evaluation of V_S30 method based on V_S profiles not included in regression database

Site Name	V_S30	Predicted V_S30	Percent Error	Actual Site Class	Predicted Site Class
192	172	176	1.8	E	E
269	271	273	0.7	D	D
CPB	250	244	-2.7	D	D
OV2	441	426	-3.3	C	C
SOP	302	301	-0.1	D	D
WVAS	397	391	-1.4	C	C
PP1	400	417	4.5	C	C
USD	493	490	-0.6	C	C
DHS	380	376	-1.1	C	C
HAV	296	295	-0.3	D	D
HEA	241	242	0.6	D	D
SG4	304	314	3.4	D	D
SG5	334	341	1.9	D	D
SR4	345	340	-1.4	D	D
SC1	316	320	1.2	D	D

THE V_S30 METHOD

Because only one point in the dispersion curve, V_R40, is needed to estimate V_S30, the standard surface wave testing procedures are simplified. For example, to measure V_R40 using the SASW technique, only a single source-receiver spacing is needed. The seismic source must have sufficient energy for this distance and wavelength. Passive techniques such as the array microtremor and refraction microtremor techniques may also be used to determine V_R40. Typically, passive techniques must be used in conjunction with active techniques (SASW and MASW) in order to define the near surface velocity structure, which may have a significant impact on V_S30.

For sites where the shear-wave velocity profile generally increases with depth, the measured dispersion curve using the SASW technique is a good approximation of the fundamental-mode Rayleigh-wave dispersion curve (Foinquinos, 1991; Brown, 1998). 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 high velocity bedrock. At such sites higher mode surface waves may dominate and the predictive V_S30 equation, which is based on fundamental-mode Raleigh wave propagation may not be valid. The MASW technique can often be used to isolate the fundamental-mode Rayleigh-dispersion curve from higher modes (Park et al., 1999) and should be used in environments where velocity inversions or steep velocity gradients are expected.

The general testing setup for the V_S30 method using SASW is shown in Figure 2 and summarized below. A vertical dynamic load at the surface generates predominantly Rayleigh waves, which are monitored by two receivers. A dynamic signal analyzer records the ground motions, transforms the time-domain records into the frequency domain, and calculates the cross power spectrum and coherence.

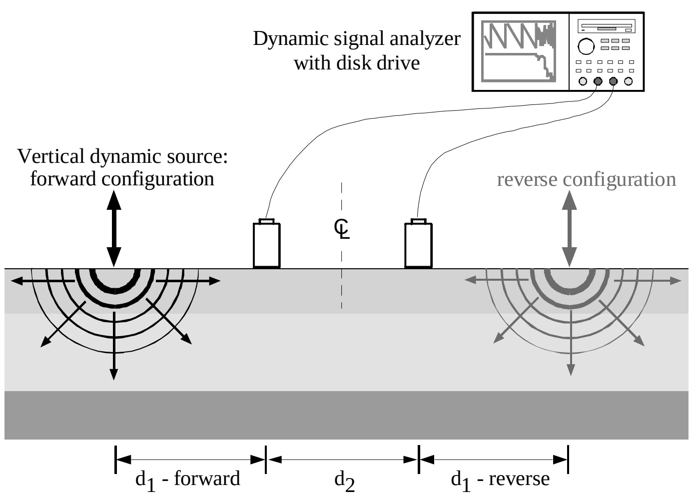

Figure 2. Basic field setup for V_S30 measurements using the SASW technique.

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 unwrapped phase of the cross power spectrum.

As stated earlier, for this new V_S30 method, a single source-receiver spacing is used. Based on practical and theoretical considerations (Sanchez-Salinero, 1987), d_1 and d_2 both equal to 30 m or more would be adequate for measuring V_R40. To minimize phase shifts due to differences in receiver coupling and lateral variability, the source location is also reversed. Eq. 2 is used to calculate a short segment of the dispersion curve, which is smoothed to obtain V_R40. Eq. 1 is then applied to estimate V_S30.

MASW data is typically acquired using a linear array of 24 to 48 geophones spaced 1 to 2m apart. The source location is typically 2 m, or more, from the end geophone and filtering techniques such as the f-k or tau-p transforms are used to extract the dispersion curve from the field data. The MASW technique is also easily adapted to 2-D mapping of shallow shear wave velocity structure.

Standard field procedures are used to acquire and reduce array microtremor data (Okada, 2003) and refraction microtremor data (Louie, 2001). Array microtremor data is often acquired using a 7- or 10-channel triangular array or a 24 channel circular array. The refraction microtremor array typically uses a linear array of 24 geophones spaced 7 to 10 m apart and assumes that surface wave energy is arriving equally from all directions. The dispersion curve is determined using various filtering techniques, V_R40 measured from the resulting dispersion curve and Eq. 1 then used to estimate V_S30. This eliminates the need to acquire SASW or MASW data to define near surface velocity structure and forward/inverse modeling of the dispersion curve to generate a V_S versus depth model.

