COMBINED USE OF ACTIVE AND PASSIVE SURFACE WAVE TECHNIQUES FOR COST EFFECTIVE UBC/IBC SITE CLASSIFICATION

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ABSTRACT

The average shear wave velocity of the upper 30m (V_S30) and upper 100ft (V_S100) are used in the 2001 Uniform Building Code (UBC) and 2000 International Buiding Code (IBC), respectively, to separate sites into classes for earthquake engineering design. Many state and local building codes are based on either the UBC or IBC.

Commonly used geophysical techniques for estimating V_S30/V_S100 require a borehole. Active and passive surface wave techniques do not require a borehole, and offer a cost effective means of estimating V_S30 or V_S100. Further, while they do not have the resolution of borehole techniques, they sample a much larger volume of earth and may, therefore, provide a more representative estimate of average shear wave velocity. The combined use of active and passive surface wave techniques in urban areas can reduce the need for costly energy sources such as bulldozers, electromechanical shakers and large weight drops.

Case histories from several sites with borehole velocity control in California and Nevada demonstrate the effectiveness of surface wave techniques for estimating V_S30/V_S100 in a variety of geologic conditions.

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 2001 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 V_S100. These site classes are as follows:

Class A – hard rock – $V_S30 > 1500$ m/s (UBC) or $V_S100 > 5{,}000$ ft/s (IBC)
Class B – rock – $760 < V_S30 \le 1500$ m/s (UBC) or $2{,}500 < V_S100 \le 5{,}000$ ft/s (IBC)

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Class C – very dense soil and soft rock – 360 < $V_S30 \leq 760$ m/s (UBC)
or 1,200 < $V_S100 \leq 2{,}500$ ft/s (IBC)

Class D – stiff soil – 180 < $V_S30 \leq 360$ m/s (UBC) or 600 < $V_S100 \leq 1{,}200$ ft/s (IBC)

Class E – soft soil – $V_S30 \leq 180$ m/s (UBC) or $V_S100 \leq 600$ ft/s (IBC)

Class F – soils requiring site-specific evaluation

Other applications of V_S imaging include seismic risk studies, seismic hazard zonation, evaluation, of liquefaction potential and characterization of strong motion seismic instrument sites.

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

Active surface wave techniques such as the spectral-analysis-of-surface-waves (SASW) and multi-channel analysis of surface waves (MASW) and passive techniques such as the 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, compressional-wave velocity, 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. In urban environments the combined use of active and passive surface wave techniques can limit the need to mobilize large energy sources such as weight drop, bulldozers and vibratory systems.

Active Surface Wave Methods

Active surface wave techniques measure surface waves generated by dynamic sources such as hammers, weight drops, electromechanical shakers, vibroseis and bulldozers. These techniques include the spectral analysis of surface waves (SASW) and multi-channel array surface wave (MASW) methods.

The SASW method is optimized for conducting V_S depth soundings. A detailed description of the SASW field procedure is given in Joh, 1997. The general testing setup for the SASW method is shown in Figure 1 and summarized below. A vertical dynamic load at the surface generates predominantly Rayleigh waves, which are monitored by two, or more, receivers. A dynamic signal analyzer records the ground motions, transforms the time history data into the frequency domain, and calculates the phase and coherence of the cross power spectrum.

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. Typically the source to near-receiver spacing (d_1) is set equal to the receiver spacing (d_2) in order to minimize near-field effects, body wave contamination and attenuation. To minimize phase shifts due to differences in receiver coupling and subsurface variability, the source location is typically reversed.

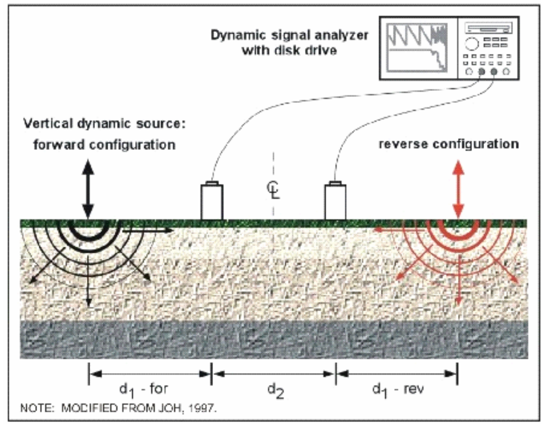

Figure 1. SASW setup.

