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DETERMINING SUBSURFACE SHEAR-WAVE VELOCITIES: A REVIEW

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ABSTRACT - It is well known that the geologic materials beneath Earth's surface can have a first-order effect on ground motions from earthquakes. Fundamental to an understanding of the effects of geology on ground motion, and central to any prediction of these effects, is a description of the geologic materials that affect wave propagation. The material properties of interest include shear- and compressional-wave velocity, as well as density and nonlinear properties of both soil and rock. Although the variations in materials within tens to hundreds of meters of the surface often exert the most influence on the ground motions, deeper variations can also be important. Predictions of site effects, including spatial variability, over the frequency range of engineering interest thus may require the spatial distribution of the relevant material properties to depths of kilometers. Such a detailed description is seldom, if ever, achieved, although it represents a challenge for future research. At present, the characterization of the geology beneath a site is often reduced to the specification of a single number: V_{30}, the time-averaged shear-wave velocity from the surface to a depth of 30 m. This number is used in some well-known building codes to specify site effects, and it is also the measure-of-choice for the new empirical ground-motion estimation models being produced by the Pacific Earthquake Engineering Research Institute's Next Generation Attenuation project. In order to obtain this number, or its generalization to other depths, most site survey methods attempt to derive the shear-wave velocity as a function of depth. This paper will discuss a number of methods for doing so, ranging from estimates based on invasive methods that require placement of receivers and/or sources beneath the surface to noninvasive methods. Special emphasis will be placed on summarizing the results and extracting the lessons learned from sites at which blind interpretations have been made by a number of investigators using different methods. Because of its importance in determining the amplitude of shear-waves, which produce most damage in earthquakes, I will concentrate on estimating subsurface shear-wave velocity rather than other geotechnical parameters.

1. Introduction

Noninvasive methods have been used for many years by "traditional" seismologists to determine the velocity structure of the Earth. The methods include the reflection seismic method used by exploration geophysicists, and the use of body-wave arrival times, surface-wave dispersion, and free-oscillation periods of Earth to determine the structure of whole earth. Those who developed and applied these methods had little interest in the velocities in the upper few hundred meters of the earth, the depth range of most interest in engineering seismology. These methods, developed for global seismology, are now being used in the determination of shallow structure to help in the specification of design ground motions for engineering purposes.

This paper begins with a brief discussion of many of the methods, arranged according to whether they are invasive or noninvasive. The noninvasive methods are further organized according to whether they use a single station or multiple stations. The multiple-station group is subdivided into those methods that use active sources, those that use passive sources, and those that combine active and passive sources.

The bulk of the paper will be a discussion of results obtained at a blind interpretation exercise conducted that I conducted at a site near San Jose, California. In the material presented here I draw heavily on the summary paper prepared by Michael Asten and myself (Asten and Boore, 2005), although all of the figures are new (and in particular, I use a different velocity model as the reference against which to compare the various models). Time- and space-considerations required that this paper not be a comprehensive survey of the development and application of methods that have been developed for determination of subsurface velocities. In particular, the reference list is highly skewed to those papers with which I am most familiar---this is a decidedly California-centric view of the world. I apologize to those authors whose work I have seemingly ignored; someday I hope to write a more comprehensive paper that will give proper credit to those who have developed the various methods discussed here.

2. Discussion of Methods

The various methods can be grouped into invasive and noninvasive methods, with subgroupings of the latter as shown in Figure 1.

- Invasive Methods
  - Surface source
    - Receiver in borehole
    - Receiver in cone penetrometer
  - Downhole source
    - Suspension PS logger
    - Crosshole
- Noninvasive Methods
  - Single station (H/V)
  - Multiple stations
    - Active sources (linear spread of receivers)
      - SASW
      - MASW
    - Passive sources (2D array of receivers)
      - FK
      - SPAC
      - ReMi (receivers in line)
    - Combined active & passive

Figure 1. Summary of methods.

Here is a short description of these methods.

2.1. Invasive Methods

These methods require data from seismometers placed beneath Earth's surface. I discuss two groups of methods, those using surface sources and those using downhole sources:

2.1.1. Surface source.

In this method, the source is at the surface and a sensor is either clamped to the edges of a cased borehole at a series of depths or the sensor is mounted near the tip of a special tool (a seismic cone penetrometer) that is pushed into the ground (seismic cone penetration testing, or SCPT). For each depth, the surface source is activated and a recording of the sensor's time series output is made. Usually a three-component seismometer package is used as the sensor, and two types of sources are commonly used: for shear-wave energy, either a plank struck with a sledge hammer on the ends or an air-activated slide hammer (Liu et al., 1988) (in either case the device is held to the ground by the weight of a truck's tires); for compressional-wave energy, usually a metal plate is struck with a sledge hammer. The first arrivals on the resulting record section are picked, and then a velocity model is found from the first arrivals. In some cases the velocities are determined from a line fit through adjacent arrivals, thus providing velocities over various intervals of depths. The resulting model need not be contiguous and need not extend to the surface. A model such as this can be used in correlations of shear-wave velocities with geologic units (e.g., Holzer et al, 2005). For purposes of predicting site amplification, however, a velocity model is needed that continues without gaps to as great as depth as possible. Such a model can be obtained by fitting the whole set of travel times in one regression computation, given a set of depths to interfaces. Iteration is used, with new layers chosen based on the residuals between the observed and predicted travel times, until the overall fit to the observed travel times is less than a specified minimum (see Boore, 2003a). A sample record section (for the CCOC borehole, discussed later) is shown here:

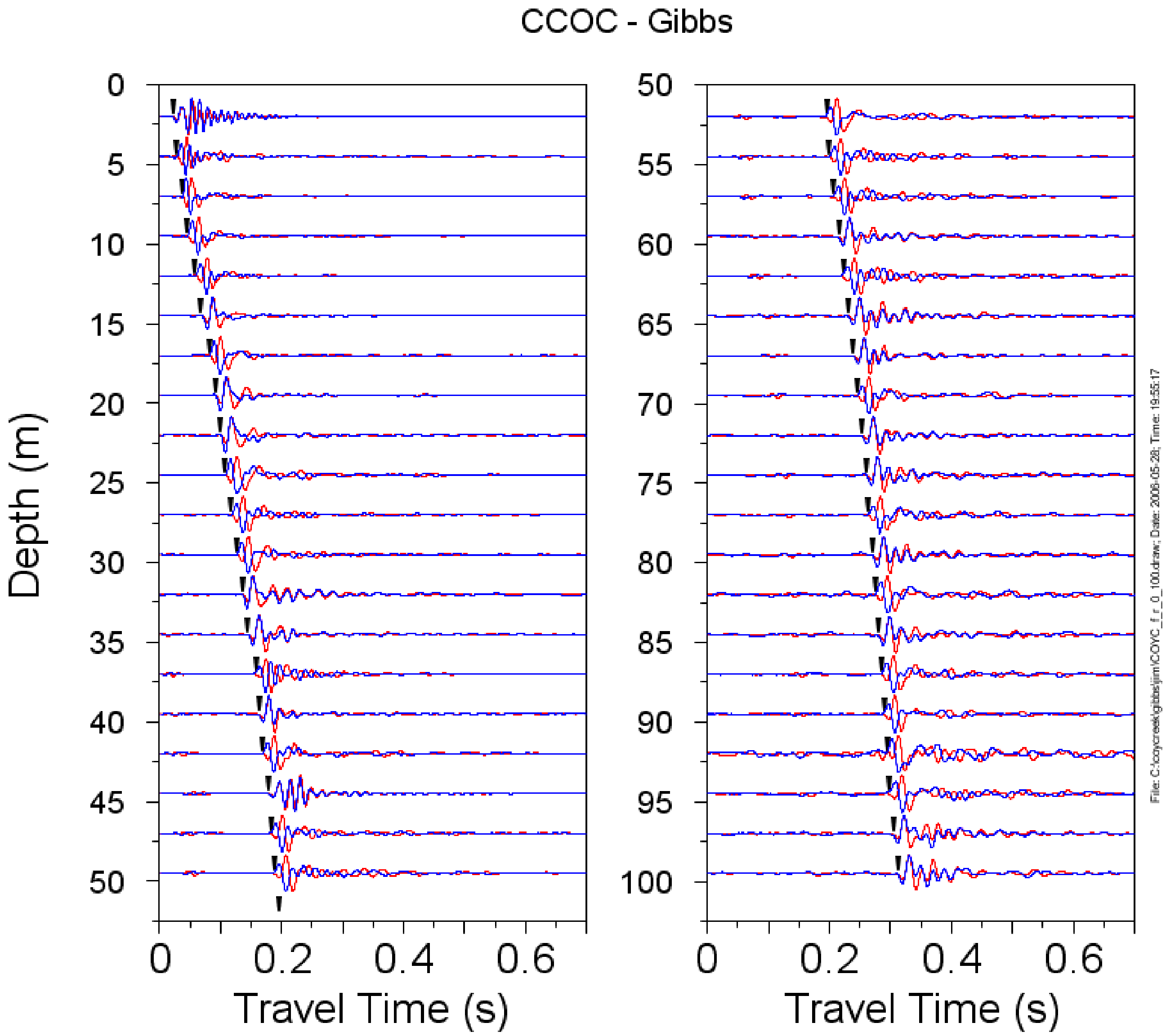

Figure 2. Record section at CCOC for surface source—downhole receiver method. The red and blue traces correspond to opposite directions of impact of the shear-wave source (although some polarity errors have resulted in similar polarities at some depths in the plot). The picked travel times are indicated by the small wedges (after Gibbs, personal communication; see also Boore, 2003a).