An example of determining V_R40 from a SASW and refraction microtremor sounding and comparison to actual V_S30 calculated from forward modeling of the surface wave dispersion curve and PS suspension log data is presented in Figure 3.

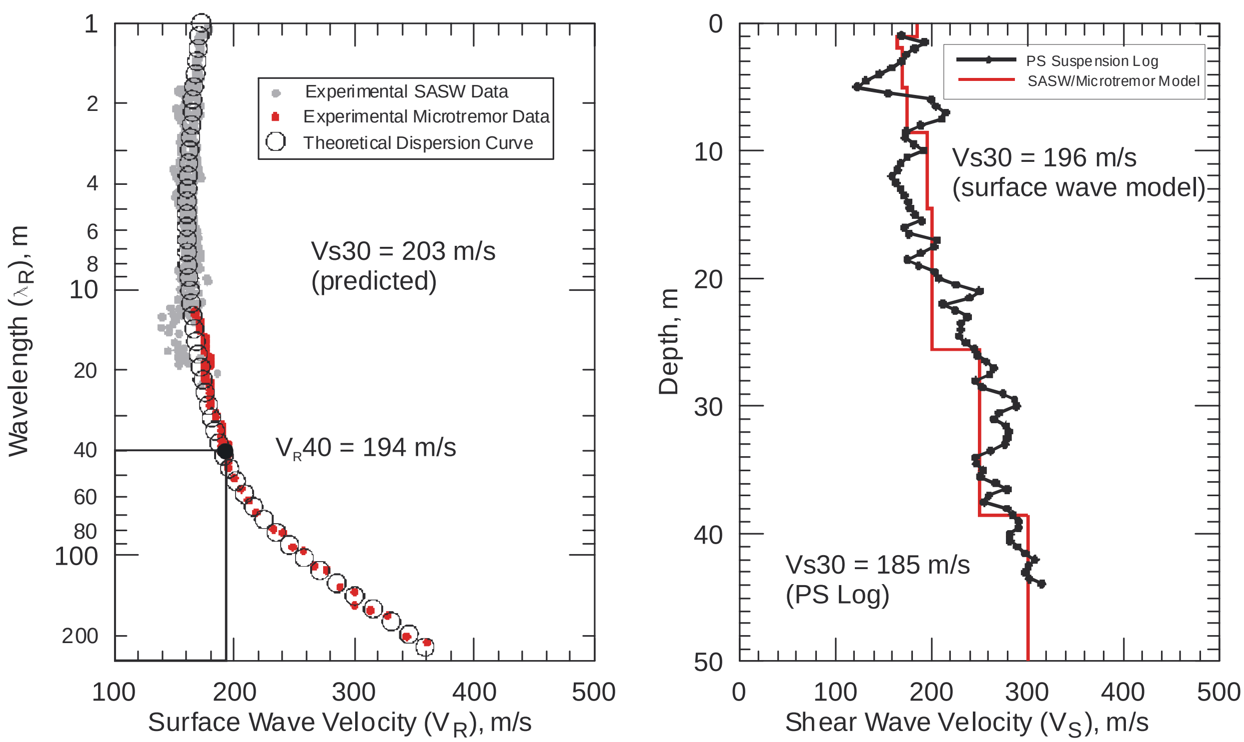

Figure 3. Example of V_S30 calculation from SASW and refraction microtremor data.

The predicted V_S30 is within 7 m/s (3%) of that determined from modeling of the surface wave dispersion curve and 18 m/s (10%) of that derived from PS suspension log V_S data.

EVALUATION OF THE V_S30 METHOD

Over the past several years, the V_S30 predictive regression equation has been applied to surface wave sounding data acquired at numerous sites in and outside of California and compared to V_S30 determined by modeling of surface wave data and occasionally PS suspension logs. Most of the surface wave data were acquired using the SASW technique but recently we have been combining SASW soundings with passive array microtremor or refraction microtremor soundings to extend depth of investigation. The predicted values of V_S30 from these investigations are compared to actual values in Table 2, below.

Table 2. Evaluation of V_S30 method based on 53 new V_S profiles acquired since 2001.