During data analysis, an interactive masking process is used to discard low quality data and to unwrap the phase spectrum, as shown in Figure 2. The dispersion curve (Rayleigh wave phase velocity versus frequency or alternatively wavelength) is calculated from the unwrapped phase spectrum by:

$$V_R = f * d_2/(\Delta\phi/360°),$$

where f is frequency, d_2 is the distance between receivers, and $\Delta\phi$ is the unwrapped phase of the cross power spectrum. To minimize near-field effects dispersion data with a wavelength greater than twice the receiver spacing is rejected.

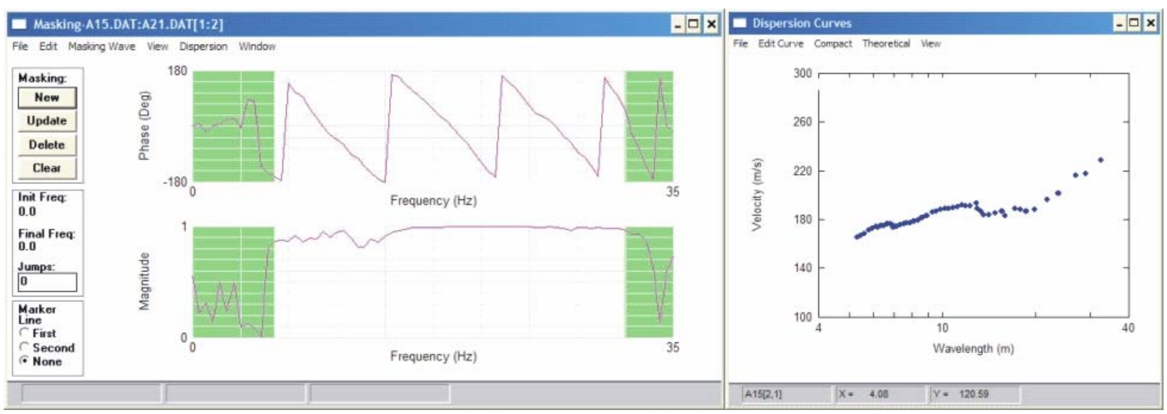

Figure 2. Masking and unwrapping of phase spectrum and resulting dispersion curve.

A detailed description of the MASW method is given by Park, 1999. The MASW field layout is similar to that of the seismic refraction technique. This technique is ideally suited to 2D V_S imaging, with data collected in a roll-along manner similar to that of the seismic reflection technique. Twenty four, or more, geophones are laid out in a linear array with 1 to 2m geophone spacing and connected to a multi-channel seismograph. The source is offset at a predetermined distance from the near geophone with several source offsets and source types evaluated. A wavefield transform, such as the f-k or τ-p transform, is applied to the time history data to isolate the surface wave dispersion curve. The dispersion curve is picked as the peak of the surface wave energy in slowness/velocity) – frequency space as shown in Figure 3.

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 contain more energy than the fundamental mode Rayleigh wave The MASW technique can often be used to isolate the fundamental-mode Rayleigh-wave dispersion curve from higher modes (Park et al., 1999) and should be used in environments where velocity inversions or steep velocity gradients are expected. Alternatively, the dispersion curve generated by the SASW technique can be modeled using techniques that take into consideration higher modes and body waves.

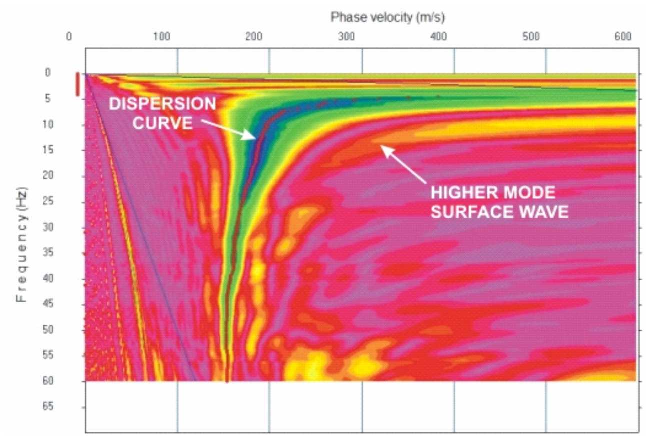

Figure 3. Wavefield transform of MASW data.

Passive Surface Wave Methods

Passive surface wave techniques measure noise; surface waves from ocean wave activity, traffic, factories, etc. These techniques include the array microtremor and refraction microtremor (REMI) techniques.