A plot of the picked travel times vs. depth is given in the next figure, along with the predicted travel times in a final model determined by Gibbs (personal communication), as well as the residuals between the observed and predicted travel times.

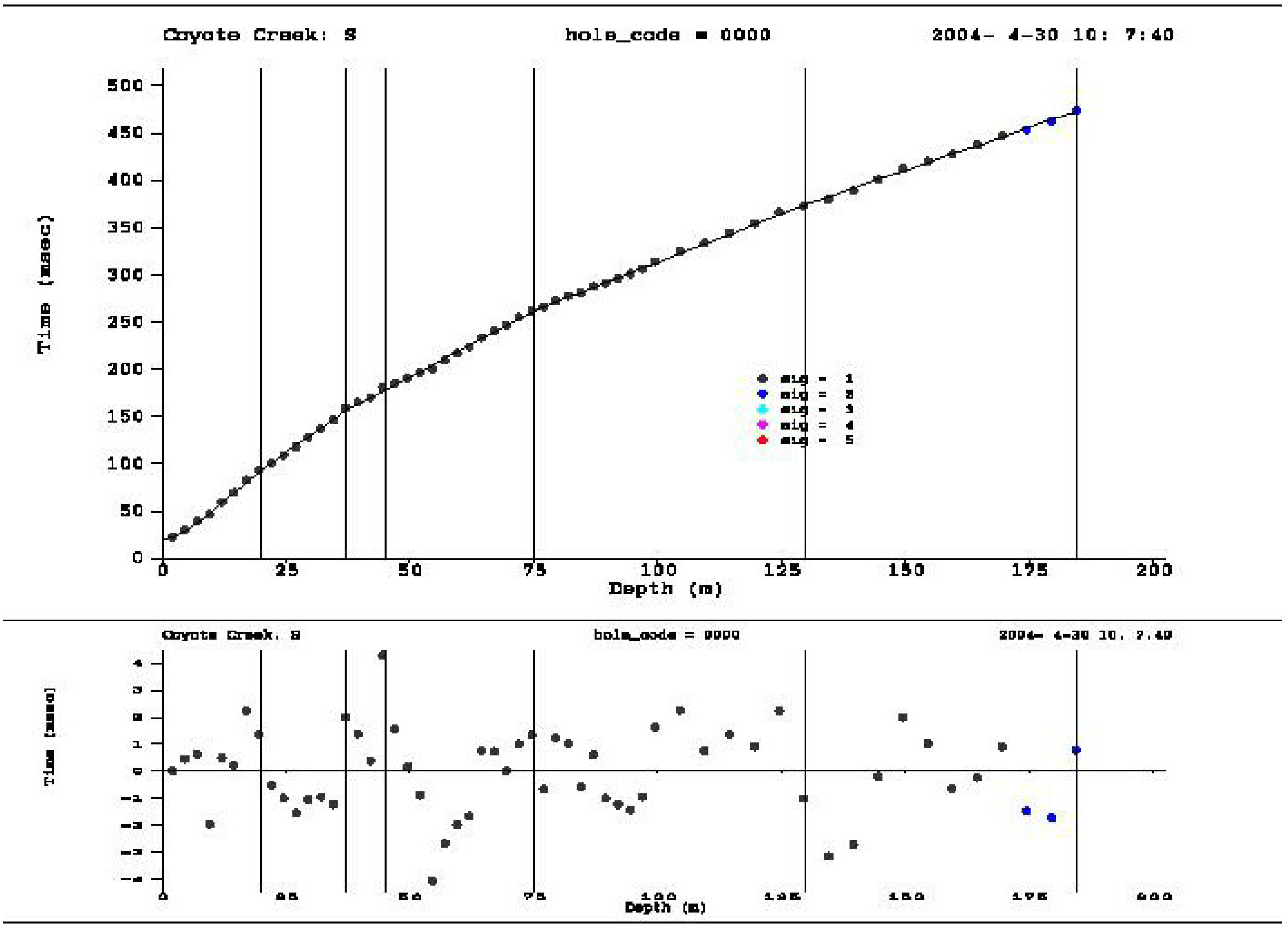

Figure 3. Fit to S-wave travel times for record section from CCOC. The depth is vertical depth in the borehole, but the travel times are from a surface source offset a few meters horizontally from the borehole---for this reason, the travel times are not zero for zero depth.

2.1.2. Downhole source.

In the past, downhole source methods usually involved crosshole studies, in which a source in one hole emitted waves that traveled more-or-less horizontally to receivers in an adjacent hole or holes. The crosshole method has several limitations: 1) it is very expensive in that it requires multiple holes whose spatial orientation needs to be known precisely; 2) the velocities are measured in the horizontal direction and may not be appropriate for waves traveling essentially vertically, as are those of most concern in earthquake engineering; 3) the velocity model may not extend without gaps from the surface to depth. On the other hand, the method is useful for detecting local variations in soil properties, such as might be important for liquefaction potential or for foundation design. For most purposes of earthquake engineering, however, the method has largely been replaced by a method developed by the Oyo Corporation. This is known by several names, the most common being variants of “Suspension P-S Velocity Logging Method”. Information on this widely-used method can be found at http://www.geovision.com/PDF/M_PS_Logging.PDF. The method makes use of a probe lowered into a hole, on which a source near the bottom of the probe emits acoustic waves which are coupled into P- and S-waves at the edges of the borehole. These waves travel in the surrounding material and are reconverted into acoustic waves, which are then recorded on two receivers mounted 1 m apart. The method works best in uncased boreholes. The wave velocities are given by the difference in travel times at the two receivers. The method can be used in relatively deep holes and can provide much finer resolution than the surface source---downhole receiver methods discussed earlier. Examples of results will be given later. Possible drawbacks are that the method sometimes does not yield accurate velocities near the surface, and also does not formally produce a model extending to the surface. In addition, it is not possible to interpolate across any zones for which data are not obtained. This is in contrast to the surface source—downhole receiver method, for which a single well-recorded travel time below depths with poor data provides an average velocity across the interval of poor data.

2.1. Non-invasive Methods

A major disadvantage of the invasive methods (except for the SCPT method, for which the depth range is limited) is the need for a borehole. For this reason, many noninvasive methods have been devised for obtaining subsurface velocity structure. As shown in Figure 1, these methods are conveniently divided into those that use active sources and those that use passive sources. Most of the methods attempt to measure Rayleigh wave phase velocities as a function of frequency (the measurement yielding an apparent horizontal velocity, with the assumption being that the apparent velocity corresponds to the phase velocity of Rayleigh surface waves), and the velocity models are obtained by inverting these apparent velocities, using either iterative forward modeling or various inversion algorithms. Many of the methods use the Spectral Analysis of Surface Wave (SASW) method introduced by Stokoe (e.g., Nazarian and Stokoe, 1984; Stokoe et al., 1994; Brown et al., 2002). This method uses the phase difference between two receivers and a variety of sources, ranging in size from small hammers for high frequencies to large vehicles (such as those used in petroleum exploration that emit vibrations at different frequencies, or a large tractor rocking back and forth) for longer periods. Modifications include multichannel recording (MASW; e.g., Park et al., 1999).

A limitation to the active source methods in general is the difficulty of generating low-frequency waves. This limits the depth for which velocity models can be obtained (note that this may not be such a severe restriction for reflection methods using active sources). Passive sources include microtremors and microseisms produced by a range of natural phenomena (e.g., ocean surf and wind) and artificial sources (e.g., traffic, machinery), and the frequencies can be quite low (earth noise at periods near 8 sec required the development of both long- and short-period sensors in the first global scale seismographic network). Measurements of microtremors are usually made on arrays of instruments placed in two-dimensional configurations, although one method uses linear arrays (the refraction microtremor [ReMi] method of Louie, 2001). Extraction of the apparent velocities can be done using beam-forming or frequency-wavenumber (f-k) methods (e.g., Horike, 1985; Kawase et al., 1998; Liu et al., 2000), or by using the SPAC method first proposed by Aki (1957) many years ago and now experiencing a resurgence of interest (e.g., Okada, 2003; Asten, 2005). One limitation in practice is that instrument arrays are usually not dense enough to resolve near-surface velocities, and yet these velocities can have an important effect on site amplifications.

Single-station methods for determining shear-wave velocities have been used over the years (e.g., Bard, 1998; Scherbaum et al., 2003). The methods make use of the frequency-dependence of Rayleigh-wave ellipticity, which in turn depends on the subsurface velocities (e.g., Boore and Toksöz, 1969). Contamination by higher modes can complicate the determination of the velocity structure from the observed ellipticity (e.g., Arai and Tokimatsu, 2004, 2005).

