Borehole Velocity Logging for Caltrans' Earthquake Engineering Program: Comparison of Field Measurements

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ABSTRACT

The ROSRINE (Resolution of Site Response Issues from the Northridge Earthquake) project examined the variability in geotechnical and geophysical measurements used in earthquake ground response analyses. As part of this effort, comparisons were made of independently acquired geophysical data from Caltrans' strong-motion array located at the I-10 La Cienega Undercrossing in Los Angeles. Sounding data were obtained using four separate in-situ testing techniques: compression and shear wave (PS) suspension logging, crosshole logging, surface-to-borehole logging and SASW [Spectral analysis of Surface Waves] sounding. Additionally, identical PS suspension log data sets were independently processed for five sites to assess subjective bias in data interpretation.

The comparisons from the La Cienega case show that velocity profiles obtained from the four measurement techniques are acceptably similar at the level of resolution usually applied to ground response analysis. Observed variations between profiles are primarily associated with fundamental differences in testing configurations and the inherent resolution of the various methods. Notably, the PS suspension and crosshole results show a remarkable consistency in delineating small-scale variations in velocity at depth.

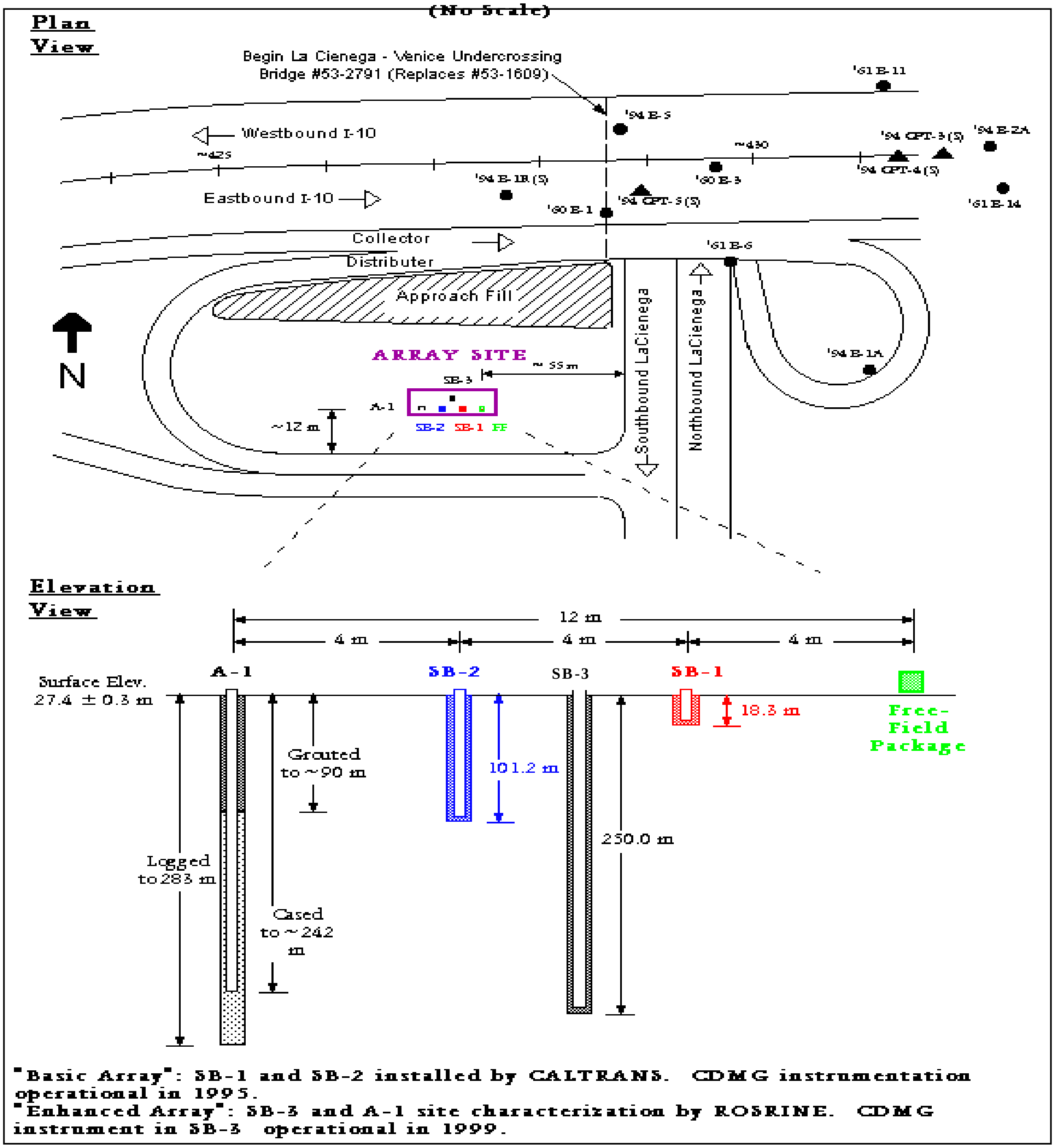
Finally, comparison of the five independently processed PS Log data sets reveals that high-quality data provide interpretations nearly free of subjective bias. However, substantial differences can be introduced when working with noisy or poor quality data due to interpreter bias or plain error. The poor quality data appear most commonly near the ground surface and, for P-waves, within the unsaturated zone.

INTRODUCTION

The Loma Prieta Earthquake of October 1989 caused extensive damage in the San Francisco Bay area, highlighting, with tragic consequences, the vulnerability of California's transportation infrastructure to moderate and large seismic events. This weakness was reinforced just over 4 years later and 400 miles further south, when America's costliest earthquake (to-date) struck near Northridge.

Besides causing structural damage and loss of life, the Loma Prieta and Northridge earthquakes resulted in substantial economic losses through disruption of the state's transportation system. These economic losses were felt statewide, and pinpointed the need for systematic hardening of road, highway and rail structures to minimize damage and disruption of the transportation network due to seismic events. To this end, Caltrans launched the Seismic Retrofit Program, an ambitious initiative designed to inspect and evaluate every structure in the State Highway System for seismic risk and, if necessary, repair and retrofit those structures to reduce that risk. A primary goal of the program is the prediction of ground-motion and foundation response from large earthquakes. Caltrans often estimates ground-motion at important bridges by site-specific response analysis, where a design spectrum is selected based on energy propagation of a given seismic event from bedrock through the overlying soil. For that analysis, shear and compressional wave velocities of subsurface materials provide critical input data for estimation of ground motion.

