PRELIMINARY DRAFT

Shear Waves - Techniques & Systems

Introduction

This paper is about conducting shear wave surveys for engineering site investigations, including principles, methods, hardware and data presentation. They are an important tool in designing buildings that don't collapse in earthquakes and a useful tool for foundation investigations.

Seismic surveys for engineering site investigations take several forms. The most common is the refraction survey, where seismic waves are generated and recorded at various points along the surface. The waves propagate through the ground along different paths from the source to the geophones, and the arrival times are recorded and analyzed to determine the structure and composition of the subsurface. If you are not familiar with this method, then you might want to review the literature and become reasonably proficient in both data acquisition and analysis before attempting the methods described in this manual. A good introduction is contained in Redpath, 1973.

The most common applications of refraction surveys are determining depth-to-bedrock, bedrock contours, depth-to-water-table, rippability, and other information which can be deduced from refraction data. Besides an indication of material properties, the depth of the materials with different velocities can be determined. A correct mathematical solution depends on the velocity increasing with depth, which is usually true for compressive waves, since materials near the surface are more highly weathered and thus lower strength.

Besides compressive (P) waves, shear waves can be used to determine material properties and they are much more diagnostic in that application.

What are shear waves?

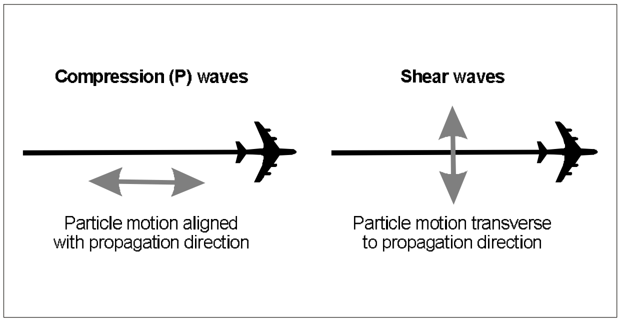

Figure 1, Particle motion and wave propagation.

In compressive waves, the ground vibrates in the same direction that the wave travels (see Figure 1). In shear waves, the ground wiggles transversely to the direction that the wave propagates. Consider a rope stretched along the ground. By jerking the rope upwards, you create a wave that moves sideways while it travels down the rope—the motion is vertical and the propagation is horizontal. If the particle motion is transverse to the wave propagation, it's a shear wave. If the particle motion is aligned with the wave propagation, it's a compressive wave. This will get clearer a little later in this manual.

Why do we care?

Assume for the moment that you can measure the velocities of the compressive (P) waves and the shear (S) waves. The P-wave velocity in a material is mostly dependent on compressive strength. Experience (with a little common sense and some helpful tables) allows us to guess something about the material based on the velocity. For example, if the P-wave velocity is 2000 ft/second (600 m/s), then we know that the material is probably a compacted soil. A sudden increase to 5000 ft/sec (1500 m/s) suggests that we have hit the water table. A velocity above 10,000 ft/sec (3000 m/s) is almost certainly a fairly competent bedrock. Solving the refraction equations will tell us the depth from the surface to each of these materials and this result is adequate for many applications such as finding the depth to groundwater or the excavation costs.

Now suppose that instead of digging a swimming pool, we want to put something a little more substantial on this site—a nuclear power plant perhaps, and that substantially all of the foundation will go in that layer with a P-wave velocity of 5000 ft/sec. Are we really comfortable assuming that this is just a saturated alluvial material? Let's consider some of the materials that might exhibit this same compressional wave velocity: saturated gravels, clay deposits, weathered rock, coal, or even quicksand. It looks like we really don't know what's down there, only that it has the same in-situ compressive strength as mud.

Suppose now that we estimate what a reasonable shear wave velocity would be for these same materials and tabulate the information:

Material	Vp ft/sec (m/s)	Vs ft/sec (m/s)
saturated gravels (clean)	5000 (1500)	1000 (300)
saturated gravels (dirty)	5000 (1500)	2000 (600)
clay deposits	5000 (1500)	3000 (900)
weathered rock	5000 (1500)	2000-3000 (600-900)
coal	5000 (1500)	3000 (900)
quicksand	5000 (1500)	0 (0)

Of course there will be wide variations in the shear wave velocities in these materials, but clearly we would know a lot more about the character of the material in-situ if we could measure the shear wave velocity. Remember, these are estimates made to illustrate a point, not a statistical sampling that should be used for actual field work. And of course actual ground conditions will vary substantially depending on how the alluvial materials are bonded together, fracturing, and voids. The key point is that shear wave velocities are dependent on the shear strength of the material where P-wave velocities are dependent on the compressive strength of the material.

In the real world, shear strength is what supports buildings and piles and keeps a ripping tooth from cutting rock. We can know a lot more about the material if we know the shear wave velocity, especially when adding geological knowledge, some more common sense, and maybe a few drill holes. For example, it turns out that shear wave velocity correlates very well with blow counts (OYO Corporation, 19__), one of the engineering geologist's favorite measurements in foundation studies.

If you know the velocities of the P and S waves and the density of the material, you can calculate the Elastic constants that relate the magnitude of the strain response to the applied stress. These elastic constants include the following:

(1) Young's Modulus (E) is the ratio of the applied stress to the fractional extension (or shortening) of the sample length parallel to the tension (or compression). Stress is force/unit area and strain is the linear change in dimension divided by the original length.

(2) Shear Modulus (G) is the ratio of the applied stress to the distortion (rotation) of a plane originally perpendicular to the applied shear stress; it is also termed the modulus of rigidity.

(3) Bulk Modulus (k) is the ratio of the confining pressure to the fractional reduction of volume in response to the applied hydrostatic pressure. The volume strain is the change in volume of the sample divided by the original volume. Bulk modulus is also termed the modulus of incompressibility.

(4) Poisson's ratio (F) is the ratio of lateral strain (perpendicular to an applied stress) to the longitudinal strain (parallel to applied stress).

For elastic and isotropic materials, the elastic constants can be calculated from the seismic velocities. For example:

Poisson's Ratio $F_p = \frac{(Vp/Vs)^2 - 2}{2(Vp/Vs)^2 - 2}$

Shear Modulus $G = d\,Vs^2$

Young's Modulus $E = 2G\,(1+F_p)$

Bulk Modulus $K = \frac{1}{3} \cdot \frac{E}{1-2F_p}$

Vp = P-wave velocity
Vs = shear wave velocity
d = density

These are of course linear dynamic characteristics and not always applicable to static performance of the foundation material

How are they measured?