A detailed discussion of the array microtremor method can be found in Okada, 2003. This technique typically uses 4 to 24 receivers aligned in a 2-dimensional array. The most common arrays are the triangle, circle, semi-circle and “L” arrays. The triangle array, which consists of several embedded equilateral triangles as shown in Figure 4, is often used as it provides good results with a relatively small number of geophones. With this array the outer side of the triangle should be at least as long as the desired depth of investigation. Typically, fifteen to twenty 30-second noise records are acquired for analysis. The spatial autocorrelation (SPAC) technique is one of several methods used to estimate the Rayleigh wave dispersion curve. A first order Bessel function is fit to the SPAC function to determine the phase velocity for a particular frequency. Figure 5 presents the degree of fitness of the Bessel function to the SPAC function for a range of frequencies and phase velocities. The dispersion

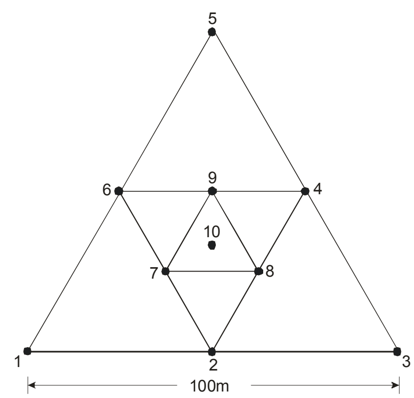

Figure 4. Triangle array geometry

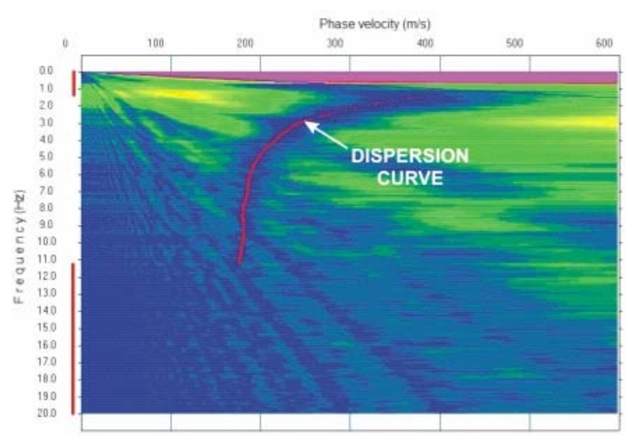

Figure 5. Dispersion curve from array microtremor measurements

curve, is the peak (best fit), as shown in Figure 5.

The refraction microtremor technique (REMI) is a passive surface wave technique developed by Dr. John Louie at University of Nevada, Reno. A detailed description of this technique can be found in Louie, 2001. Twenty-four, 4.5 Hz geophones are laid out in a linear array with a typical spacing of 6 to 8m and fifteen to twenty 30-second noise records are acquired. A slowness-frequency (p-f) transform is used to separate Rayleigh wave energy from that of other waves. Because the noise field can originate from any direction, the wavefield transform is conducted for multiple vectors through the geophone array, all of which are summed. The dispersion curve is defined as the lower envelope of the Rayleigh wave energy in p-f space as shown in Figure 6. Because the lower envelope is picked rather than the energy peak (energy traveling along the profile is slower than that approaching from an angle), this technique may be somewhat more subjective than the others, particularly at low frequencies. The SPAC technique can also be used to estimate the dispersion curve from linear-array microtremor data assuming omni-directional noise sources. Any many sites, sufficient space is not available or there are too many obstructions for 2D arrays and linear arrays are the easiest to implement.

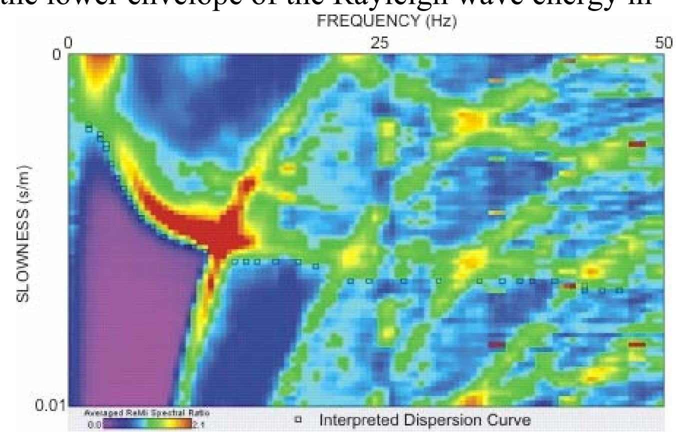

Figure 6. Wavefield transform of REMI data

Case Histories

Five case histories where active and surface wave techniques were used to characterize V_S30 at sites with PS suspension logs in Southern California, Northern California and Nevada are presented below. All modeling was conducted using forward modeling software assuming either fundamental mode or effective mode dispersion curves. Density values between 1.8 and 2.0 g/cc were typically assumed for sediments and the depth to groundwater was fixed where known by setting V_P to 1,600 m/s. A Poisson’s ratio of 0.33 was assumed for unsaturated sediments.