Site Name	Actual V_S30[1]	Predicted V_S30	Percent Error	UBC Site Class	Predicted UBC Site Class	Comments
San Diego, CA - A	229	248	8	D	D	groundwater (gw) @ 3m
Arrowhead, CA	360	376	4	C	C	weathered rock @ 20m
Stanford, CA - A	375	392	5	C	C	gw @ 14m
Stanford, CA - B	374	382	2	C	C	gw @ 14m
UC Davis A	230	230	0	D	D	gwr @ 13m
UC Davis B	232	220	-5	D	D	gw @ 13m
San Diego, CA - B	597	658	10	C	C	sedimentary rock @ 2-7m
UC Berkley A	386	387	0	C	C	sedimentary rock @ < 20m
UC Berkley B	437	481	10	C	C	sedimentary rock @ < 20m
San Diego, CA - C	292	330	13	D	D	gw @ 4.5m
San Diego, CA - D	298	310	4	D	D	gw @ 4.5m
Simi Valley, CA - A	192	201	5	D	D	gw @ 6m
Simi Valley, CA - B	246	269	9	D	D	gw @ 6m
Sakhalin Island, Russia - A	322	355	10	D	D	
Sakhalin Island, Russia - B	305	298	-2	D	D	
Sakhalin Island, Russia - C	332	327	-2	D	D	
Sakhalin Island, Russia - D	181	190	5	D	D	gw @ 1 m
Sakhalin Island, Russia - E	282	277	-2	D	D	gw @ 4 m
San Quentin, CA - A	872	726	-17	B	B	bedrock at 3-4m
San Quentin, CA - B	840	756	-10	B	B	bedrock at 3-4m
Rialto, CA - A	426	450	6	C	C	sand/gravel pit site
Rialto, CA - B	444	475	7	C	C	sand/gravel pit site
Rialto, CA - B	441	461	4	C	C	sand/gravel pit site
Sacramento, CA - A	344	355	3	D	D	gw @ 10m
Sacramento, CA - B	407	418	3	C	C	gw @ 10m
Dillon, CO - A	512	507	-1	C	C	gw @ 12m, sed rock @ 22m
Dillon, CO - B	493	530	7	C	C	gw @ 13m, sed rock @ 24m

Site Name	Actual V_S30[1]	Predicted V_S30	Percent Error	UBC Site Class	Predicted UBC Site Class	Comments
Dillon, CO - C	495	515	4	C	C	gw @ 13m, sed rock @ 24m
Dillon, CO - D	484	506	4	C	C	gw @ 13m, sed rock @ 24m
Fresno, CA - A	461	481	4	C	C	sand/gravel pit site, gw @ 3m
Fresno, CA - B	461	493	7	C	C	sand/gravel pit site, gw @ 3m
Fresno, CA - C	447	500	12	C	C	sand/gravel pit site, gw @ 3m
Irwindale, CA - D1	362	382	6	C	C	sand/gravel pit site, gw @ 43m
Irwindale, CA - D2	319	331	4	D	D	sand/gravel pit site, gw @ 2m
Irwindale, CA - H1	374	399	7	C	C	sand/gravel pit site, gw @ 9m
Irwindale, CA - H2	441	452	3	C	C	sand/gravel pit site, gw @ 51m
Irwindale, CA - R1	567	575	1	C	C	sand/gravel pit site, gw @ >50m
Irwindale, CA - R2	545	557	2	C	C	sand/gravel pit site, gw @ >20m
Irwindale, CA - U1	452	470	4	C	C	sand/gravel pit site, gw @ >30m
Irwindale, CA - U2	395	448	13	C	C	sand/gravel pit site, gw @ 2m
Martin County, KY - A	250	282	13	D	D	slurry impoundment, gw @ 16m
Martin County, KY - B	441	396	-10	C	C	slurry impoundment, gw @ 44m
Martin County, KY - C	441	428	-3	C	C	slurry impoundment, gw @ 44m
Martin County, KY - D	370	345	-7	C	D	slurry impoundment, gw @ 35m
Orange, CA - A	347	370	7	D	C	
Orange, CA - B	422	413	-2	C	C	
Las Vegas, NV - A	484[2]	507	5	C	C	
Las Vegas, NV - B	1048[2]	1096	5	B	B	
Las Vegas, NV - D	818[2]	846	3	B	B	
Las Vegas, NV - C	906[2]	948	5	B	B	
San Fransisco, CA - A	716[2]	831	16	C	B	shallow sed. rock
San Fransisco, CA - B	626[2]	565	-10	C	C	shallow sed. rock
Terminal Island, CA	196[2]	203	3	D	D	gw @ 5m
Terminal Island, CA	185[3]	203	10	D	D	same as above

1. Actual V_S30 from modeled SASW data unless otherwise noted.
2. V_S30 from modeled combined SASW and refraction microtremor data
3. V_S30 from PS suspension logging data

The 53 surface wave soundings presented above were acquired on 20 different projects. One project also included a PS suspension log for a 54th comparison. Twenty-one of the soundings were acquired in Southern California, 15 in Northern California, 4 in Nevada, 4 in Colorado, 4 in Kentucky and 5 on Sakhalin Island, Russia. The average and median error/difference between the predicted and actual V_S30 are 6 and 5%, respectively. Of the 54 comparisons between predicted and actual V_S30, 7 have differences of 10% and 6 have differences of above 10%. Of these 13 soundings, 6 were acquired at sites with shallow bedrock and the associated abrupt increase in velocity. An additional 4 of the soundings were at Class D sites with V_S30 differences of 18 to 38 m/s. Only 3 of the 54 comparisons were assigned different site classes based on actual versus predicted V_S30. The above comparison confirms previous estimates that the predictive regression relationship between V_S30 and V_R40 is generally reliable to within 10%. Further testing, particularly at sites outside California would still be beneficial.