The simplistic answer is that shear waves are collected and measured just like P-waves and all other waves. An energy source is used to generate elastic waves in the ground, and these elastic waves are detected at multiple locations by vibration sensors. The signals are collected and displayed on a seismograph. There is one major problem of course, the shear waves travel slower than the P-waves and they will be imbedded in the complex seismograph somewhere after the first arrival. When P-waves are used for refraction surveys, identification is simple since the P-wave arrives first (the "P" stands for

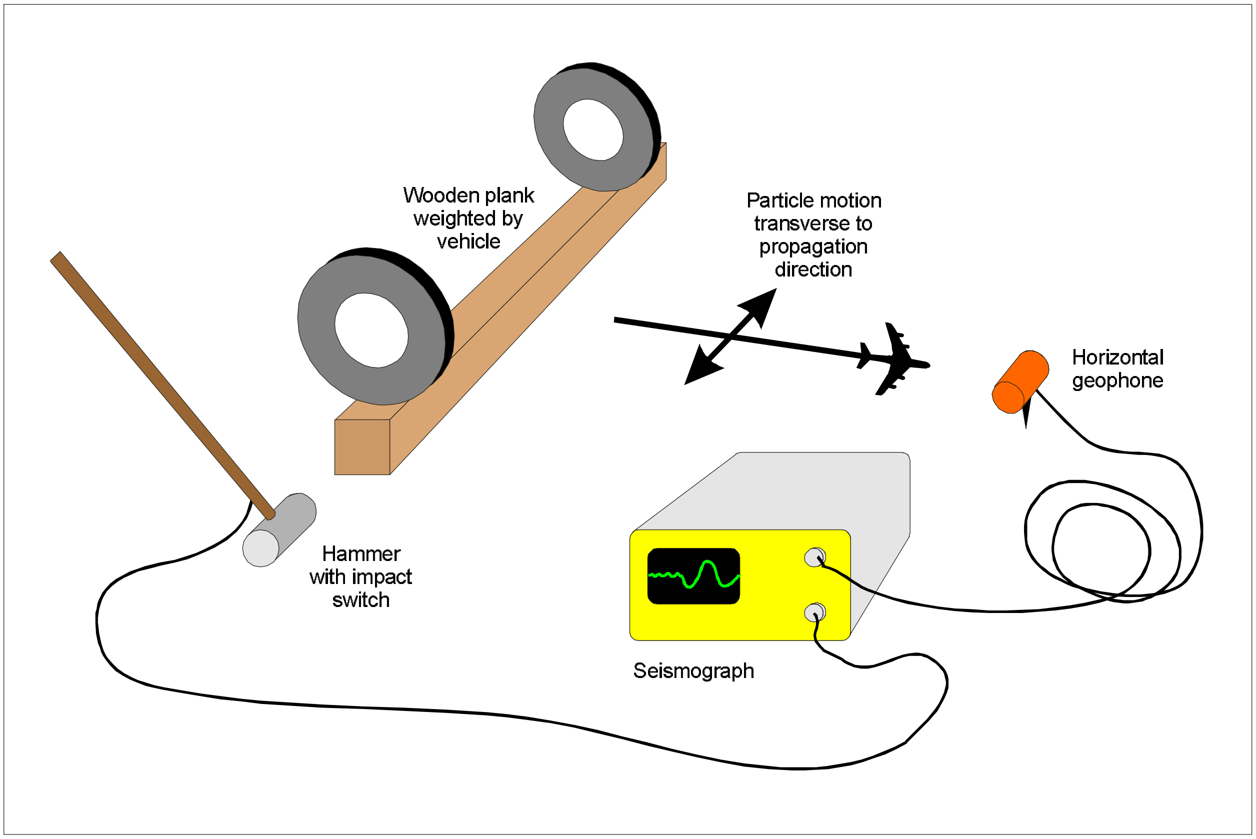

Figure 2

primary, as in first arrival). Many other waves will be buried in the later part of the seismic record. In addition to the shear waves, there are P waves with different refraction paths, reflections, surface waves and various converted waves. Occasionally, you see examples of composite records with shear wave arrivals identified by the amplitude or frequency, but as a practical matter it is impossible to reliably pick a shear wave out of a normal refraction record.

So what's the solution? The answer is to use a seismic energy source that generates mostly shear waves, and vibration sensors that only detect shear waves. Consider Figure 2. which illustrates the basic field procedure. One extremely effective and popular mechanism to generate a clean shear wave is simply a wooden plank weighted down with a vehicle. By hitting the end of the plank with a hammer, a shearing stress is applied to the ground. The shear wave propagates in the direction perpendicular to the plank towards the geophone.

Moving-coil geophones are normally used as the vibration sensors for seismic surveys. They are available with different sensitive axes, usually horizontal or vertical. In this illustration, we are using a horizontal geophone which is sensitive to motion in the horizontal plane. The geophone is oriented parallel to the plank, in the same axis as the particle motion. It will be sensitive to the shear waves and relatively insensitive to any compressive waves from the plank.

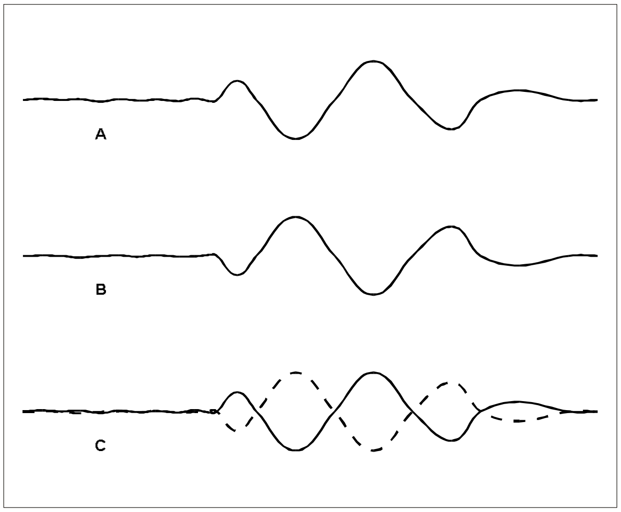

Figure 3

The seismic record from this survey will resemble an ordinary seismic record and an illustrative example is shown in Figure 3A. There is an obvious classic wavelet with a strong first arrival followed by larger excursions which die down after a few cycles. Generally, a good shear wave record will be less complex than refraction data, because we aren't dealing with multiple arrivals, and the dominant frequencies will be lower than in refraction surveys. To confirm that we really have a shear wave, take another record by hitting the other end of the plank. It should look like the one in Figure 3B. The first break is in the opposite direction, which is your confirmation that the arrival is most likely a shear wave. Many analysts like to superimpose the records as shown in Figure 3C., for better comparison, either by making a transparent copy or with a computer editing program.