Port of Los Angeles, California

The surface wave dispersion curves and three possible shear wave velocity models and PS suspension log for a site at the Port of Los Angeles, California are presented in Figure 7. Active surface wave methods applied to this investigation included the SASW and MASW techniques. Passive methods included a 100m 7-station triangle array with 1-Hz geophones, 50m 10-station triangle array with 4.5-Hz geophones and a 24-channel linear-array with 4.5-Hz geophones and 7.5m station spacing. Conditions at this site were very poor for active surface wave techniques because of the presence of very low velocity hydraulic fill. In fact, with active surface wave techniques it was only possible to image to a depth of about 12.5m with a weight drop source typically capable of imaging to 30m. Passive techniques were able to extend depth of investigation to about 75m.

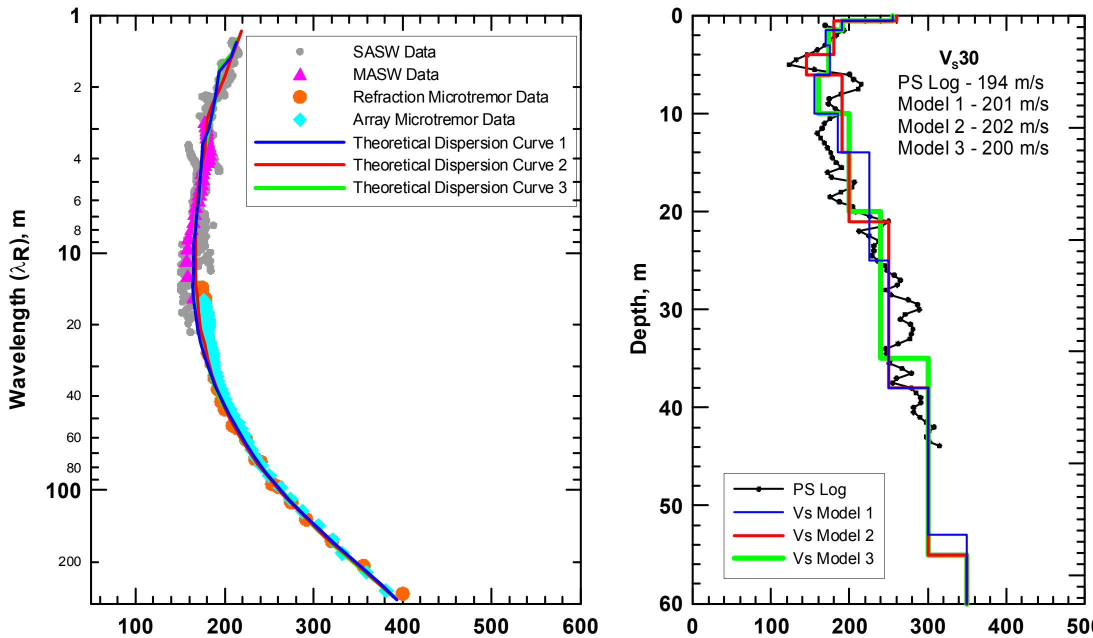

Figure 7. Surface wave dispersion curve, V_S models and PS suspension log from a site at the Port of Los Angeles, California.

There is excellent agreement in the dispersion curves generated from all techniques over the overlapping wavelength ranges. The minor differences probably result from variable velocity of the hydraulic fill within the sampling volume of the specific methods. Three V_S versus depth models were generated to illustrate the difficulty modeling the highly variable, near surface velocity structure evident in the PS log. Equivalence, multiple models equally well fitting field observations, is a common problem facing most geophysical exploration methods. The V_S structure resulting from surface wave modeling does not have the resolution of the PS suspension log but adequately represents subsurface velocity structure. The three surface wave models yielded similar values for the average shear-wave velocity of the upper 30m (V_S30), 200 to 202 m/s, illustrating that V_S30 can be more accurately resolved than the actual model layer thicknesses and velocities. V_S30 estimated from the PS log (194 m/s) is within 3-4% of that estimated from the three surface wave models (200 - 202 m/s). The small differences in V_S30 between the two methods may easily result from the different sampling regimes (borehole versus large area) rather than errors in either of the methods. According to the 2001 UBC this site is classified as Site Class D, stiff soil.