The primary task of the geophysicist for this program is to acquire the seismic velocity data needed for developing ground response models. Both shear and compressional velocity data are used in the



"Basic Array": SB-1 and SB-2 installed by CALTRANS. CDMG instrumentation operational in 1995.
"Enhanced Array": SB-3 and A-1 site characterization by ROSRINE. CDMG instrument in SB-3 operational in 1999.

Figure 1. Location and description of the ROSRINE array at the La Cienaga Boulevard Undercrossing, Interstate 10 in Los Angeles, California. Boreholes drilled for the initial construction and post-Northridge rebuilding of the crossing are shown for reference. Boreholes SB-2, SB-3 and A-1 were used for assessment of in situ shear-wave velocity measurement techniques. Modified from Roblee (1998).

modeling process. The data are collected through borehole geophysical logs, whereby probes are passed down a borehole and measurements are made at discrete intervals. Early in the retrofit program, velocity logs were acquired using a locking geophone and a shear wave source at the surface. These *surface-to-borehole* velocity logs proved time consuming and were limited in depth. In 1992, logging efficiency significantly improved with the acquisition of a downhole PS suspension logging system. Due to its rapid data acquisition, increased depth range, greater resolution and constant signal strength with depth, the PS suspension tool has been adopted as Caltrans' *de facto* standard method over the earlier surface-to-borehole logging method. After the Northridge earthquake of 1994, Caltrans' Research Program, with support from the National Science Foundation (NSF) and the Electric Power Research Institute (EPRI), initiated the Resolution of Site Response Issues from the Northridge Earthquake (ROSRINE) project. The project is described in Schneider et al. (1997), Nigbor et.al (1997), Roblee et.al. (1998), Nigbor et al. (1998), and Roblee (1998). The primary objective of ROSRINE has been the collection, compilation and dissemination of high quality subsurface data, obtained primarily from instrument sites that recorded strong shaking during the 1994 Northridge earthquake. Site characterization is being accomplished in cooperation with geologists, geotechnical engineers and geophysicists from a variety of public and private organizations. To date, approximately 40 strong-motion recording sites have been characterized with typical sites having geologic and geophysical logs to depths of 100 meters or more. These data can be viewed and downloaded from http://geoinfo.usc.edu/rosrine/. Ultimately, these data are being used to refine procedures and models used for estimating earthquake ground response.

One aspect of the ROSRINE project was a comparison and assessment of available methods to obtain in-situ shear and compression wave velocity data. This was accomplished at an instrumentation array site installed near the La Cienega Undercrossing of Interstate 10 in Los Angeles (see Fig. 1). The La Cienega site is considered a deep-soil site that is representative of Los Angeles Basin soils. The composite stratigraphic section of the first 100 meters (shown in Fig. 2) reveals bedded fine and coarse alluvial deposits. Rock was not encountered within the upper 300 meters investigated at this site. At the La Cienega Array site, geophysical logs of formation seismic velocity were obtained and compared from four independent methods: PS suspension logging, surface-to-borehole logging, crosshole logging and spectral analysis of surface waves (SASW) logging. This paper discusses these methods used to collect formation velocity data and presents results of their comparison from the La Cienega Array site. Additionally, this paper also presents comparisons of results from two independent interpretations of identical PS suspension log data sets. These data were acquired at each of 5 ROSRINE sites to establish the repeatability of PS suspension data.

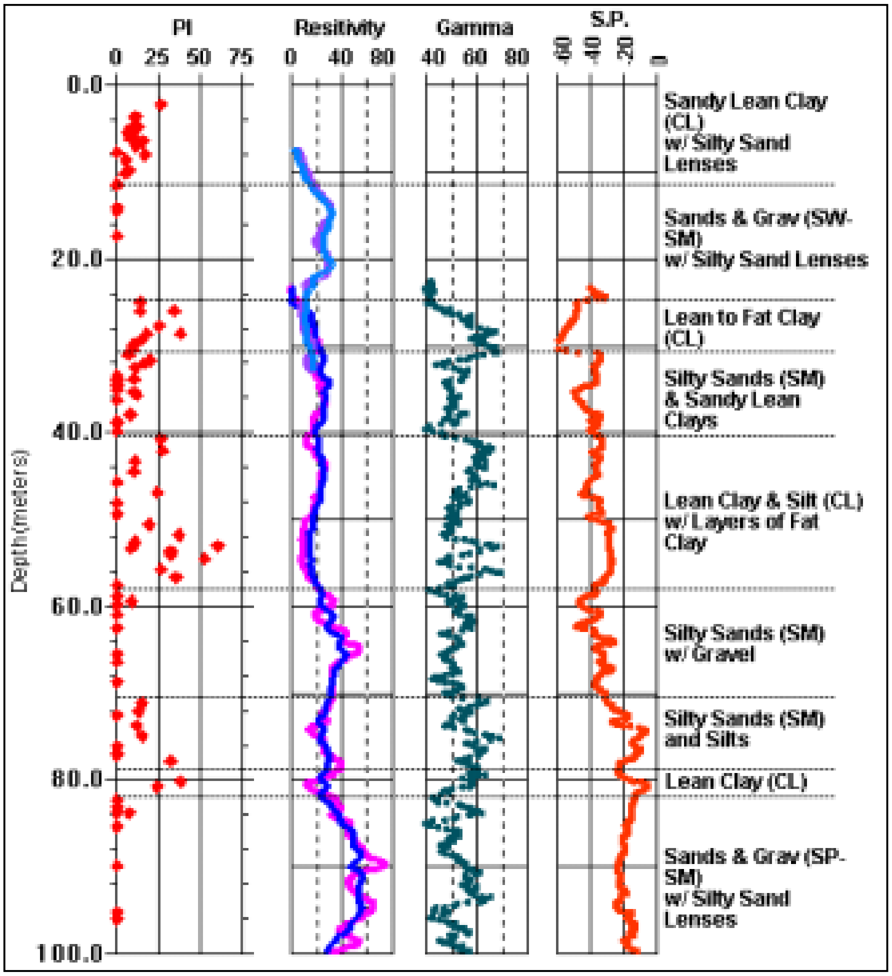


Figure 2. Representative stratigraphic section of the ROSRINE La Cienega site. Only the first 100 meters are shown. Plasticity indices of soil samples and geophysical logs are presented for correlation. USCS nomenclature provided in parentheses. PI = plasticity index, S.P. = spontaneous potential. Modified from Roblee (1998).

PS Suspension Logging

Caltrans uses a suspension-type logging system for measurement of both shear and compressional wave velocity. Kitsunezaki (1980) describes the design and principles of operation for the system. In this system, both source and receiver are suspended within the borehole. Provided the average specific gravity of the receiver is close to unity, resonance due to suspension is avoided and response of the receiver housing is nearly flat.