Of course this same setup can be used with multiple geophone locations just like a refraction survey, and the same calculations can be used to analyze the data. The problem is that the analysis relies on the same assumption—that the shear wave velocity increases with depth. In those situations where determining the shear wave velocities is an important objective of the survey, it is highly unlikely that this assumption is valid. Besides the probability that there will be layers with lower velocities than those above, it is also likely that there will be thin beds that are not resolved by standard refraction analysis. For these reasons, surface shear wave refraction surveys are not an acceptable method for analysis of layered alluvial materials or any other situation where there is likely to be a low-velocity layer.

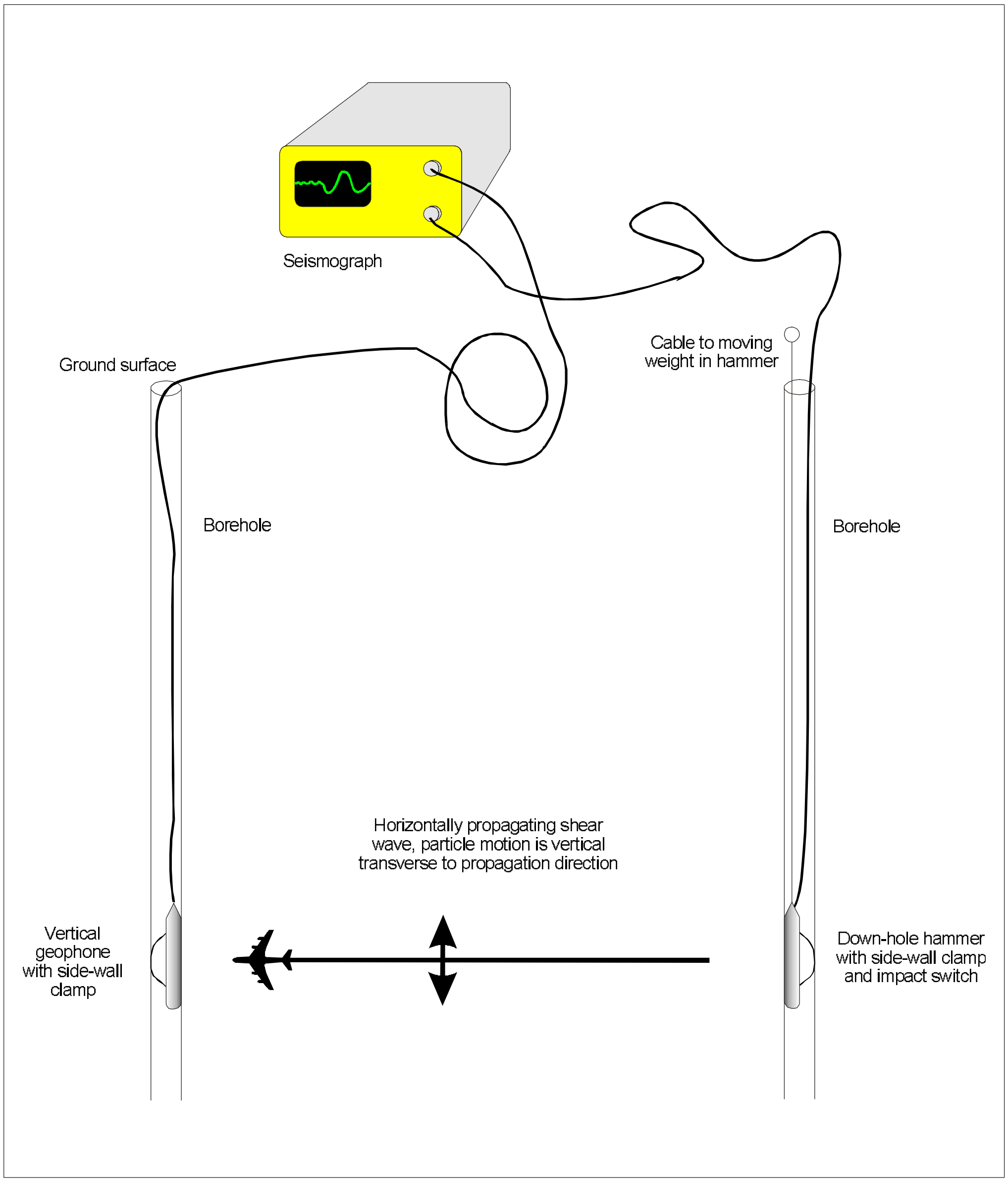

Figure 4, Cross hole shear wave measurements.

Field Techniques

Because subsurface shear wave velocities cannot be reliably measured on the surface, the normal procedure is to conduct the surveys in boreholes. There are two principal methods: cross-hole and downhole.