Most methods based on the inversion of apparent velocities vs. frequency make the assumption that the velocities correspond to fundamental-mode surface waves. This is not always so, particularly at longer periods for which the offset between the source and the receivers may not be sufficient for the body and surface waves to be differentiated in time and in amplitude. This is one reason that some studies use a combination of active and passive sources, combining the dispersion curves for the two observation methods. Here is an example, from Yoon and Rix (2005):

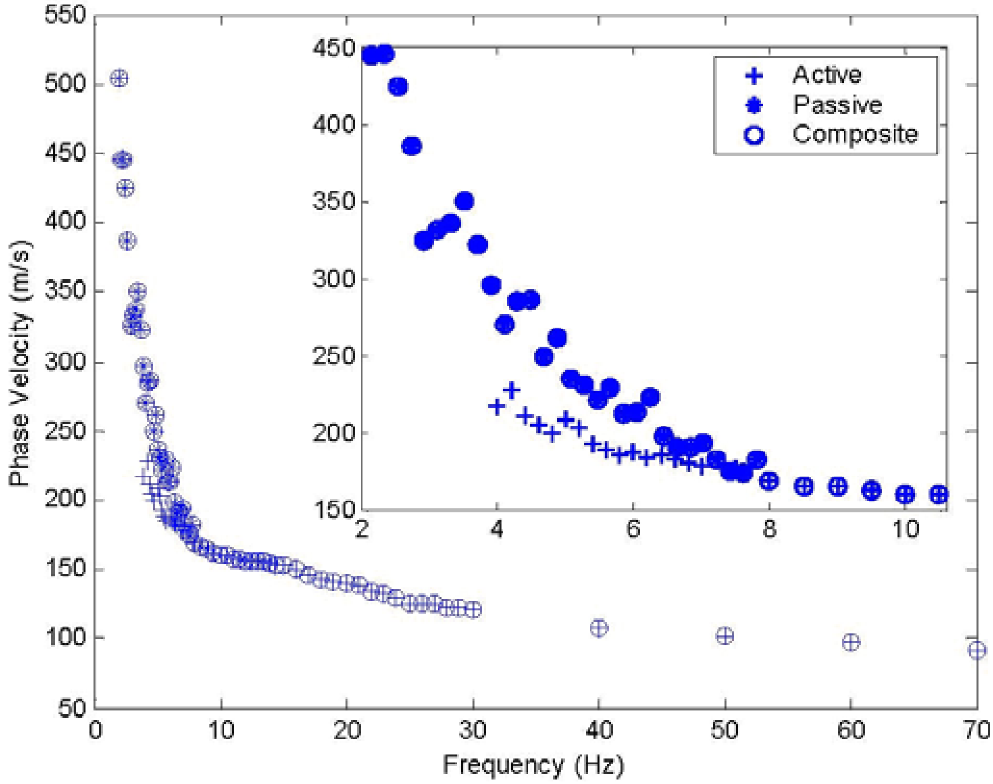

Figure 4. Dispersion curves from active and passive sources (from Yoon and Rix, 2005). The inset shows detail for periods less than about 10 Hz.

3. Comparison of Velocity Models Determined Using Different Methods

Comparisons of velocity models obtained from measurements made at a common site are important for assessing the strengths and weaknesses of different methods. Such comparisons in the United States have been reported in several studies. To my knowledge, the first was from a site near Gilroy, California, and compared velocities obtained from surface source---downhole receiver, suspension PS log, crosshole, and SASW methods (EPRI, 1993). Another study was that of Brown et al. (2002), which reported on blind interpretations of SASW and surface source---downhole receiver measurements. Xia et al. (2002) report on comparisons between MASW and borehole measurements. More recently, two blind interpretation experiments were conducted near San Jose, California (Asten and Boore, 2005; Stephenson et al, 2005). The rest of this paper will use results from the experiment described by Asten and Boore. A number of researchers volunteered their time and equipment to make measurements and to provide interpretations at a site for which a borehole was available and which had room for the deployment of arrays (Figure 5). See the open-file report edited by Asten and Boore (2005) for a complete list of measurements and documentation of individual results (which I will not reference separately here).

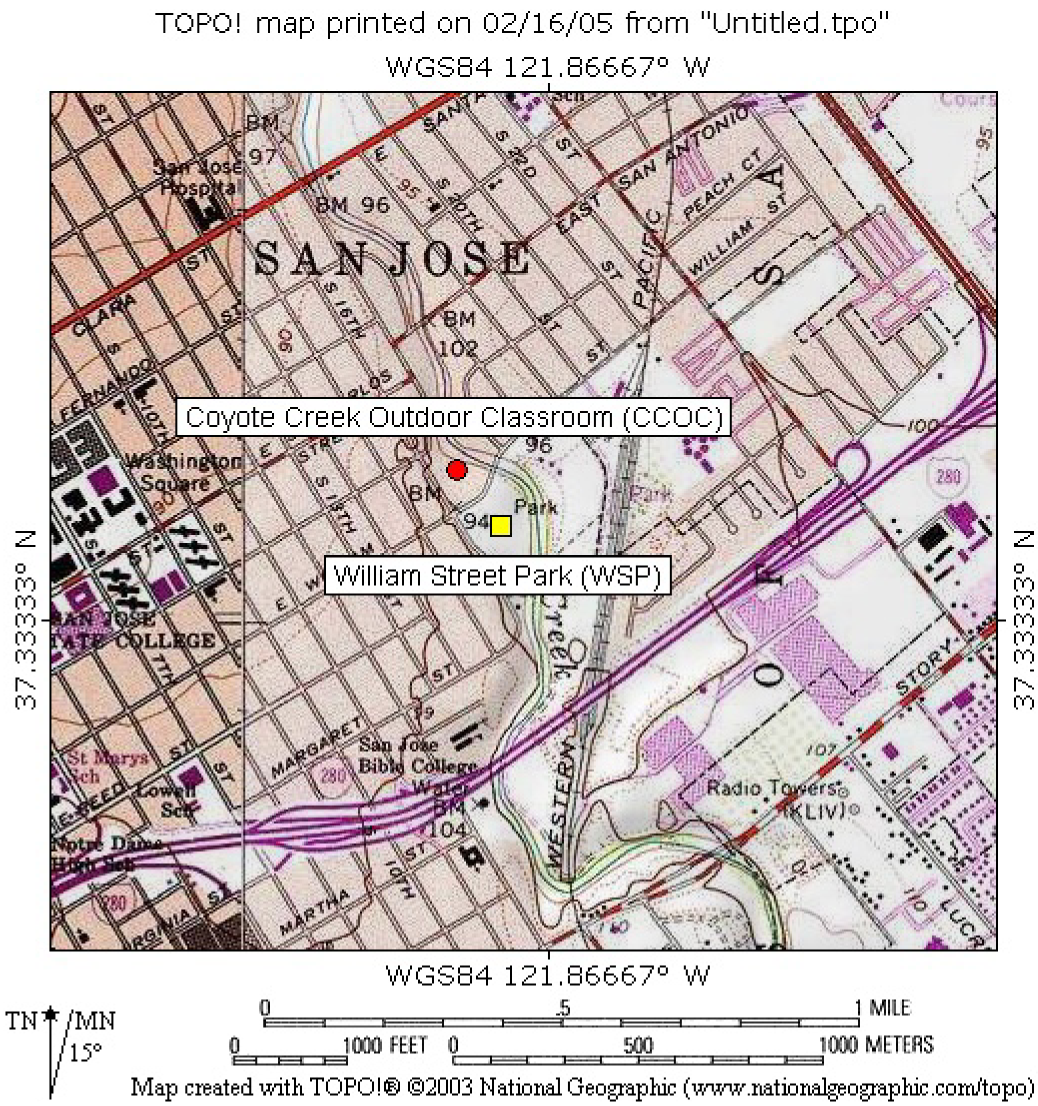

Figure 5. Location map of the CCOC blind interpretation experiment.

The borehole was located at the Coyote Creek Outdoor Classroom (CCOC), but most of the measurements were made at the nearby William Street Park (WSP). At CCOC, invasive measurements included seismic cone penetration testing (SCPT) (made before the borehole was drilled), surface source---downhole receiver, and suspension PS log. Noninvasive measurements included SASW measurements made by two teams. At WSP there was one SCPT measurement that extended only to 21 m. There were many noninvasive measurements, including seismic reflection, SASW carried out by three teams, MASW carried out by three teams (two of which also used array measurements of microtremors), SPAC processing of array data collected by two groups, two independent interpretations of one set of ReMi data, and an interpretation of H/V spectral ratios. In sum, 5 and 13 preferred velocity models were provided for CCOC and WSP, respectively, although some researchers also provided alternate interpretations.

The site is underlain by about 400 m of flat-lying Quaternary sediments (Wentworth and Tinsley, 2005). According to Wentworth and Tinsley, the depositional history is such that they expect little change in layer thickness and properties between the borehole site (CCOC) and the park where most measurements were made (WSP). The section consists of alternating layers of sands, gravel, silts, and combinations thereof (as indicated in Figure 6).