Measurement of shear-wave velocity relies on indirect excitation of the borehole wall via a dipole force. Application of the dipole force generates a pseudo-Rayleigh flexural mode within the borehole. As discussed in Schmitt (1988), the flexural mode is dispersive and at low frequency propagates at a velocity equivalent to a shear wave (Figure 3). The upper frequency bound at which flexural mode velocity diverges from shear-wave velocity is formation dependent, but, in practice, appears to occur above approximately 1500 Hz (Owen and Vickery, 1997).

For velocity logging, suspension log data density is typically 1 or 0.5 meters/reading. This provides good stratigraphic delineation for beds greater or equal to 1-meter thickness, and velocity resolution is significantly better than surface-to-borehole logs or SASW soundings at depth. Compared to crosshole logs, the PS suspension log provides comparable resolution with the advantage of reduced cost, since only one borehole is needed for measurement. The primary disadvantages of the tool are its cost and relative insensitivity in highly fractured, hard rock formations (this is discussed in more detail below).

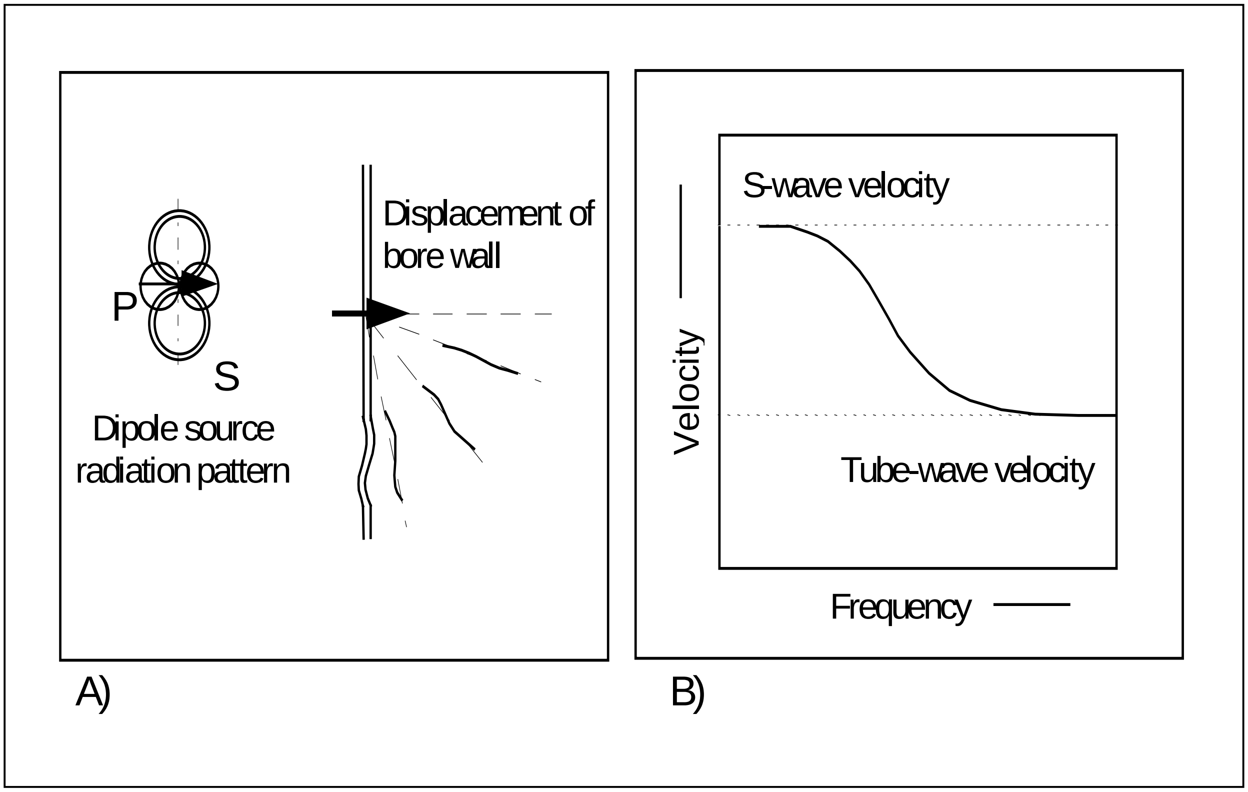


Figure 3. A) Illustration of dipole force and borehole displacement. Maximum flexural mode displacement occurs where force direction is normal to the borehole wall. B) Illustration of flexural wave dispersion. At low frequencies, flexural-wave velocity is equivalent to shear-wave velocity. With increasing frequency, flexural-wave velocity asymptotically approaches that of a tube wave. The cutoff at very low frequency reflects conversion of flexural mode to pure shear at wavelengths significantly larger than borehole diameter. From Kitsunezaki (1980) and Schmitt (1988).

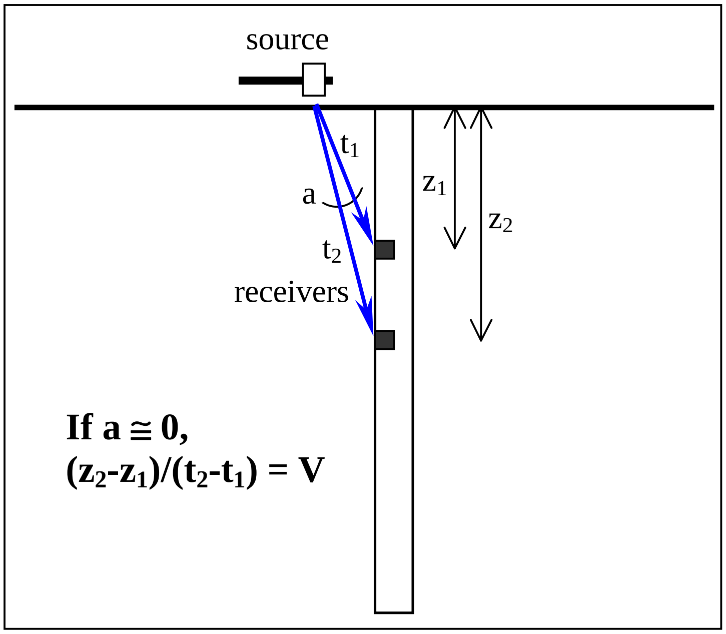


Figure 4. Diagram of the surface-to-borehole logging method. Travel time from a shear wave generated at the surface is measured at different depths in a borehole. Typical surface sources are sledge hammer and striker plate or pneumatic rams. t = travel time, z = depth, V = velocity, a = divergence angle between raypaths.