Dolphin Park, Carson, California

A surface wave sounding was conducted at Dolphin Park, Carson, California about 75m from a deep borehole that had been logged using the Oyo PS suspension logging technique. PS logging not conducted in upper 10m of the borehole as conductor casing was required for the 300+m borehole. The MASW technique was used to characterize near-surface velocity structure and array (7-channel, 60m triangle array) and refraction (24-channel linear array, 172.5m line) microtremor techniques to characterize deeper velocity structure. The surface wave dispersion curves and two possible shear wave velocity models and PS suspension log for this site are presented in Figure 8. The surface wave V_S models are valid to about 60 to 70m. There is good agreement above 70m depth between the two surface wave V_S models and the PS Log. V_S30 (180 and 183 m/s) and V_S60 (240 and 243 m/s) are almost the same for both surface wave models again demonstrating that the average V_S more accurately constrained than individual layer thicknesses and velocities. According to the 2001 UBC this site is classified as Site Class D/E, stiff soil/soft soil based on the average shear-wave velocity of the upper 30m.

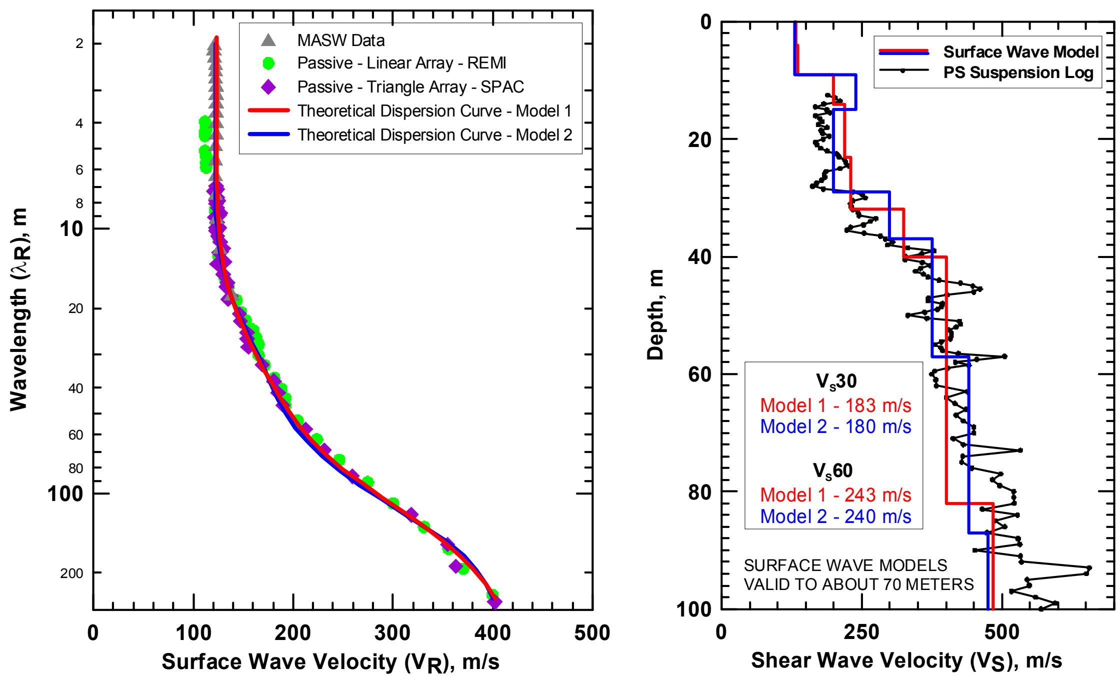

Figure 8. Surface wave dispersion curve, V_S models and PS suspension log from Dolphin Park, Carson, California.

Proposed High-Rise Apartment Complex, Sacramento, California

A surface wave sounding was conducted in the vicinity of a borehole logged using the Oyo PS suspension logging technique at the site of a proposed high-rise apartment complex in downtown Sacramento, California. The SASW technique was used to characterize near-surface velocity structure and the linear array (24-channel, 115m line) microtremor technique was used to characterize deeper velocity structure. The surface wave dispersion curves, shear wave velocity model and PS suspension log are presented in Figure 9. The surface wave V_S model is valid to about 40 to 50m. There is good agreement between the surface wave V_S model and the PS Log, although the surface wave model underestimates velocity of the layer at 28m depth. A decrease in shear wave velocity below this layer may explain the underestimated velocity in the surface wave model. V_S30 estimated using the surface wave method is 276 m/s, about 8% higher than that determined from the PS suspension log (255 m/s). According to the 2001 UBC this site is therefore classified as Site Class D, stiff soil.