In comparing the results from the various methods, it is convenient to have a reference model. In this case an average of the slownesses from the invasive methods at CCOC is used for the reference model. As shown in Figure 6, the suspension PS log *S*-wave velocities correspond quite well with the lithology, at least at depths below about 35 m: coarser layers have higher velocities, as expected.

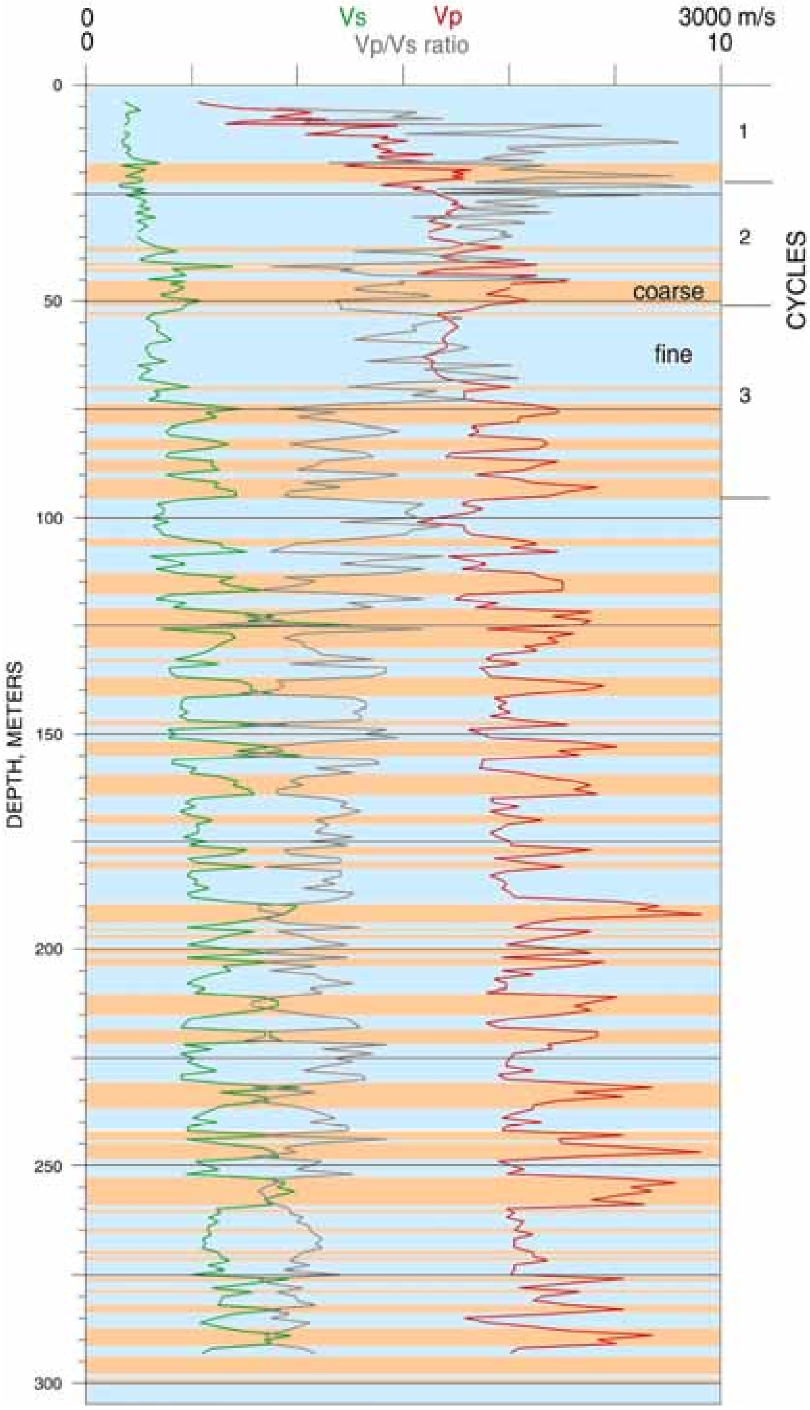

Figure 6. Seismic velocities from suspension PS log and simplified lithology, from Wentworth and Tinsley (2005). The blue and orange colors represent fine- and coarse-grained sediments, respectively.

The coarse layer around 20 m is not matched by an increase in the *S*-wave velocity, however (although the *P*-wave velocity does have an increase around 20 m). The tip resistance and the friction ratio from the SCPT measurements are in agreement with a gravelly layer between about 19 and 23 m depth (see Figure 4 in Wentworth and Tinsley, 2005). In addition, the seismic travel times from the SCPT measurements (T. Holzer, personal commun., 2005) and from the surface source—downhole receiver (SS-DHR) measurements of Gibbs are in agreement and show a high velocity layer in that depth range (although the blind interpretation by Gibbs did not allow velocity variations at the depth scale over which the change takes place). Figure 7 compares the SCPT and the SS-DHR travel times, reduced by a velocity of 250 m/s to display better the change in slope of the travel time vs. depth function.

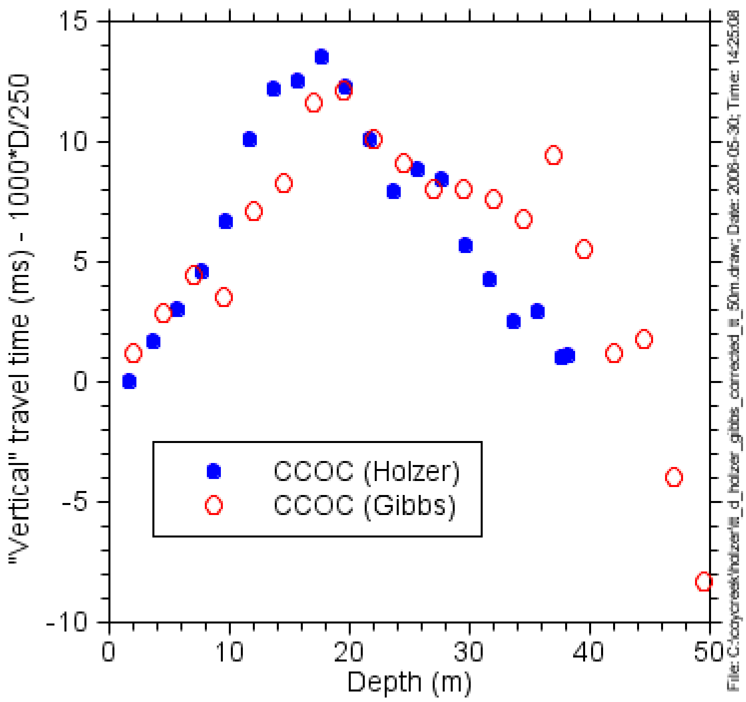

Figure 7. Reduced travel times(corrected for horizontal offset of source from borehole) at CCOC.

The previous two figures suggest that the suspension PS log velocity model may be less accurate at shallow depths than at deeper depths. For this reason, a reference model was constructed by averaging the independently-derived velocity models from the three invasive methods (after averaging the suspension PS log slowness over 10m depth intervals).

The comparisons of velocity models in this paper are in terms of slowness (inverse velocity, with units of msec/m) rather than velocity. The reasons for doing so are given in Brown et al. (2002): "First, it is a more fundamental quantity than the velocity for site response studies. Theoretical responses of layered systems, both site response and surface wave dispersion, involve travel time across the layers, and this travel time is linearly proportional to the slowness ($t = s * h$, rather than $t = (1/v) * h$, where t is travel time, s is slowness, v is velocity, and h is layer thickness). Second, slowness models from a number of boreholes can be averaged directly depth-by-depth to obtain an average slowness profile for a certain class of sites (linear averaging of velocities, as is sometimes done, is incorrect). Third, interpretations of travel times from borehole measurements usually involve fitting lines to travel time versus depth; the slope of this fit is slowness, not velocity, and the statistics of the fit apply to slowness rather than velocity. Fourth, and probably most important for this study, a visual comparison of slowness versus depth obtained from different methods … is preferable to comparing velocities: apparent large differences in velocities in the deeper, higher velocity portions of a profile attract the eye but are less important in site response than less pronounced differences in the lower velocities near the surface--- plotting slowness emphasizes differences in material properties of most importance for site response (which is again fundamentally related to the time a wave spends in a layer)."

Comparisons of the reference model with the invasive and the noninvasive models at CCOC are given in Figure 8.