Surface-to-Borehole Logging

In the surface-to-borehole method, a source is located at the surface near the borehole, and one or more receivers are placed down-hole (Figure 4). Assuming the divergence angle (a) of the raypath traveling to the different receivers is negligible, the difference in traveltimes between receivers reduces to a function of the vertical velocity of the material between the receivers (Telford et al., 1976). Hence, surface-to-borehole logging is also known as *interval velocity* logging.

The primary advantage of surface-to-borehole logging lies in the initial cost of equipment. Sources, receivers and recording units for that type of velocity logging are relatively inexpensive, and data can be acquired and processed with minimal training. However, the surface-to-borehole logging method typically requires use of a cased and grouted borehole that adds significantly to operational costs. Another disadvantage is that since the energy source is at the surface, signal attenuation requires increasing energy to measure greater depths. Although attenuation may be overcome somewhat by signal stacking or larger energy sources, practical limitations on source size limit the maximum depth of investigation with that method. Additionally, difficulty generating shear waves over water generally limits that method to land use only. Nevertheless, the surface-to-borehole method can yield reliable average velocities to relatively large depths, provided that sufficiently large layer thickness intervals are used.

Crosshole Logging

Crosshole shear-wave logging is similar to surface-to-borehole logging, with the exception that the source is now located in a second cased borehole adjacent to and at the same elevation as the receiver (Figure 5). The primary benefit of crosshole logging over PS suspension logging is that a larger volume of undisturbed material away from the borehole is sampled during measurement and data are acquired across a two-dimensional section, hypothetically increasing the representativeness of the data set. Compared to surface-to-borehole logging, hole diameter and closer proximity to the receiver mean utilization of smaller energy sources. However, currently available in-hole sources typically become increasingly difficult to operate as measurement depth increases. Furthermore, boreholes are rarely plumb, and deviations of the hole from vertical must

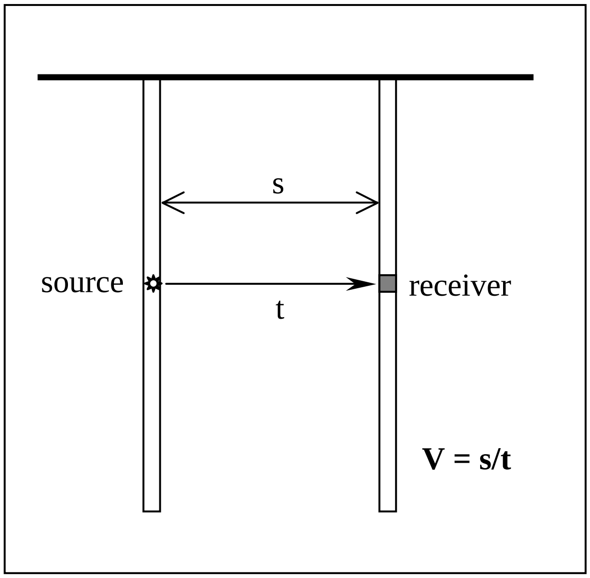


Figure 5. Conceptual diagram of crosshole velocity logging. V = velocity, s = separation, t = travel time.

be measured in order to determine the length of the travel path and assure data validity. In addition, the requirement of a second cased and grouted borehole makes this method more expensive compared to the other logging or sounding techniques compared in this paper.

Spectral Analysis of Surface Waves

The spectral analysis of surface waves (SASW) method uses the dispersive characteristics of Rayleigh waves and the exponential decay of surface-wave particle displacement with depth to calculate a shear-wave velocity profile. As described in Sheu et al. (1986) and Rix et al. (1992), dispersion occurs in layered media due to interaction of surface waves with different velocities in the layers. Because of exponential decay, short-wavelength surface waves are more affected by shallow layers, longer-wavelength surface waves by deeper layers.

A conceptual illustration of the SASW technique is presented in Figure 6. By recording time histories of surface-wave displacements at varying frequencies and source-receiver separations, digital signal processing techniques can be used to calculate the cross-power spectrum between receivers and derive a dispersion curve relating surface-wave velocity to wavelength. An inversion technique (e.g., Nazarian, 1984) can then be applied to the dispersion curve to develop a model of shear-wave velocity versus depth.

The main advantage of SASW is that no borehole is needed to derive shear-wave velocities, thus the expense and time associated with drilling a borehole is eliminated. Setup and data acquisition is rapid, and dispersion curves are developed in real-time (thus giving a rough evaluation of velocity profiles while in the field). The disadvantages of the technique are that substantial training is required for operation of the equipment and processing of data. Like the other techniques previously discussed, external noise is problematic. Greater source-receiver separations and larger energy sources are needed for greater depth of investigation, a potential drawback in areas of limited access. Additionally, surface-waves decay rapidly with depth and resolution decreases with increasing depth. The method, therefore, is currently limited to relatively shallow depths (roughly 30 meters or less), especially in noisy highway environments. Nevertheless, SASW does provide the best resolution in the very-near surface region (roughly 3 m) of all methods described herein.

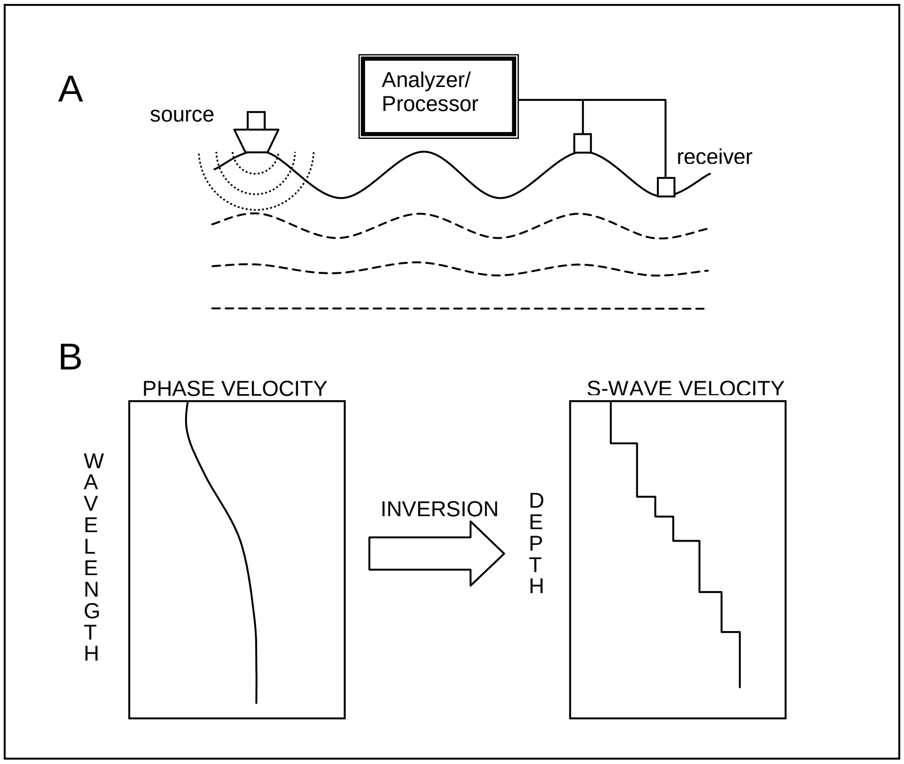


Figure 6. Illustration of the SASW method. A. Conceptual diagram of instrument setup (ground displacement greatly exaggerated). Relative particle displacement at depth from surface waves represented by dashed lines. B. Conceptual illustration of the inversion process. Modified from Rix et al. (1992).