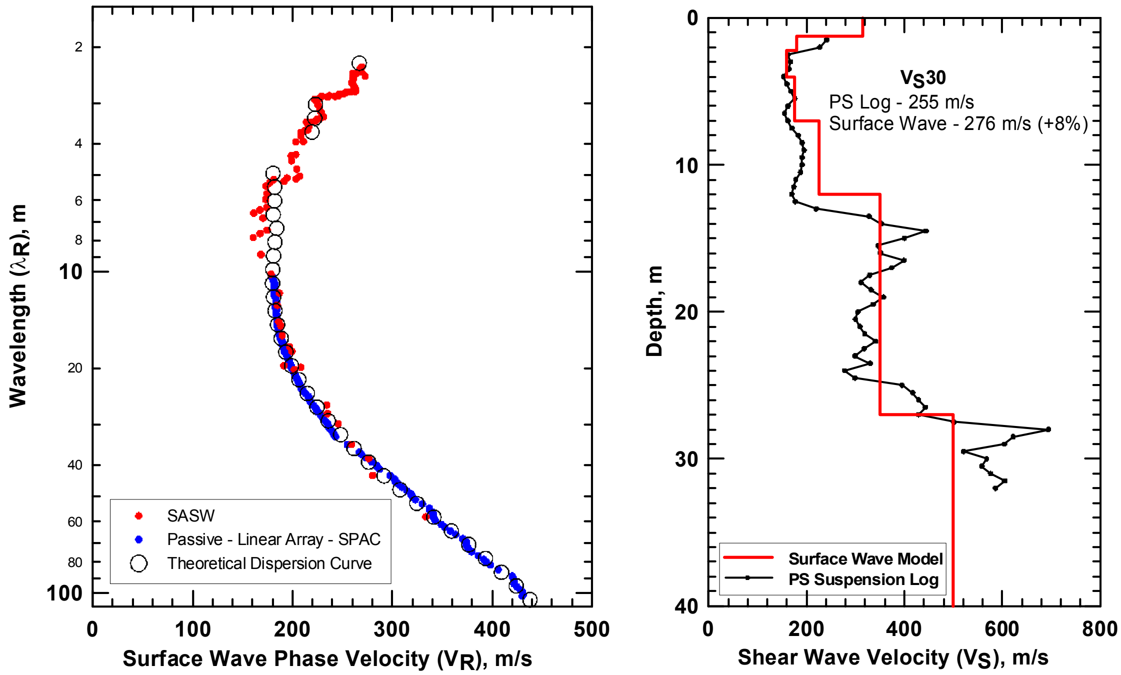

Figure 9. Surface wave dispersion curve, V_S models and PS suspension log at a proposed high-rise apartment complex site in downtown Sacramento, California.

Proposed Casino Site, Las Vegas, Nevada

A surface wave sounding was conducted in the vicinity of a borehole logged using the Oyo PS suspension logging technique at a proposed casino site in Las Vegas, Nevada. Due to proposed underground structures, the client requested the average Vs between 15 and 45 m for site classification. The SASW and MASW techniques were used to characterize near-surface velocity structure and the refraction microtremor technique (24-channel, 172.5m linear array) was used to characterize deeper velocity structure. The surface wave dispersion curves, shear wave velocity model and PS suspension log are presented in Figure 10. The MASW sounding was conducted next to the borehole and the SASW sounding was conducted along the western portion of the microtremor array, which was located about 20 m from the borehole. Lateral variability of near-surface V_S would therefore appear to be the cause of the slight difference of the dispersion curves between the two techniques and also between the SASW and passive data at small wavelengths. The dispersion curve from the linear-array passive data was estimated using both the REMI and SPAC techniques with relatively good agreement between the two methods.

The PS log indicates that velocity structure at this site is quite complex due to the multiple caliche layers, particularly a thick caliche zone at 10m. Surface wave techniques detect the upper caliche zone but underestimate the velocity. PS logging also had a difficult time accurately determining Vs in this zone due to P wave contamination. Accurate P wave velocities on the order of 3,000 to 4,000 m/s were however determined and indicate that shear wave velocity is greater than 1,000 m/s. Surface wave techniques appear to provide a reasonable estimate of average V_S structure below a depth of 28m where the thick caliche layers are no longer present. The surface wave V_S model is valid to about 75m.

Surface wave techniques underestimate V_S30 by 15% (467 m/s versus 536 m/s from the PS Log) and V_S 15-45m by 5% (459 m/s versus 484 m/s), primarily due to the underestimate of the velocity of the thick caliche zone. The modeled shear wave velocity is reasonable in other portions of the borehole. V_S30 in two other boreholes drilled within 150m of the borehole was 515 m/s and 393 m/s (no thick caliche zone). Vs 15-45m in these boreholes was 452 and 478 m/s, respectively. The UBC/IBC site classification at this site is C, very dense soil and soft rock at all of the borehole locations based on PS suspension logging and/or surface wave techniques.