DISCUSSION AND CONCLUSIONS

A large body of work has developed in support of using surface wave methods for accurate estimation of V_S30. Demonstrated reliability and accuracy recommends this method for standard practice. The variety of applications and techniques available allow broader application in a variety of circumstances, including urban settings where boreholes are prohibitive. We continue to observe that the results from surface wave methods probably represent the average properties of the entire site better than a single borehole measurement, because surface wave measurements are averaged over a larger volume of the subsurface.

A simple method of estimating V_S30 from V_R40 was previously been presented (Brown et al., 2000a, 2000b) and is discussed again, herein. Recent experience with this method confirms previous estimates that it is generally reliable to within 10%. This method can be adapted to any surface wave technique including the SASW, MASW, array microtremor and refraction microtremor methods and offers a very efficient and cost effective means to determine V_S30 on a large scale.

The V_S30 method is not designed to replace complete forward or inverse modeling of surface wave dispersion data, rather it offers a means for rapid, cost effective characterization of large areas such as in seismic hazard zonation studies and for determining V_S30 for UBC/IBC site classification. We believe that the simplified V_S30 method using SASW, MASW or microtremor data can reliably be used for site classification providing V_S30 is not within 10% of a site class boundary. If the predicted V_S30 is between 5 and 10% of a site class boundary then full modeling of surface wave data should be implemented to determine V_S30. If V_S30 is within 5% of a site class boundary, confirmation using borehole velocity techniques could be considered depending on the nature of the structure being constructed and local seismic hazard. Borehole velocity measurements may only provide better V_S30 estimates than surface wave techniques when data quality is high and the V_S of subsurface soils does not exhibit significant lateral variation. However, corroboration between two methods at sites with V_S30 near a class boundary provides an increased level of confidence. Of course, when high resolution data on the vertical variation of V_S with depth is required; borehole techniques, particularly PS suspension logging and the crosshole seismic method are expected to provide superior results.

When conducting surface wave investigations at a single location for determining V_S30 for site classification, it may be practical to acquire a complete set of sounding data even if the V_S30 method is used to analyze the data. A complete surface wave dispersion curve would then be available for forward/inverse modeling if predicted V_S30 is within 10% of a class boundary. Depending upon field procedures, it may only take an extra hour or two to acquire a complete set of surface wave dispersion data - four or five additional receiver spacings when using SASW, smaller receiver spacing dataset when using MASW or a shallow MASW/SASW sounding to define near-surface velocity structure when using the microtremor method.

REFERENCES

1. Brown, L.T., Diehl, J.G., and Nigbor, R.L., 2000a, A simplified procedure to measure average shear-wave velocity to a depth of 30 meters (V_S30), *Proceedings of the 12th World Conference on Earthquake Engineering, Auckland, New Zealand, February 2000.*
2. Brown, L.T., Diehl, J.G., and Nigbor, R.L., 2000b, A simplified procedure to measure average shear-wave velocity to a depth of 30 meters (V_S30), *Proceedings of the 6th International Conference on Seismic Zonation, Palm Springs, California, November, 2000.*
3. 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.
4. Building Seismic Safety Council (BSSC), *1994, NEHRP Recommended provisions for the development of seismic regulations for new buildings, part I: Provisions*, developed for the Federal Emergency Management Agency, Washington D.C.
5. Foinquinos, M.R., 1991, Analytical study and inversion for the spectral-analysis-of-surface-waves method, Master's thesis, University of Texas at Austin.
6. Konno, K., and Kataoka, S., 2000, New method for estimating the average s-wave velocity of the ground, *Proceedings of the 6th International Conference on Seismic Zonation, Palm Springs, California, November, 2000.*
7. Louie, J.N., 2001, "Faster, Better: Shear-Wave Velocity to 100 Meters Depth from Refraction Microtremor Arrays", Bulletin of the Seismological Society of America, vol. 91, no. 2, p. 347-364.
8. Okada, H., 2003, The Microtremor Survey Method, Geophysical Monograph Series Number 12, Society of Exploration Geophysicists.
9. Park., C.B., Miller, R.D. and J. Xia, 1999, Multichannel analysis of surface waves, *Geophysics*, Vol. 64 No. 3, p. 800-808.
10. Sanchez-Salinero, I., 1987, Analytical investigation of seismic methods used for engineering applications, Ph.D. dissertation, University of Texas at Austin.
11. 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.