COMPARISON OF RESULTS

Figures 7 through 9 present shear-wave velocity profiles obtained using each of four separate in situ testing techniques (PS suspension logging, crosshole logging, downhole logging, and SASW profiling) performed by four independent testing entities. (The results for compressional-wave velocity are presented in Figure 10). All borehole techniques (except shallow crosshole measurements) were acquired in three boreholes (SB-2, SB-3, and A-1) located within 7-m of each other, as shown in Figure 1. Surface-wave measurements were performed over a centerline with receivers extending as far as 40 m from the borehole locations. Caltrans and Agbabian Associates (now Geovision Geophysical Services) each performed independent PS suspension logging measurements. Surface-to-borehole measurements were logged by the USGS, and the University of Texas performed both crosshole and SASW measurements. Since the PS log data exhibited the greatest resolution with depth and demonstrated excellent repeatability for this site (discussed below), PS log data were used as the baseline for comparison of the other methods.

The results in Fig. 7 show that the surface-to-borehole data had the lowest resolution of the methods, although the overall trends in the data were similar in general shape to the PS log data. The interpretation scheme makes thin velocity variations difficult to detect and leads to averaging velocities over relatively thick layers. Furthermore, as depth (and strata velocity) increases it becomes increasingly difficult to distinguish small variations in travel time. This is exacerbated by the loss of high-frequency signal content

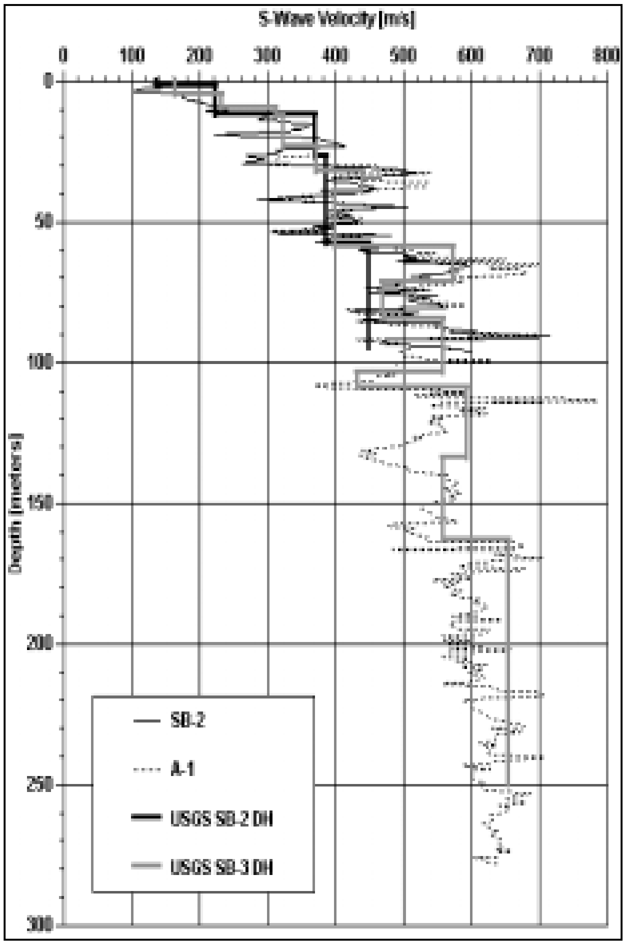


Figure 7. Comparison of PS log to surface-to-borehole data at the ROSRINE La Cienega site. See Figure 1 for hole locations. DH = surface-to- borehole data.

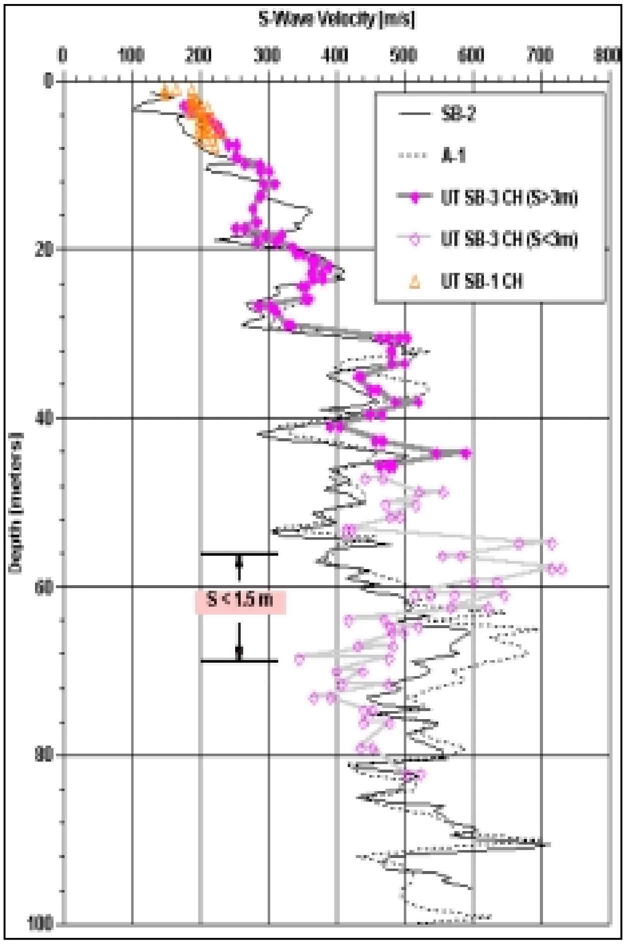


Figure 8. Comparison of PS log to crosshole data at La Cienega. Note difference in depth scale compared to Fig. 7. See Figure 1 for hole locations. CH = crosshole data.