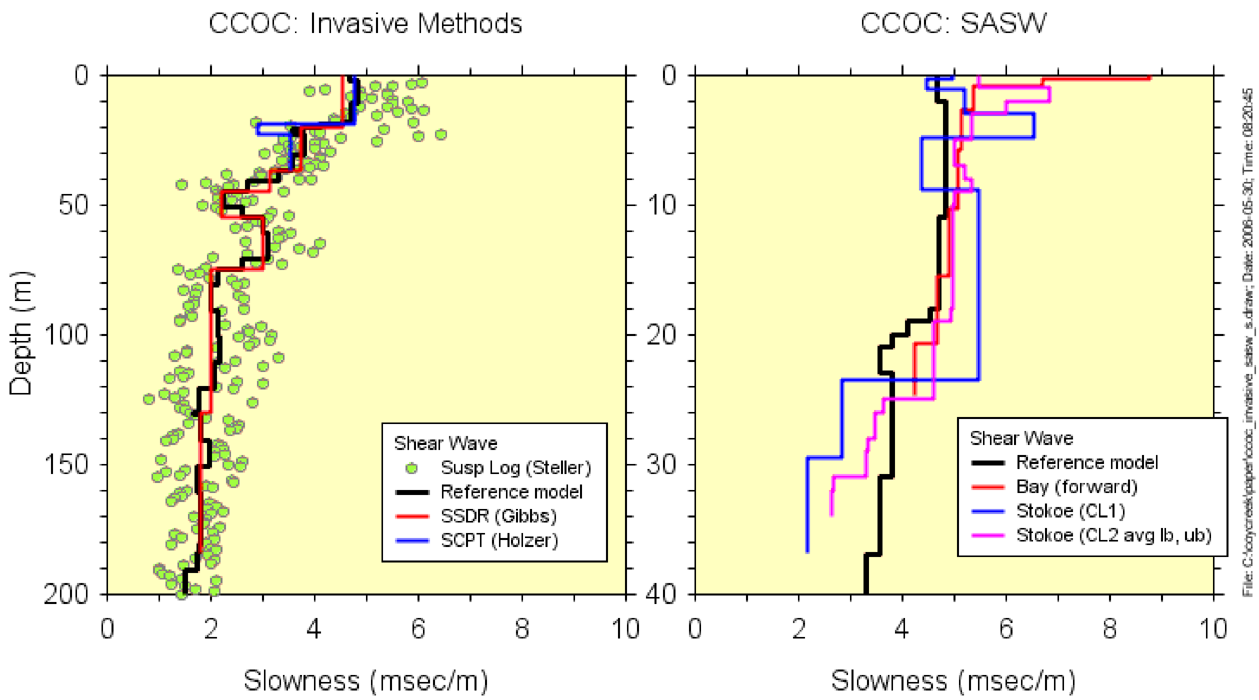

Figure 8. Comparison of reference model with models from invasive and noninvasive measurements at CCOC.

Similar comparisons for the active, passive, and combined source measurements at WSP are given in Figure 9, 10, and 11.

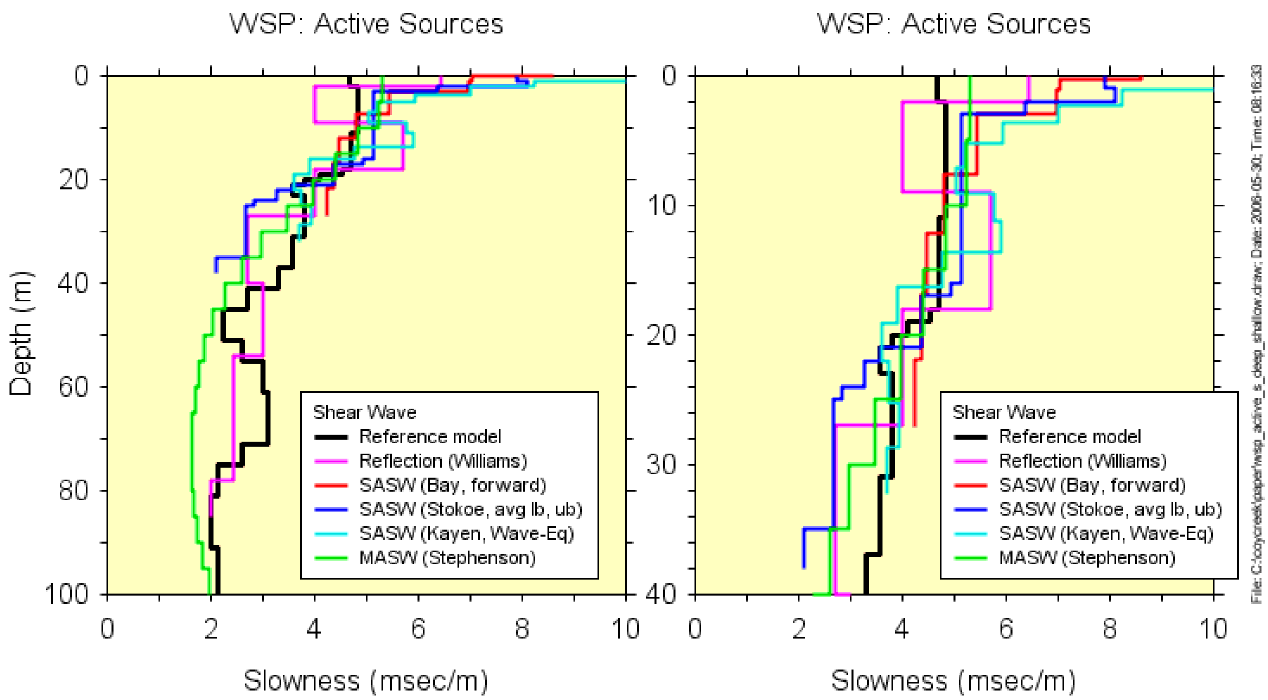

Figure 9. Comparison of reference model and models from active source measurements at WSP. An expanded depth scale is used in the right-hand graph to show better the details at shallow depths.

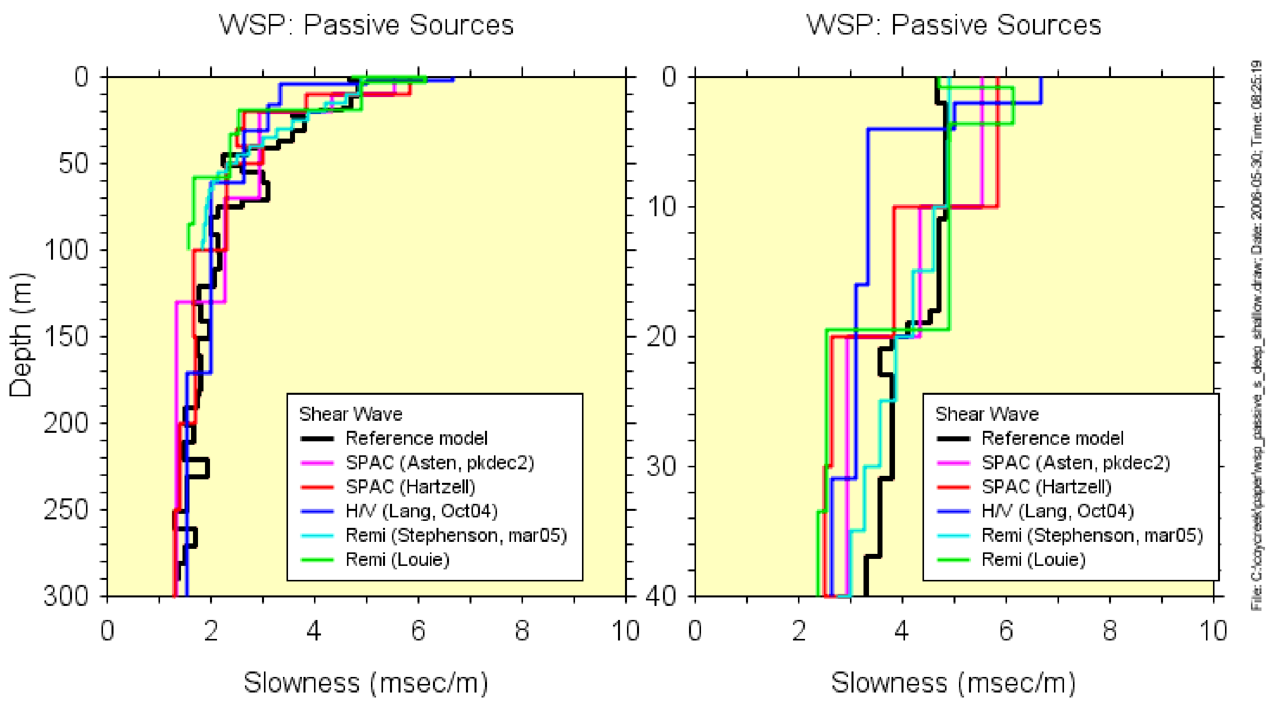

Figure 10. Comparison of reference model and models from passive source measurements at WSP. An expanded depth scale is used in the right-hand graph to show better the details at shallow depths.