The crosshole survey is shown in Figure 4. Two (or three) holes are drilled side-by-side, typically with 10 foot (3 m) spacing. A down-hole hammer is clamped in one hole at some depth. A vertical geophone is

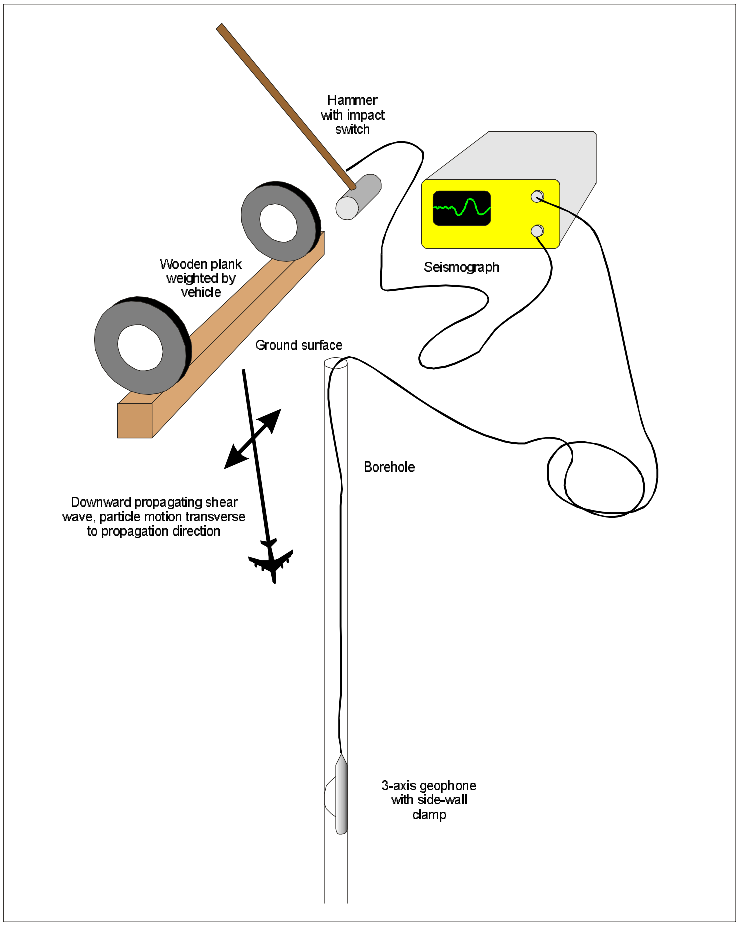

Figure 5, Down-hole shear wave configuration

clamped at the same depth in the adjacent hole. The hammer is a special tool with an internal weight that can bang downward (as the weight is allowed to drop) or upward (as the weight is pulled upward with a cable) to generate a pair of shear waves of opposite polarity. A pair of records is taken as shown earlier in Figure 3. The procedure is repeated at different depths until a complete set of measurements has been taken. The shear wave velocity for each geologic layer is calculated from the distance between the holes and the travel time.

Downhole is a simple extension of the surface survey described earlier, with a setup as shown in Figure 5. A borehole is prepared and the plank-vehicle combination located near the top of the hole. A horizontal geophone is clamped in the hole (actually a set of three geophones, 2 horizontal and one vertical geophone) and the data is acquired by collecting records from impacts on either end of the plank. A third record is collected by hitting the top of the plank to collect P-wave velocity data. The geophone is moved a short distance and the whole sequence repeated until records have been obtained at intervals from the surface to the bottom of the survey.

There are significant logistic and technical differences between the two methods, and generally practitioners will have a strong preference for one method over the other. The cross-hole method was popularized earlier than downhole and is an ASTM standard, so it will often be specified on bid documents, and there will not be a free choice in that case. Occasionally, both types will be conducted to determine anisotrophy, since cross hole surveys measures Sv and down hole surveys measure Sh. Here are some of the advantages and disadvantages of the two methods:

Cross-hole surveys require two (or three) boreholes instead of one, and the holes must be surveyed to know the distance between them at each depth.

A down-hole hammer is required, an extra piece of equipment which is not widely available.

Cross-hole shear waves can refract down (or up) and travel through higher velocity layers, just like surface refraction surveys, taking the quickest path between the holes. This limits the ability to resolve thin layers, or even to determine their dimensions.

Down hole surveys eliminate most of these problems. Only one hole is needed, the energy source is the surface plank-hammer combination, and since the waves travel vertically, there are no ambiguities about the path. The main disadvantage of downhole surveys is that attenuation and the natural filtering of the earth rounds off the arrivals so that it can be difficult to pick the first breaks with the necessary precision.

Data Analysis and Interpretation

If the P-wave and shear-wave velocities for the various layers are measured, and the density determined or estimated, then that information can be used to predict how the foundation will respond to an earthquake, including the ground spectral amplification ratios. Then, clever structural engineers can design buildings to resonate at different frequencies than the ground, as well as designing for the expected acceleration levels at the site.

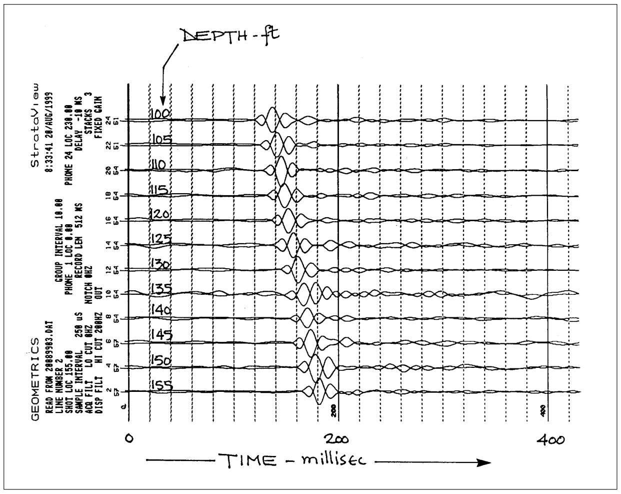

Figure 6, Sample shear wave data showing stacked traces with opposite polarities.