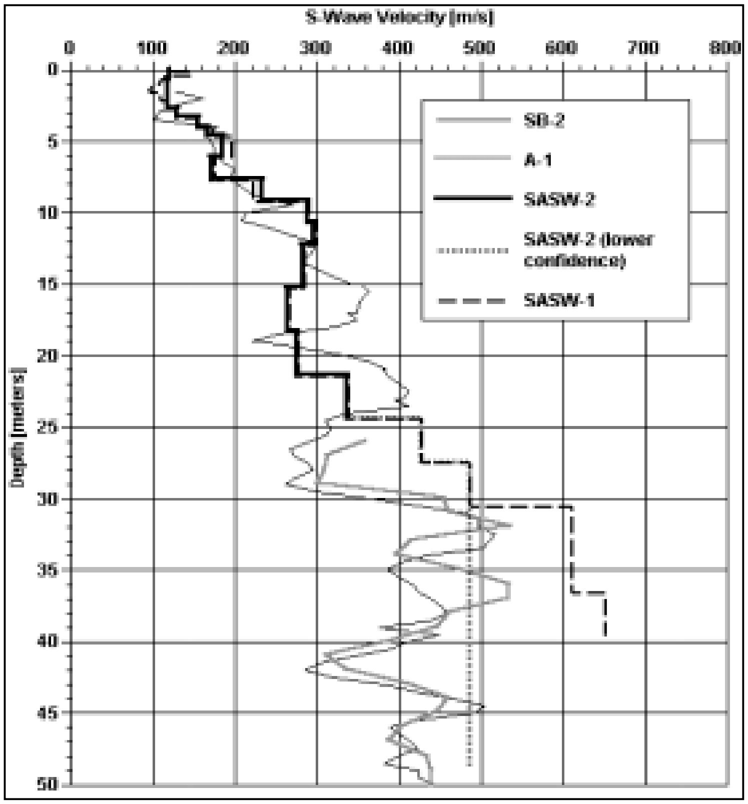


Figure 9 Comparison of PS log to Spectral Analysis of Surface Wave (SASW) data at La Cienega. SASW measurements performed on ground surface. "Lower confidence" line is extrapolated to greater depth from SASW-2 data.

for the longer distances. Thus, there is an apparent loss of resolution with depth as indicated by the increasingly thick layering. This loss of resolution is probably why a significant velocity inversion that was detected by the PS logger was not resolved with the surface-to-borehole method.

The crosshole results matched the PS log data remarkably quite well (Figure 8). Resolution was comparable to the PS log and velocity reversals were similarly detected. However, velocities from a zone between 54 and 70 meters depth were significantly different. Deviation logs from the holes used in this survey revealed that the holes converged and borehole separation was 1.5 meters or less within this zone. At this relatively large depth, the potential error associated with borehole deviation surveys makes definitive identification of borehole separation distance difficult. Further, this close distance yielded compressed P- and S-wave arrivals, thus increasing interference and reducing ability to distinguish the waves as separate and distinct events on the seismic records. Subsequently, the reduced data quality yielded less than optimal results for this interval.

In Figure 9, the SASW data are presented in similar fashion to the surface-to-borehole data. In the near-surface region, SASW velocity resolution is comparable to that of the PS log and clearly provides more detail than the surface-to-borehole log. As depth increases, the SASW results must be averaged over thicker layers since longer wavelengths and greater receiver separations are utilized. This leads to loss of resolution and averaging of properties over greater horizontal extent. The SASW results are the most limited in investigation depth. Beyond 24 meters, the analysts at UT considered the interpretation less reliable. Within the upper 24 meters, the SASW results are in good agreement with the PS suspension and crosshole results. However, the "less confident" results presented below 24 meters diverge significantly from the other methods. It should be noted that greater survey depths could be expected at sites that are not as noisy or space-limited as the I-10 La Cienega site.

For the P-wave results (Figure 10), PS log, surface-to-borehole and crosshole results are compared. Only shear-wave velocities are derived from SASW. P-wave velocities are generally comparable, again with reduced resolution for the surface-to-borehole data. Notable exceptions are overall higher velocities in the crosshole set and a significantly higher velocity zone (between 14 and 23 meters) on the crosshole and surface-to-borehole data. The generally higher crosshole velocities may be the result of a small systematic timing error in establishing the initiation of source impact. Such an error would have a greater effect on faster-velocity material and would have negligible impact on the much slower shear-wave velocities. The localized higher-velocity zone shown in the surface-to-borehole results cannot be fully explained, but may be related to inadvertent ground modification associated with placement of casing in Borehole SB-3 to approximately 20-m depth.

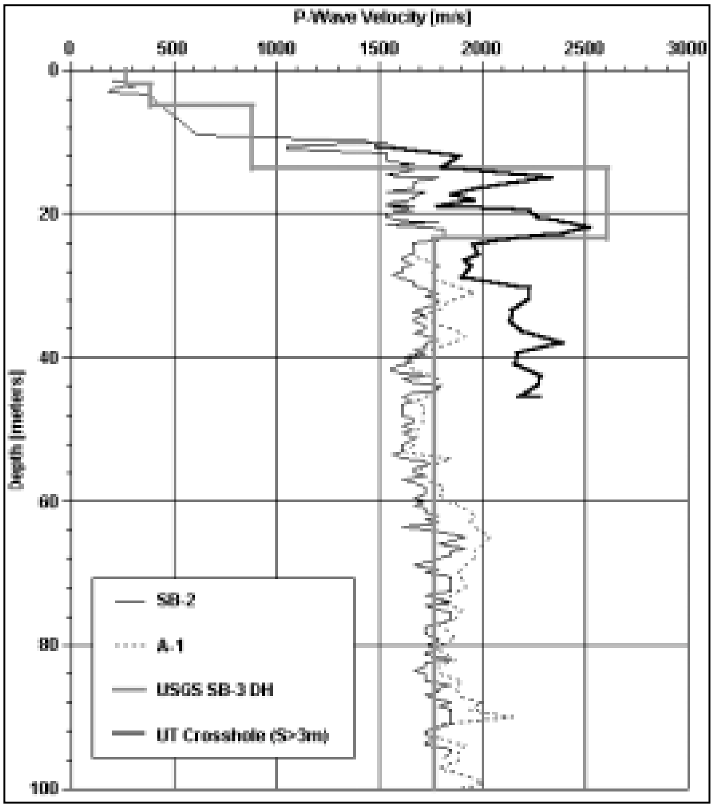


Figure 10. Comparison of P-wave results from LA Cienega. Only the upper 100 meters are shown. See text for discussion

PS SUSPENSION REPEATABILITY

The repeatability of PS suspension logger measurements was assessed in two ways using subsets of the ROSRINE data. First, two independently-acquired and independently-interpreted data sets from nearby boreholes at the La Cienega site are compared to assess the overall repeatability of PS measurements. Second, two independent interpretations were made of data from each of 5 ROSRINE sites including La Cienega to assess the potential for subjective bias in interpretation. A summary of those results is presented in Table 1.