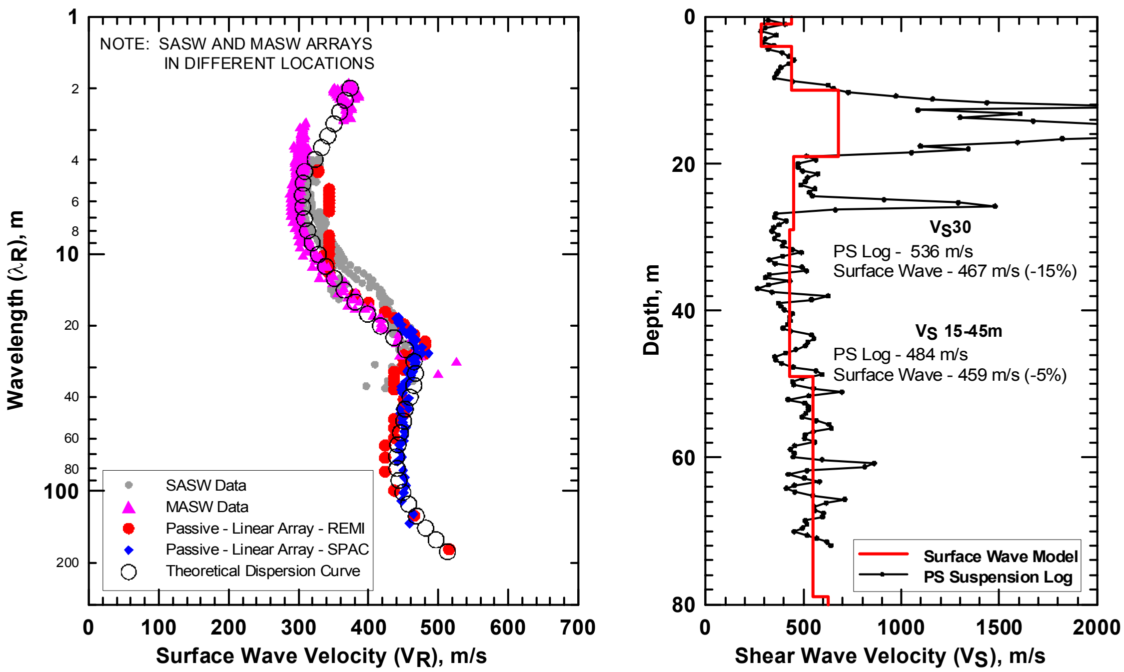

Figure 10. Surface wave dispersion curve, V_S models and PS suspension log at a proposed casino site in Las Vegas, Nevada.

Proposed Power Plant, Romoland, California

The surface wave dispersion curves and three possible shear wave velocity models and PS suspension log from a proposed power plant in Romoland, California are presented in Figure 11. The PS suspension log shows complex velocity structure with a general increase in velocity with depth. Active surface wave methods applied to this investigation included the SASW and MASW techniques. The passive method consisted of a 24-channel linear-array with 4.5-Hz geophones and 7.5m geophone spacing for 172.5m array length. The significant scatter in various dispersion curves most likely due to lateral V_S variability. Surface wave models are therefore not as accurate as there is more flexibility in the definition of an average dispersion curve. Three possible VS models are presented in Figure 11: a simple model with VS increasing with depth, a more complex model that better fits dispersion data and a complex model with layer contacts constrained by PS suspension log. There is only a 4% difference in Vs30 estimated from 3 models (443 to 461 m/s) and this difference would probably be less if the theoretical dispersion curves were identical. The simple model does not accurately reflect subsurface velocity structure. The other models are better with the model constrained by the PS suspension log being the best. All of the models significantly underestimate velocity below 25m raising the possibility that V_S may decrease below the 30m depth of the borehole. V_S30 from the surface wave models is 3 to 7% below that calculated from PS log (475 m/s). Both the PS Suspension log and surface wave models indicate that the site is UBC site class C, very dense soil and soft rock. Crystalline rock was expected at depth at this site and the surface wave data indicate that it may be located at about 105m although the surface wave models are probably only reliable to about 80m.