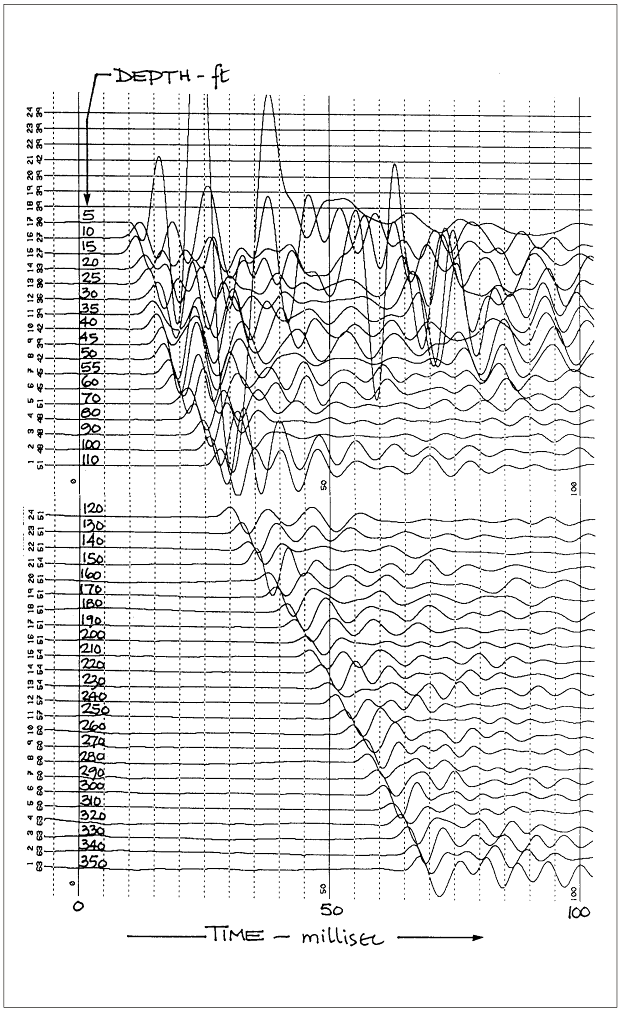

Figure 7, Composite down hole P-wave section

As a general rule, the person acquiring the data will prepare a report that describes the field procedures, shows the raw data, and tabulates the results in the form of Vp and Vs for various layers and depths. Raw data should include both P-wave and S-wave waveforms (in both polarities, see Figure 6.) in sufficient detail to allow independent review. Tabulated data should be presented as a stacked section showing the P-waves and shear waves displayed side-by-side (see Figures 7 and 8 for examples of P-wave and shear wave sections of data taken at the same site).

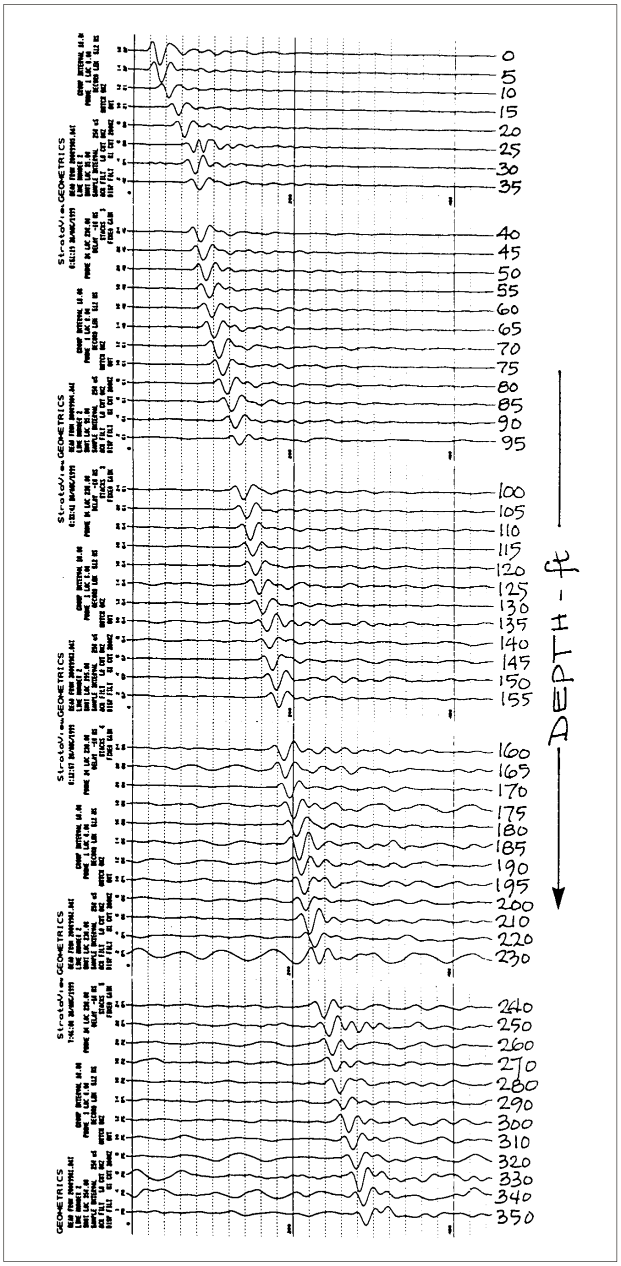

Figure 8, Composite down hole shear wave section, in same borehole as Figure 7.

Analysis of the stacked section can take two forms. One approach is to superimpose “best fit” lines of the data arrivals to make a general interpretation of the structure. The second approach is to look specifically at the interval velocities between adjacent traces. The preferred method depends on the purpose the data will serve and the structure.

Cross hole data is relatively simple to interpret and display, since there is only one record at each depth, and the velocity, Sv, is calculated from the arrival time and separation.

In the case of down-hole data, there will be two horizontal geophones that may be oriented in a random azimuth. If the geophones happen to be rotated off the azimuth of the plank, then the shear wave data will appear on both horizontal geophones. Since worst case is 70% of the total waveform, at least one will have a decent signal. The reverse polarity test by recording data from the other end of the plank must be made before the geophone is re-positioned so that valid comparisons can be made.

Equipment

The Seismograph

The seismograph is simply an instrument to amplify, record and plot the signals from the geophones with a precise time reference to the impact. When the first edition of this booklet was written 25 years ago, there were a number of choices in recording device including oscilloscopes, multi-purpose data acquisition systems, and single or multi-channel seismographs, none of them ideal. Since that time, technology has advanced to the point that modern exploration seismographs designed for engineering applications are just about perfect for the job to the extent that no other instrument should be considered, especially since they can be rented for short term use. Consider the following list of features found in virtually every modern seismograph:

Figure 6, Modern exploration seismograph suitable for shear wave studies.

Precise time synchronization with the hammer switch and fast data sampling.

Stacking or summing of multiple hammer blows to allow surveys to greater depths and in the presence of cultural noise.

Floating point amplifiers which eliminate the need for operator gain adjustments, regardless of the distance between the hammer and geophone, and ensuring maximum resolution of the signal.

Analog and digital filters to reduce or eliminate cultural and system related noise.

High-resolution digital recording in PC compatible media for later playback, analysis or processing.

High-contrast digital plotters with precise time scales and control of the display parameters and appearance.