The logs of the independently acquired and interpreted data sets from the La Cienega site are shown in Figure 11. These results show remarkable similarity in both general trends and in detection of small-scale variability. The data indicate that variations in velocity with small changes in depth, typical of PS data, are primarily the result of geologic variability rather than measurement or interpretation errors. However, experience indicates that individual data points should not be overemphasized in the characterization of a site.

The single data set acquired from borehole SB-2 at La Cienega was independently interpreted by two analysts at Caltrans. Tabulated statistics presented in Table 1 reveal that, although interpreted shear-wave velocities for a few individual points differed by as much as 48% (in very-near-surface zones of poor data quality), the average difference was insignificant and overall precision was excellent. This information contributed to the selection of PS suspension log data as the baseline for comparison of the other velocity measurement techniques presented in this paper.

The La Cienega PS log data are generally of excellent quality. Therefore, there was a low likelihood of significant differences between two interpretations of the same data set. The four additional sites selected for comparison were of varying data quality, with the Arleta site (Figure 12) representing the best quality of the four and the poorest represented by the near-surface portion of the Pacoima site (Figure 13). These four sites can be considered a continuum of variable data quality. Repeatability of velocity from these sites should, therefore, provide representative information to evaluate efficacy of the PS suspension technique.

Consideration of quality PS log records should be divided between the data and the interpretation. Poor data are manifested by noisy traces (low signal/noise ratios), interference between P- and S-wave events and absence of identifiable events on the traces. These can be the result of large external vibrations (noise), geologic conditions (e.g., highly-fractured rock or very soft formations) or operator error. For interpretation of that data, bias or other discrepancy between interpreters can result from error or from differences in data processing (primarily application of different filter parameters).

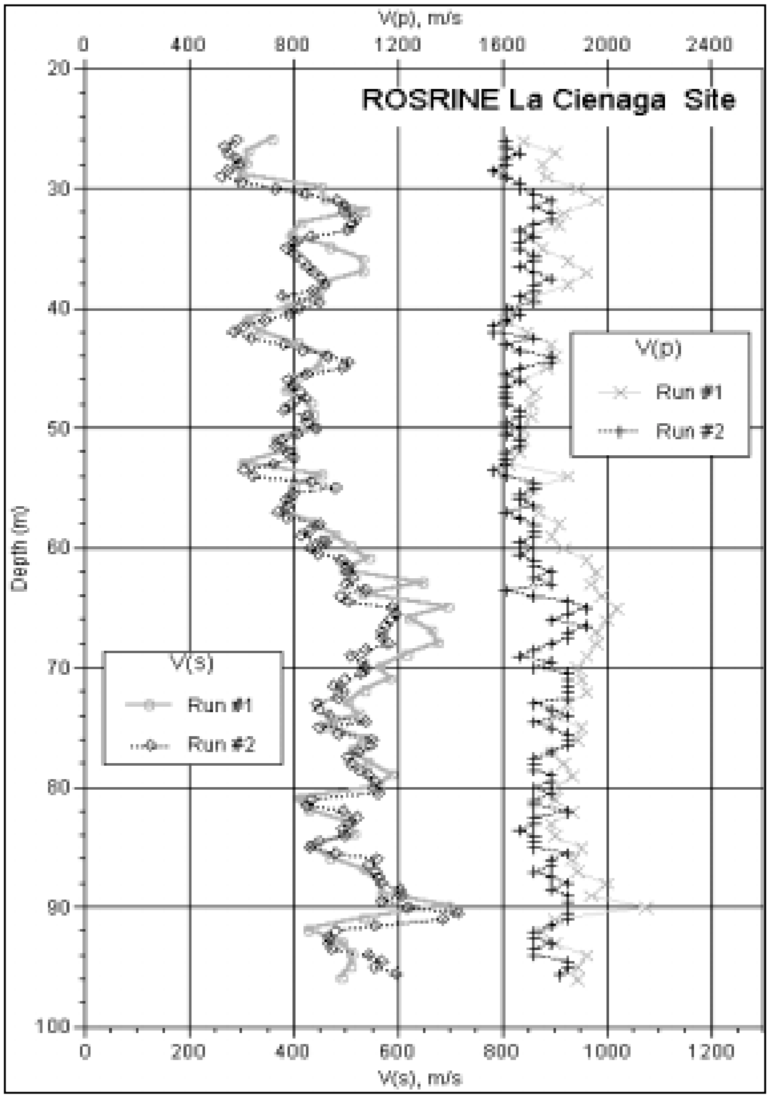


Figure 11. Two interpretations of PS log data from the ROSRINE La Cienega site. Run #1 acquired from hole A-1, Run #2 from hole SB-2. See Figure 1 for hole locations, Table 1 and text for additional discussion.

The results in Table 1 show that, of the four sites, the mean relative difference (the measure of variation between interpretations) is below 10 percent for all but Pacoima. Even at the Pacoima site, data within the relatively unweathered zone below 12 meters has excellent repeatability. However, in the near-surface region, where the rock is highly fractured and data quality is exceptionally poor, the interpretations differ markedly. This is reflected in the strong bias toward lower velocities in the Caltrans interpretation and the increase in standard deviation of the relative difference between shear wave data sets. It should be noted that the first interpreter (from Agbabian) had complementary surface-to-borehole measurements available to constrain the PS interpretation. This information was not made available to the Caltrans interpreter. This case illustrates that complementary velocity measurements are highly beneficial at difficult sites.

The weathered material at Pacoima is representative of a class of materials where the PS suspension tool encounters difficulty. In these very stiff and highly variable materials, high velocities, diffractions and multiple wave conversions result in interference with P- and S-waves. In addition, high rock rigidity creates difficulty generating shear-wave displacement of the bore wall with the relatively low-energy source within the PS suspension probe. The PS log, therefore, tends to have limited effectiveness in hard, fractured rock.

Finally, it is interesting to note in Table 1 that a negative bias (tendency toward lower velocities) exists on the Caltrans data for all four sites. Except for the upper Pacoima data, the difference is small (8% or less). It likely represents an interpreter bias in the identification of particular events on a given waveform or different filtering parameters employed in processing of the data.