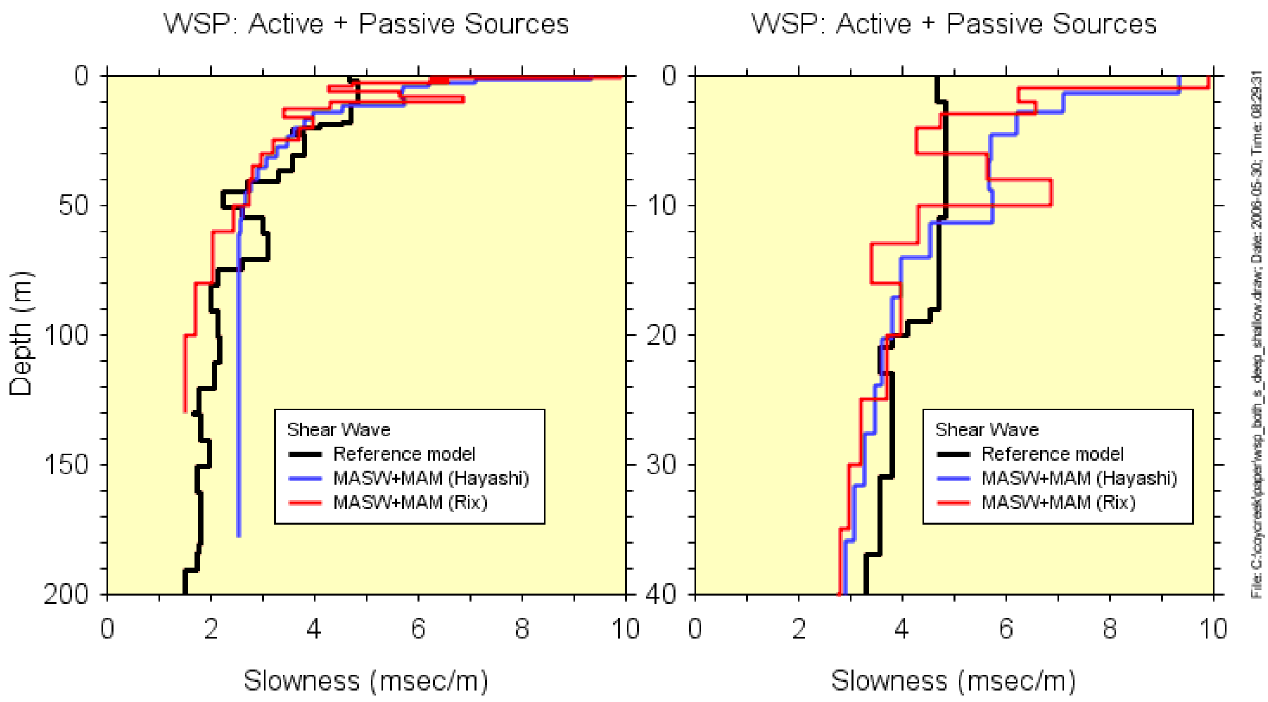

Figure 11. Comparison of reference model and models from combined active--passive source measurements at WSP. An expanded depth scale is used in the right-hand graph to show better the details at shallow depths.

Several observations can be made from these figures. In general, the slownesses from the active sources are larger than for the reference model at shallow depths and are generally smaller than the reference slownesses at greater depths. Second, none of the models from the noninvasive measurements detected the zone of increased slowness between about 50 and 75 m depth (this increased slowness is clearly found by both invasive measurements extending to these depths, and it corresponds to zone of relatively fine-grained materials [Wentworth and Tinsley, 2005]).

Plots of slowness (or velocity) provide only a qualitative comparison of the results from different measurement and interpretation methods. I have attempted to make quantitative comparisons that are related to site amplification. I feel that this is an improvement over the usual comparison plots of slowness or velocity vs. depth. My comparisons start with the cumulative travel time from the surface to any depth. From this plot, the time-averaged velocity from the surface can be computed (the average velocity to 30 m---V_{30}--- is used to characterize sites in building codes and in empirical regression analysis). A plot of this travel time for the CCOC models is shown on the left side of Figure 12, and the derived average velocities are given on the right side of the figure.

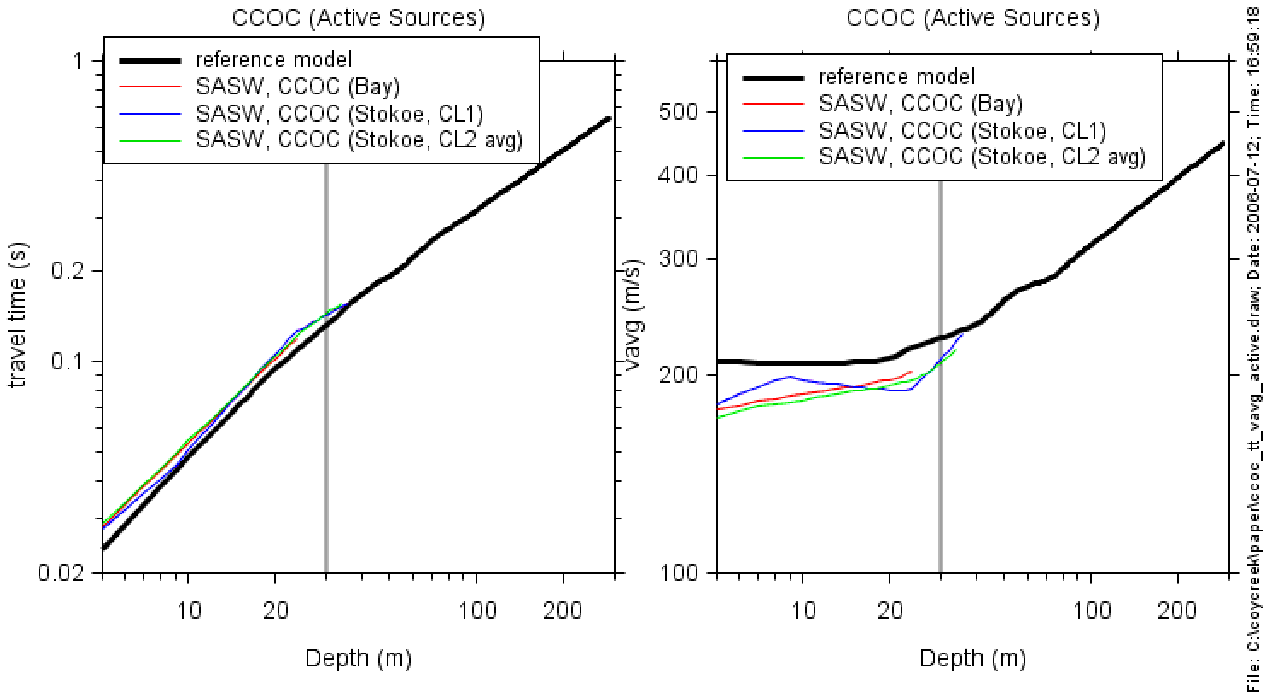

Figure 12. Cumulative travel and time-averaged velocity for CCOC models.

A plot of the time-averaged velocities for both CCOC and WSP is given in Figure 13, separated by type of source.

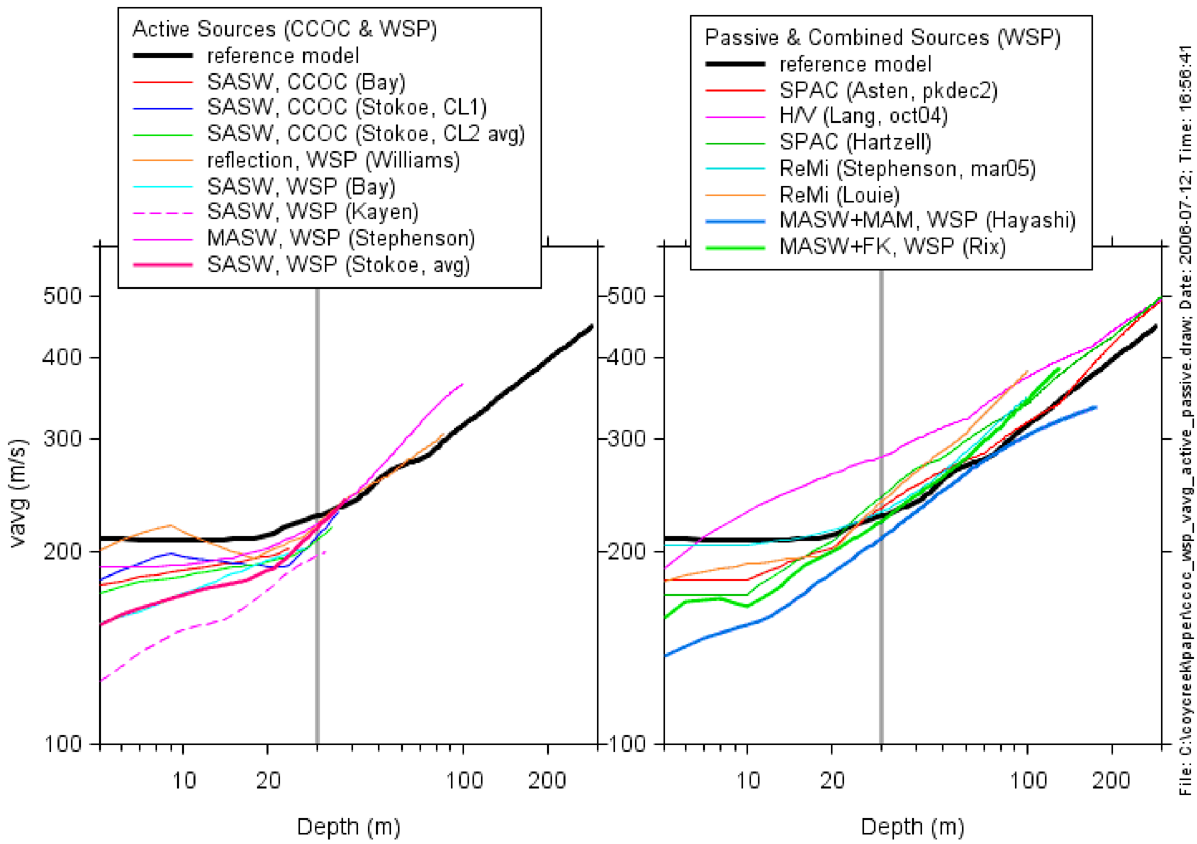

Figure 13. Time-averaged velocities for all models.