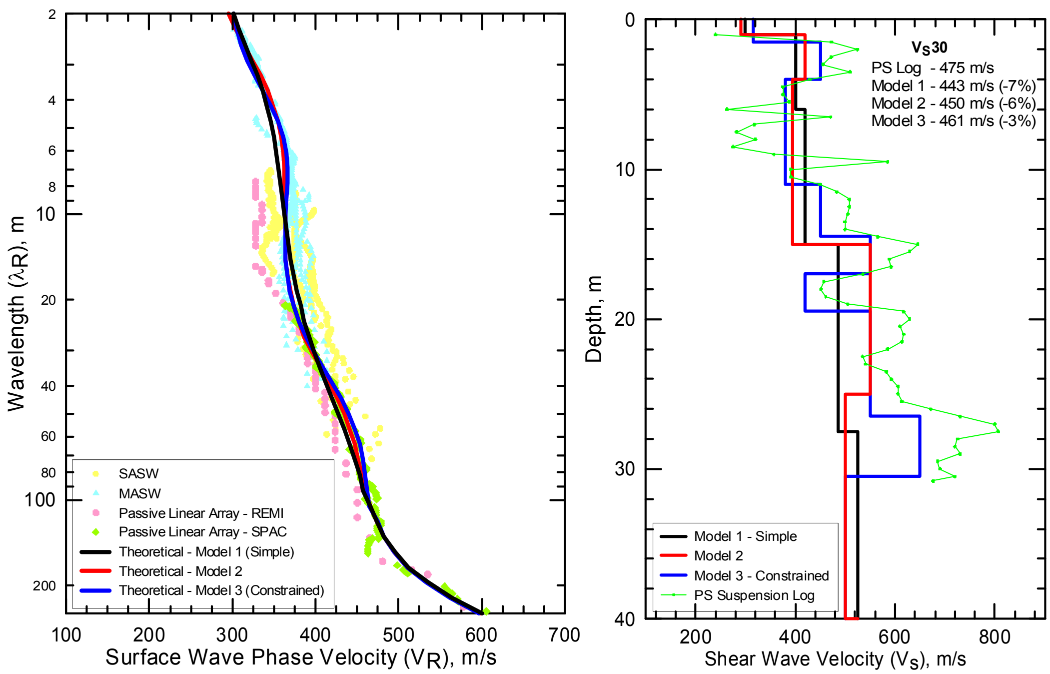

Figure 11. Surface wave dispersion curve, V_S models and PS suspension log at a proposed power plant site in Romoland, California.

Conclusions

In contrast to borehole measurements which are point estimates, surface wave testing is a global measurement in which a much larger volume of the subsurface is sampled. The resulting profile is representative of the subsurface properties averaged over distances of 30 to 100m, or more. Although surface wave techniques do not have the layer sensitivity or accuracy (velocity and layer thickness) of borehole techniques; the average velocity over a large depth interval (i.e. V_S30 or V_S100) is often very well constrained as shown in some of the earlier case histories. Because surface wave methods are non-invasive and non-destructive, it is relatively easy to obtain the necessary permits for testing. At sites that are favorable for surface wave propagation, surface wave techniques allow appreciable cost and time savings for UBC/IBC site classification as it is not necessary to drill 30m boreholes.

The combined use of active and passive techniques may offer significant advantages on many investigations. It can be very costly to mobilize large energy sources for 30m active surface wave soundings. In urban environments, the combined use of active and passive surface wave techniques can image to these depths without the need for large energy sources. The case histories presented above show that the dispersion curves from active and passive surface wave techniques are generally in good agreement, making the combined use of the two techniques viable. It is not recommended that passive surface wave techniques be applied alone for UBC/IBC site classification investigations. Passive surface wave techniques do not generally characterize near surface velocity, which may have a significant impact on V_S30 and so should always be used in conjunction with SASW or MASW.

Finally, the presented case histories demonstrate that surface wave techniques can provide accurate estimates of V_S30 relative to PS suspension logging measurements in a variety of geologic conditions. It should be noted that PS suspension logging and surface wave measurements may both provide different but correct estimates of V_S30 in some conditions. When there is significant lateral variability of subsurface velocities “point source” borehole measurements will not be the same as “global” surface wave measurements. Additionally, if some subsurface sediment units are anisotropic (horizontal polarized S-waves (S_H) and vertically polarized S-waves (S_V) have slightly different velocities) then V_S30 estimates derived from PS suspension logging, which measures S_H velocity, will differ slightly from that derived from surface wave techniques, which are sensitive to S_V velocity. The largest potential errors in V_S30 estimates form surface wave soundings are expected to occur at sites with thick high velocity layers (i.e. caliche) underlain by softer soils or sites with highly variable subsurface velocity structure (i.e. alternating high and low velocity layers). Borehole logging techniques, such as PS suspension logging, should be used at sites expected to exhibit such velocity structure unless surface wave techniques are demonstrated to provide reasonable estimates of V_S30.

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