DISCUSSION

When the four techniques used in this project are considered overall, each velocity set follows a similar general pattern. With the downhole sources (PS suspension and crosshole) there is a remarkable consistency in delineating small-scale variations in velocity. For those two methods, over small depth ranges, velocities may differ by as much as 30%, but more typically are within 10% of one another (Roblee et al., 1998). The surface-to-borehole measurements are determined on the basis of average

	Arleta		La Cienaga		Pacoima (Lower)		Pacoima (Upper)		Sepulveda		Tarzana	
	V(s)	V(p)	V(s)	V(p)	V(s)	V(p)	V(s)	V(p)	V(s)	V(p)	V(s)	V(p)
Max. Relative Difference	0.25	0.41	0.10	0.04	0.03	0.26	-0.38	-0.37	0.24	No V(p) Data	0.61	0.46
Min. Relative Difference	-0.17	-0.37	-0.48	-0.14	-0.22	-0.31	-0.74	-0.71	-0.49		-0.49	-0.40
Mean Relative Difference	-0.02	-0.08	0.00	-0.05	-0.01	-0.02	-0.52	-0.53	-0.02		-0.01	-0.02
Standard Deviation	0.04	0.12	0.05	0.04	0.04	0.15	0.11	0.10	0.08		0.10	0.10

Table 1. Summary of results for PS suspension log repeatability assessment. Caltrans' data set was arbitrarily chosen for the baseline. For the La Cienega site only, V(p) differences are based on data from different boreholes. The Pacoima site is divided into upper (above 12 meters) and lower (below 12 meters) segments to emphasize differences between these zones.

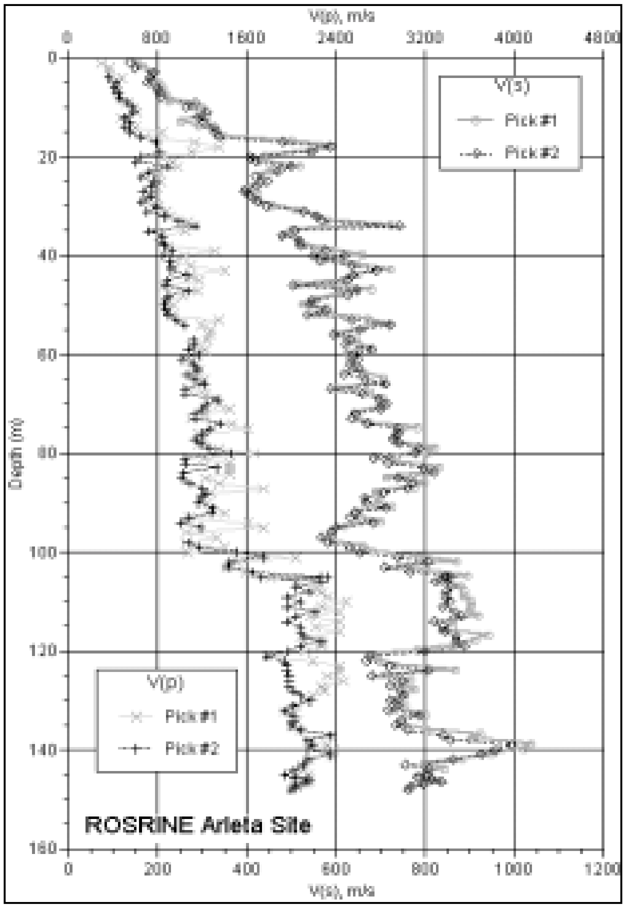


Figure 12. Two interpretations of PS log data from the ROSRINE Arleta site. Pick #2 = Caltrans' interpretation. See Table 1 and text for additional discussion.

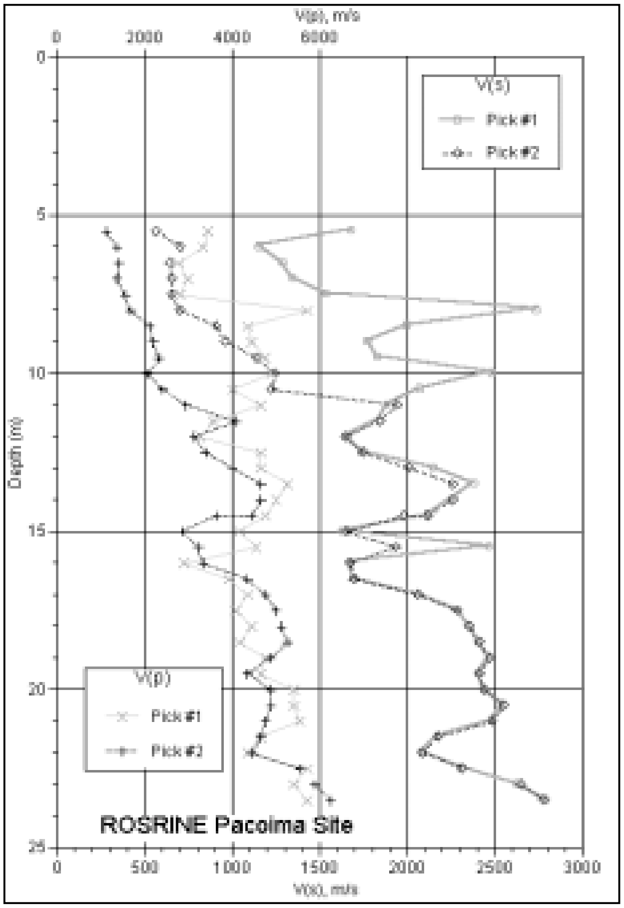


Figure 13. Two interpretations of PS log data from the ROSRINE Pacoima site. Note different depth scale than in Fig. 12. Pick #2 = Caltrans' interpretation. See Table 1 and text for additional discussion.

layer velocities and, therefore, do not reveal such detail. However, at the scale required for ground response analysis, differences in resolution between surface-to-borehole and PS log and crosshole results may not be highly significant. Only in the case of significant velocity reversals (laterally extensive low-velocity layers) would this resolution difference be critical. In those instances, the higher resolution afforded by the PS log could be crucial to adequate velocity characterization.

The results of the La Cienega comparisons show that, at the level of resolution usually applied to ground response analysis, velocity profiles obtained from the four measurement techniques are acceptably similar, though the PS-logger and the surface-to-borehole logs were capable of substantially greater depths of characterization. The variations observed between profiles are primarily associated with the fundamental differences in the testing configurations and in the inherent resolution of the different methods. Comparison of the independently processed PS log data sets shows that high-quality data provide interpretations nearly free of subjective bias. However, substantial differences can be introduced when working with poor quality data due to interpreter bias, differences in processing parameters or plain error. The poor quality data usually appear near the ground surface and (for P-waves) within the unsaturated zone. This limitation indicates that addition of a second technique, one focused on very shallow measurement (such as SASW), may prove an effective complement to PS suspension logging. Additionally, surface-to-borehole measurements may provide an ideal complement at sites where highly-fractured rock is encountered. Despite these limitations, the improvement in logging efficiency, combined with increased depth range, greater resolution and constant signal strength with depth, PS suspension logging is Caltrans' method of choice for supporting seismic design and retrofit.

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