These plots show that for depths less than about 20 m, the time-averaged surface-to-depth velocities for almost all models are slower than those from the reference model velocity. For greater depths, the passive source models have somewhat higher velocities than do the active source models (but note that in general the passive source models use lower frequencies than do the active source models, and thus may provide better models at greater depths). Interestingly, the average velocities for the models tend to converge around 30 m depth, which as noted earlier is the depth used for site characterization in some modern building codes and recent empirical ground-motion estimation models. Because of the convergence, which I assume is coincidental, there is little variation in the values of V_{30}.

To see the implication of the various values of V_{30}, I computed the linear amplification used in the empirical ground-motion estimation model of Boore et al. (1997). This model gives the amplification of the ground motion *Y*, relative to a reference velocity V_{ref}, by this equation:

$$\log Y = b_l \log(V_{ref} / V_{30}) \quad (1)$$

where b_l (and therefore *Y)* is a function of period. I used the values of V_{30} computed for the models (those values from Figure 13) and values of b_l from Choi and Stewart (2005, which are similar to those of Boore et al., 1997, but extend to shorter and longer periods) to compute the amplification for each model relative to the reference model. The results (Figure 14) show that none of the models produce amplifications that are substantially different than those from the reference model, in spite of the detailed differences in the slowness. This is largely a result of the coincidental (?) convergence of the time-averaged velocities at 30 m.

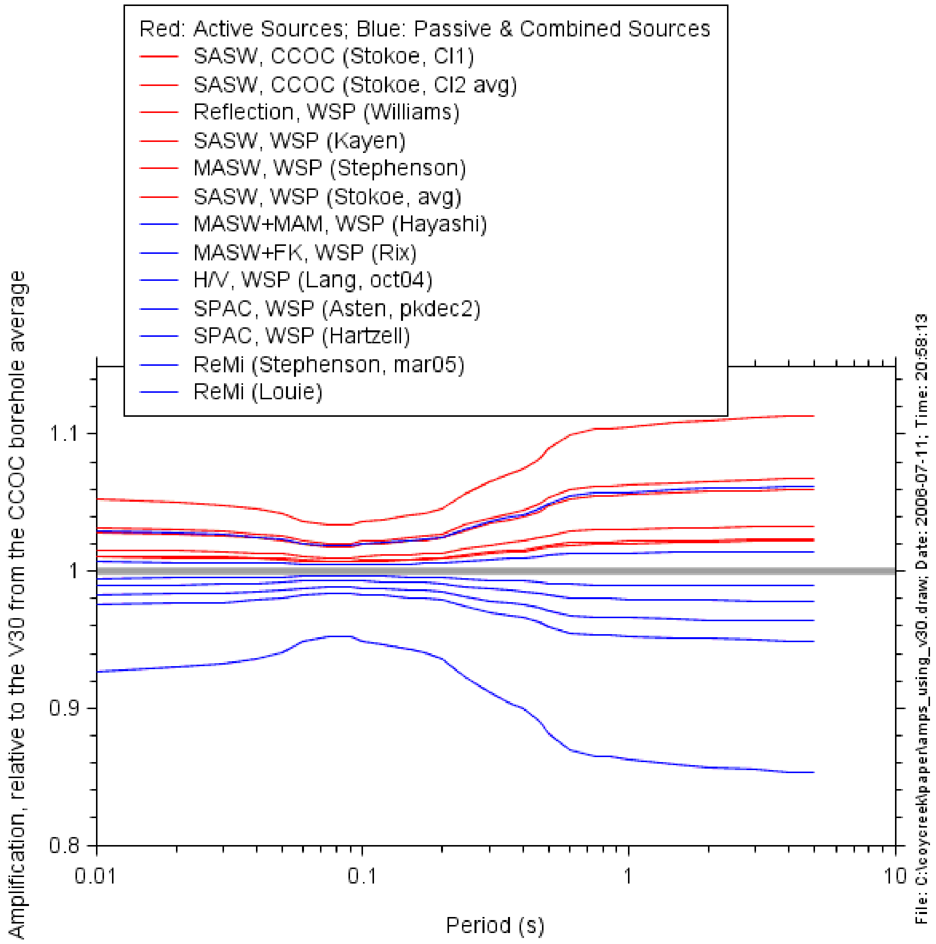

Figure 14. Amplifications based on equation used in recent empirical ground-motion estimation models. No amplifications are given for Bay et al. because their preferred models did not reach 30 m. I have used different colors for models from active and for passive (including combined) sources. The differences in amplifications are very small.

To see the consequence of differences in slowness at other depths, I computed the square-root-impedance approximation to site amplification (relative to a halfspace with velocity of 1500 m/s, ignoring differences in density)---see Boore (2003b) for a discussion of this method for computing amplifications (the method has been used in comparisons of velocities from different methods by Brown et al., 2002, and by Stephenson et al., 2005). The results are shown in Figure 15.

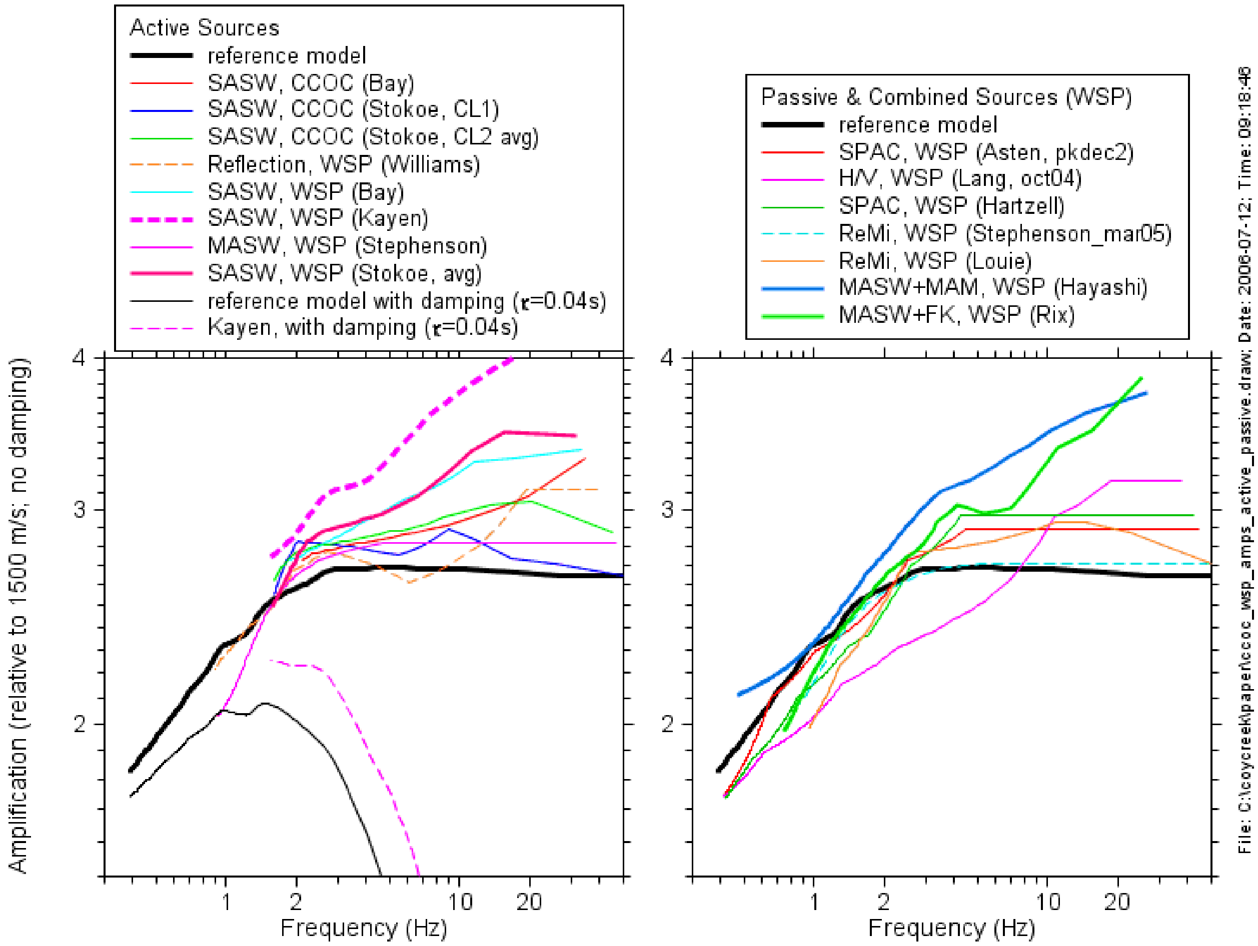

Figure 15. Approximate site amplifications based on square-root-impedance method. The effect of including damping (represented by a factor $\exp(-\pi\kappa f)$*, where* $\kappa = 0.04s$*), is shown for two of the models. If it is assumed that the damping for all models is given by this factor, it should be noted that the ratios of amplifications for different models with and without damping is the same.*

The variations in the velocity models at depths shallower than 30 m can produce substantial differences in amplification at relatively high frequencies, but it should be noted that no damping has been included in these computations. Including realistic values of damping reduces the amplifications considerably (as shown in the figure above), so that the differences in the curves shown in Figure 15 at high frequencies can be thought of as worst-case scenarios (except that resonances in layers have not been taken into account---these could produce narrow regions of increased or decreased amplification for specific models). At longer periods, for which damping is less important, the results in Figure 15 indicate a range of amplifications of about 15%. This value is quite small compared to the aleatory uncertainty in ground-motion observations.