Only the first two features were available when the first edition was written, and all this is available in a small, battery-powered suitcase with a user-friendly operator interface. One popular instrument is shown in Figure 9.

Hammer

There is nothing magic about the hammer, except that an impact switch (normally supplied as an accessory to the seismograph) is attached to the handle near the head with electrical tape. Of course they are available in different weights from four lbs. (2 Kg) to 16 lbs. (7 Kg). Different users prefer different weights and the best choice is not obvious. It is clear that the impedance match between the hammer and the plank affect the dominant frequencies and energy transfer (though not to the extent that soil conditions affect them). A 16-lb hammer will push more energy into the ground at lower frequencies, and it would be the obvious choice for deep, downhole surveys. Some users would argue that with an 8-lb hammer, they can swing it at a higher velocity, and more often without tiring the hammer operator.

Down hole hammer

Cross-hole surveys require a down-hole hammer, which is simply a device that can be clamped into the borehole and then banged up or down, impacting a shear force against the borehole wall. Some practitioners construct their own and some are available commercially. The usual approach is to start with a metal pipe, closed on each end, with a moving weight inside. The moving weight is attached to a cable (fed through a hole in the end) to the surface. The operator pulls up on the cable to create an upward impact, then releases the cable to let the weight drop and create a downward impact. An impact switch is attached to the pipe to provide a precise zero time.

The hammer is clamped in the hole with an inflatable bladder or some mechanical mechanism. The amount of energy from these downhole hammers is limited, but generally adequate for the small separations between holes in a cross-hole survey. Falling weight hammers don’t work underwater, so wet holes must be pumped dry before the survey.

In one variations on the down hole hammer, a scissor jack was attached to a long rod, hammered at the surface. It is also possible to do the survey while the second hole is being drilled, by banging on the drill rod a regular intervals. The time required for the signal to propagate down the drill rod must be subtracted, and the hole must still be surveyed after the survey.

Plank

The plank can be an ordinary fence post or railroad tie. It should be long enough to protrude from both sides of the vehicle used to weight it down. The ground should be prepared by scraping the surface with a flat shovel to expose the firm subsoil to provide a good shear contact. It is not necessary or desirable to excavate and backfill the site because that will tend to convert the shear stress into compressive stress.

Some users like to enhance their plank. The first improvement is to put steel plates on the end to reduce the wear and tear from extended pounding. Another improvement is to bolt short pieces of angle iron to the bottom of the plank, transverse to the long axis, to provide a better gripping surface.

Typically the plank is located a short distance from the hole to reduce tube waves, particularly the sound of the impact from traveling down the hole.

Geophones

The basic sensing element is the geophone, containing a magnet and a coil of wire that generates a small voltage when vibrated. The coil is supported by springs, making a pendulum with a natural oscillation frequency. The output signal is reasonably flat for vibrations with frequencies above the natural frequency, so the sensor must be chosen with a frequency low enough to capture the signals in the shear waves. The frequency content is higher for shallow holes in firm soil, and lower for deep holes in soft soil. Looking at some of the data in this report, the lowest frequency seen is about 20 Hz, which suggests using geophones with a natural frequency of 10 or 14 Hz. Much lower frequency sensors are excessively tilt sensitive and may have spurious resonances at higher frequencies in the bandpass of interest. Higher frequency sensors are likely to lose some of the information but have the advantage of operating in any position, such as horizontal drill holes in rock.

A down-hole geophone is constructed with three geophone elements in an X-Y-Z orthogonal configuration in a sealed cylindrical package. The geophone must be firmly clamped against the side of the hole so that it follows the ground vibrations exactly. Geophones are typically clamped with either inflatable bladders or mechanical arms, home made or purchased from a commercial source. The clamping device must be located on just one side of the geophone so that the housing is firmly pressed directly against the wall.

Home-constructed systems usually employ a bicycle inner tube attached to the geophone package. Plastic tubing extends to the surface, where a bicycle

Figure 9, Typical mechanical wall-lock geophone pump is used to inflate the tube. Such systems perform the clamping function adequately, but lack a certain robustness which hinders productivity. The systems tend to leak, bladders pop, are inconvenient to re-position, and increasing pressure is required as water depth increases. They often don't fit into existing boreholes. Nonetheless, they do the job and are economical. Every geophone manufacturer has a down-hole, 3-component geophone assembly available as a building block. Commercial bladder-clamped systems are also available, and are more reliable because of the extra engineering effort, but they tend to suffer from many of the same problems.

Mechanical arm systems are more complex and thus difficult to construct and more costly. However, they are generally more satisfactory to use. They are reliable, operate at greater depths, are easy and quick to re-position. DC-motor powered units are easier to handle on the surface since there is no air line. One such unit is shown in Figure 9, available commercially for purchase or rental.

Preparing the hole

We have so far carefully glossed over the details of the borehole, using the construct of a simple hole in the ground. In fact, you can use a simple hole in the ground and it will work very well unless there are washed out segments where the tool can't make decent contact.

In practice, holes in alluvial materials have a tendency to close in, leaving your geophone permanently secured in place. To prevent collapse or washouts, bore holes are normally cased with plastic pipe. The space between the outside of the pipe must be backfilled with pea gravel, grout, or drilling mud (?) to ensure that the pipe follows the motions of the adjacent soil exactly. Any voids outside the pipe will allow the pipe to shake in response to vibrations above or below the tool location, and mode conversions between P and S-waves will occur. Bad data is normally caused by bad backfilling in an otherwise properly conducted survey.

Put a cap on the bottom of the pipe to keep mud and debris out and to allow pumping the pipe dry if necessary. Avoid connecting pipe segments with anything that projects into the hole (like pop rivets) far enough to interfere with movement of the tool.

Field procedure

As discussed earlier, you must collect data from impacts on either end of the plank to confirm that you are looking at shear waves and not P-waves, or some odd reflection, or tube waves, or some other problem (not that this makes good data a certainty, but it puts you further along the path to excellence).

Start with the geophone at the top of the hole and take three separate records—one on each end of the plank and one vertical to get the P-wave information (or two for cross-hole). Look at the records and see if they meet the test of reasonableness: shear waves that reverse and a P wave that arrives in about half the time with higher frequencies. Next, position the geophone at the next lower depth and repeat the process. Continue until you have records available from a few depths, then stack tape vertically on the side of the truck to see how your section looks. Plot up a section on some graph paper. If the data looks reasonable, continue the survey until you reach the required depth.

Now, while still in the field, plot your complete section, P-waves and S-waves, and look at it again. Does it look reasonable? Are the P-wave velocities reasonable for the types of materials? Are the shear wave velocities lower than the P-wave velocities? Do the plots follow a reasonable progression down the hole? Are any of the interval velocities unusually fast or slow or even negative? Some variation is normal because of the short time intervals, but if arrivals come in sooner as you go down the hole, that's a sign of a serious problem. Be ready to repeat some of the points or the whole survey while you are at the site. It's expensive to go back again (or to never get another job from that client). While it's tempting to just save the data on some digital media and go back to the office to work up the report, it's crucial to do enough data analysis in the field to know that the data is good.

After you gain some experience, skill and confidence (preferably in that order), some modifications to the field procedure can be made to speed things up and simplify the process. If your system is designed so that you can select which channel on the seismograph is connected to which geophone, then the stacked section can be acquired directly in the instrument. Selecting the seismograph channel can be done with rotary switches in a separate box, or by using standard geophone clip connectors and a conventional spread cable with multiple takeouts gathered up on the surface. Just connect the geophone to the takeout which matches the desired channel. After you acquire 12 or 24 channels of data, you can save the digital data and plot out the paper copy. This procedure was used for the composite records shown earlier in Figures 7 and 8.

If you start at the bottom of the hole and drag the geophone up (without unclamping), it will not rotate significantly and the geophones will not twist around—another key to an attractive stacked section. The reverse impacts don’t have to be plotted (other than a representative sample), since comparing the data on sequential levels can provide quality control. Of course conducting the survey with this procedure cuts the field time required substantially. The P-wave section can be acquired as a separate traverse or at the same time as desired.

Shear waves are body waves, not refracted signals, and you don’t lose signal strength at refraction interfaces. They are also lower frequency, and suffer less from the high-cut filtering that the earth applies to seismic waves. Consequently, downhole survey data can work surprisingly deep. It is not uncommon to get good data down as far as 600 feet (200 meters) or more, especially with multiple hammer blows.

If you would like to try shear-wave stacking, this can usually clean up your records. The procedure is to connect a polarity-reversal switch to the geophone, and then, using a stacking seismograph, apply blows to opposite ends of the plank while reversing the geophone polarity. The shear waves will stack, while waves that don’t reverse polarity will tend to cancel out. If your seismograph offers subtractive stacking as a feature, then the switch is not required.

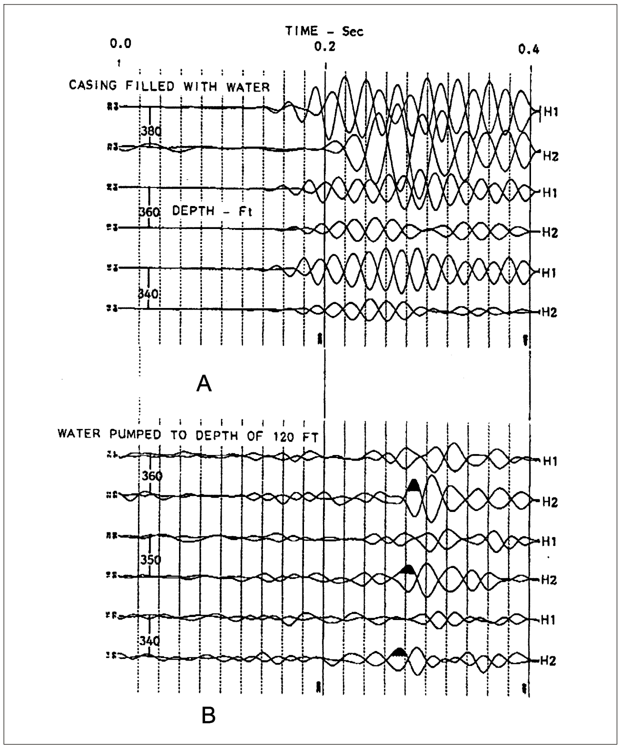

Figure 10, Comparison of tube waves in wet and dry borehole.

Remember to put a little slack in the cable after clamping the geophone to prevent the waves running down the cable from shaking the geophone.

Picking arrival times

The first breaks from shear waves are very gradual, particularly as the geophone gets deeper, and it is difficult to precisely pick the “first arrivals”. To get more precise time interval measurements, it is common to pick the first large peak in the wavelet. Purists would argue that dispersion stretches the wave slightly, but the effect is modest and certainly less than the error picking the first break.

Some users like to put multiple geophones in the hole. By having say two geophones separated by a 10 ft interval, the pair of arrivals can be more precisely measured. Since they record the vibrations from a single hammer blow, any timing errors can be eliminated and the close similarity between the two records allows more precise time comparisons. The geophones can be connected with a flexible, but non-rotating mechanism such as a motorcycle chain.

Most seismographs are equipped with filters, analog or digital or both. Filters are generally used to remove geophysical noise from the data that might obscure the signals of interest. Examples are low-frequency vibrations from wind blowing on trees or the sound of the hammer hitting the plank. All analog filters (and many digital filters) introduce some phase shift into the signal. So, if you use filters, use the same filter for the whole survey.

Orientation

There are two horizontal sensors in a downhole geophone, which will be oriented at random if left to their own devices. The maximum signal is the vector sum of the output from both geophones. Since the seismograph has digital recording, it is not too difficult to make this calculation later and it is often done this way in an academic environment. Your data will be just as good if you take the signal from the geophone most closely aligned to the plank, and adjust the trace size on the display to normalize the excursions.

Better surveys and data do result if one of the geophones is continuously aligned with the plank. The other horizontal geophone can be ignored, the survey goes much faster, the stacked section is easy to plot and interpret, and problems with anisotrophy are eliminated. One way to accomplish this is to case the hole with grooved (slope indicator) pipe and modify the geophone to track in the groove. It is also possible to purchase commercial geophones with automatic orientation systems that will align the geophone in the azimuth of your choice. (Can we make the advantages stronger here??)