4. Discussion and Conclusions

Many methods have been developed for obtaining subsurface seismic velocities. No one method is the best for all circumstances. In addition, different methods might give different velocity models for a number of reasons. For example, the various methods use waves with different frequencies and dispersion of seismic body waves might produce some difference in velocities for these different methods, all else being equal. As examples, the waves used for certain invasive methods and for high-resolution reflection have frequencies in the 20—70 Hz range, while those for nonintrusive methods using passive sources are generally much lower. But the expected difference in the derived seismic velocities is only on the order of a percent or two. More importantly, different volumes being sampled by the different methods could yield different velocities (intrusive methods sample a region close to the borehole or to the cone penetrometer, whereas surface waves sample progressively greater volumes of material both laterally and in depth as the wave frequency decreases). Seismic velocity anisotropy can be substantial, so that waves propagating more-or-less horizontally might have a different velocity than those propagating vertically (it is the latter which is of most concern for earthquake engineering). Finally, spatial variations in velocity might produce apparent differences in comparisons of velocities derived from measurements that are not made in the same location. For example, many of the nonintrusive methods require substantial spatial areas for deployment of instruments and cannot be precisely collocated with boreholes. This can lead to substantial differences in velocity. One such example, discussed by Brown et al. (2002), comes from a location where the borehole was located on compacted fill, but the SASW measurements were made on a nearby well-watered golf course (Figure 16).

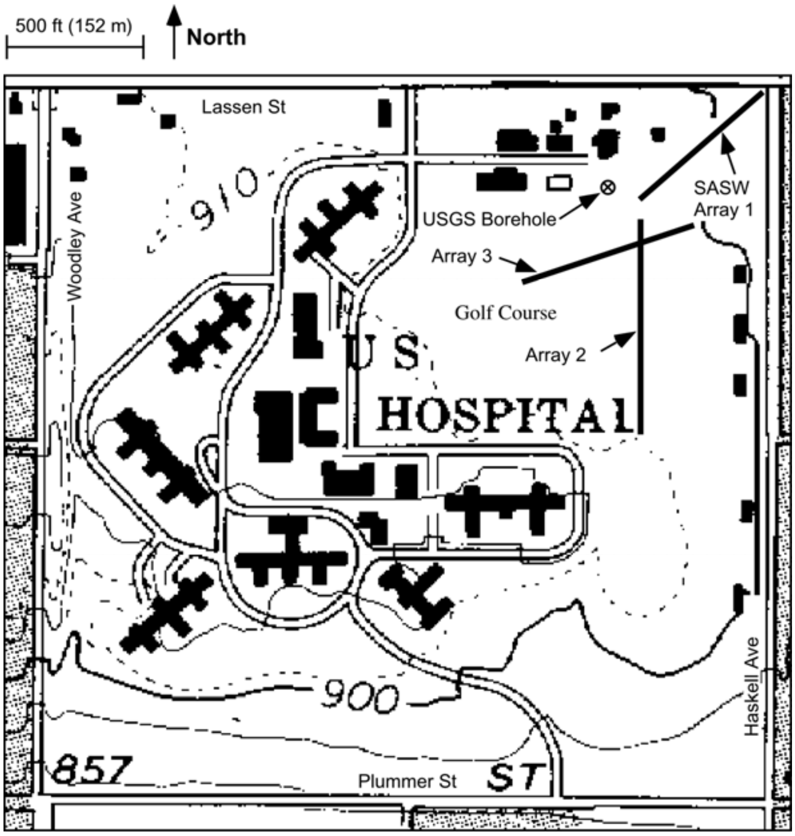

Figure 16. Location map for comparison of slowness from borehole and SASW measurements, from Brown et al. (2002).

The slowness models are substantially different at shallow depths (left side, Figure 17), and a comparison of the observed dispersion and that expected for the model based on the borehole data (right side, Figure 17) show that the difference in velocities is not a function of SASW measurement error (and neither is it a result of errors in the travel times from the invasive methods, although that is not shown here).

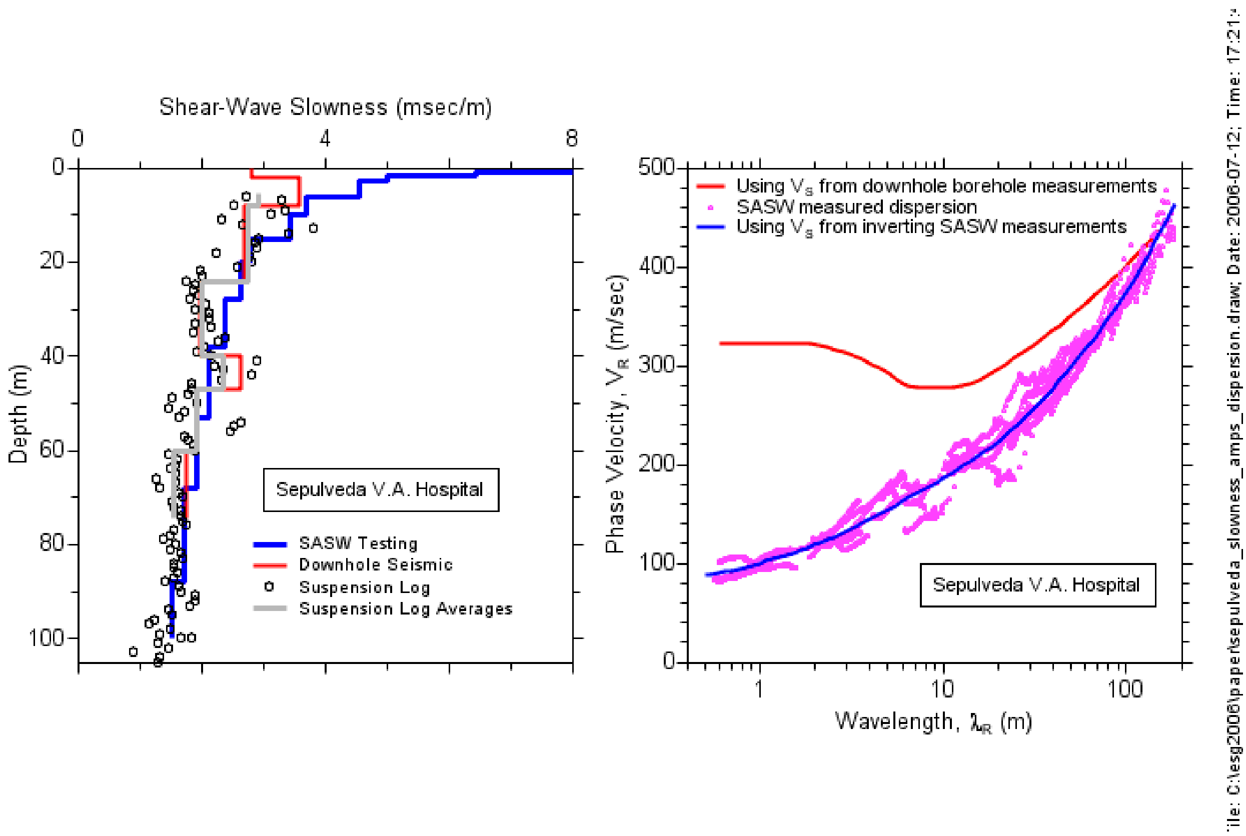

Figure 17. Shear-wave slowness and phase velocity at the Sepulveda Veteran's Administration hospital, San Fernando Valley, California (after Brown et al, 2002).

To compare the models obtained from various methods, I used the recent blind interpretation experiment near San Jose, California. Although the details of the velocity models differ, those differences are of little importance in some commonly-used measures and estimates of site amplification---a very encouraging result. Similar results have been found at other locations (e.g., EPRI, 1993 and Liu et al., 2000), although the subsurface geologic materials are similar to those at the San Jose site. It can be argued that the velocity structure at the San Jose site did not provide a good test of the methods---there were no large impedance contrasts, at least at depths less than 300 m, and the velocity gradient was not very large. It would be useful to perform additional blind interpretation experiments at more challenging sites.

5. Acknowledgments

I thank the organizers of the ESG2006 conference for the opportunity to contribute this paper. I also thank Michael Asten for reviewing this article, as well as those colleagues who have contributed data and insight into deriving subsurface velocity structure.

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