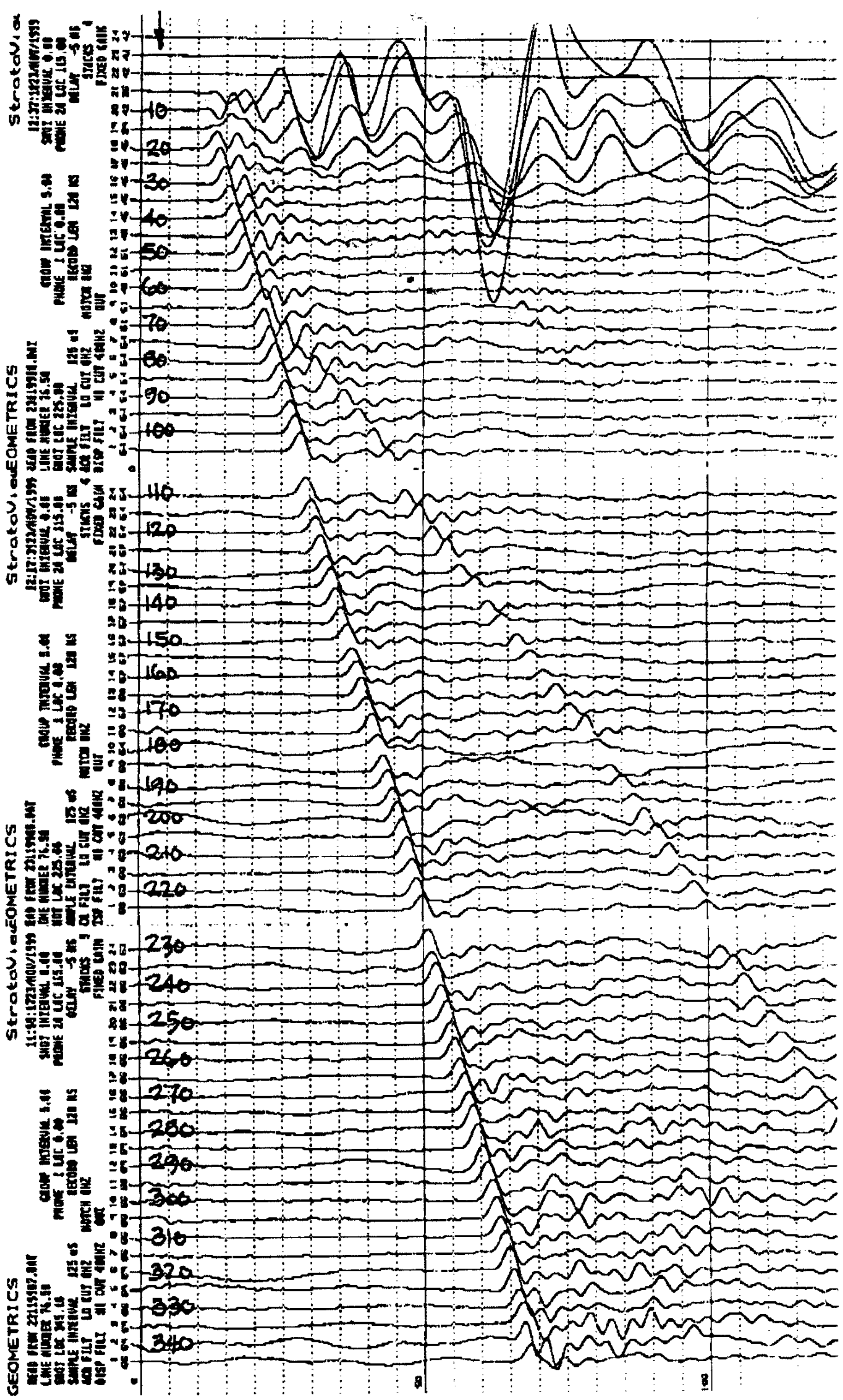

Figure 11, Composite downhole P wave record showing tube waves.

Tube waves

Waves that propagate down the borehole are called tube waves. They resemble shear waves and can even reverse polarity as seen in Figure 10A. Experienced skillful geophysicists have been known to conduct an entire shear wave survey picking only the tube wave arrivals. As a general rule, they are less of a problem for shallow surveys (<100 ft), but on deep wells are more likely to be mistaken for shear waves. The reason is that tube waves attenuate less rapidly than shear waves, and thus have relatively stronger signals at greater depths. One solution is to pump the water out of the hole, or at least enough to move the tube waves away from the shear wave arrivals. Figure 10B shows data from the same depth as in Figure 10A with the water pumped out down to a depth of 120 feet. The shear waves are now visible where they were obscured by the tube waves. Tube waves are generally recognizable because their velocity is constant, as seen in the composite record in Figure 11. The first arrivals are the P waves. The tube waves intersect the P waves at about 60 ft depth (the water height in the pipe???). Yet another reason to plot composite sections while still in the field.

Data Processing

Since modern seismographs have digital data storage, computers can simplify the processing and display of data. At this time, no general purpose shear wave processing software is commercially available because of the limited number of potential customers. Programs designed to display seismic reflection data can plot shear wave data using their rudimentary editing routines. It would be nice to be able to cross-correlate records from sequential depths to get a more precise measurement of delta-time and thus interval velocity. F-K filters could be used to remove tube waves.

Anisotropy

The shear wave velocities are always the same in the vertical (Sv) and in the horizontal (Sh) plane. Sh velocities may also vary in different azimuths, a situation known as horizontal anisotropy, usually as a result of regional stresses or local mass movement. In this case, the ground spectral response will be different, depending on which way the plank and geophones are oriented. (Anisotropy skews the data????)

In anisotropic situations, the survey should be conducted with an orientable geophone as described earlier and the results from both orientations reported.

The devil is in the details

From the preceding, it would appear that measuring shear wave velocities is a trivial exercise. To the contrary, like many skills, it is difficult for the uninitiated. In fact, the authors suggest that the beginner not try this alone. If you feel the desire or opportunity to conduct your own shear wave survey, it might be wise to hire the services of someone actually experienced in the practice, then go along and swing the hammer for them. Look at real records Learn the tricks. Especially learn to recognize what good data looks like.

References

Redpath, etc

OYO reference on shear wave velocities and blow counts here.

* available from Geometrics Inc