# Borehole Shear-Wave Surveys for Engineering Site Investigations

**Doug Crice**

***Geostuff***

19623 Via Escuela Drive
Saratoga, CA 95070 USA

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## Introduction

There is a trend in building codes to require shear wave velocity studies as part of foundation investigations for major structures. Shear wave velocity measurements are an important tool in designing buildings for site specific conditions such as ground-spectral earthquake response. And, they are a much more diagnostic tool for engineering properties than P-wave velocities. Consequently, engineers that are more comfortable with soil mechanics than the wave equation are taking an interest in geophysics.

Since most practicing geophysicists seldom get an opportunity to conduct one of these surveys, it seemed worthwhile to document some of the methods used. The techniques are seldom covered in textbooks or papers, the former because they're too esoteric and the latter because they're common knowledge. Of course it isn't common knowledge—geophysicists that know how to actually conduct shear wave surveys are few and widely scattered.

## What are shear waves and why do we care?

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 is propagating.

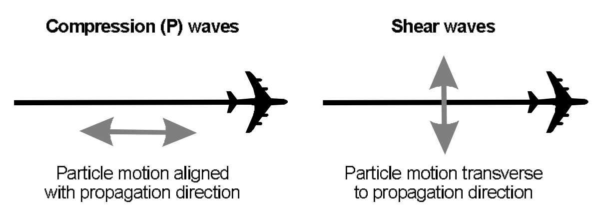



Figure 1, Particle motion and wave propagation.

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 once the velocity is known. 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. A refraction analysis 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. No longer can we assume that this is just a saturated alluvial material. 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 approximately the same compressive wave velocities.

Reasonable values for shear wave velocities are listed in the following table. While there will be wide variations in the velocities in these materials, clearly the

| 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) |

shear wave velocity tells us a lot more about the character of the material in-situ. Shear wave velocities are dependent on the shear strength of the material and shear strength is what supports buildings and piles and keeps a ripping tooth from cutting rock. If we know the shear wave velocity, add some geological knowledge, a little common sense, and maybe a few drill holes, you can know a lot more about the material. Empirical studies by OYO Corporation[1] showed that shear wave velocity correlates very well with blow counts, one of engineering geology's well-established measurements.

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

(1) Young's Modulus (E), stress/strain, 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 properties can be calculated from the seismic velocities. For example:

| | | |
|---|---|---|
| Poisson's Ratio | $F_p =$ | $\dfrac{(Vp/Vs)^2 - 2}{2(Vp/Vs)^2 - 2}$ |
| Shear Modulus | $G=$ | $d\ Vs^2$ |
| Young's Modulus | $E=$ | $2G\ (1+F_p)$ |
| Bulk Modulus | $K=$ | $\dfrac{1}{3} \cdot \dfrac{E}{1-2F_p}$ |

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

These are of course elastic linear dynamic characteristics and are not always applicable to static performance of the foundation material when subjected to large static or dynamic loads.

## How are shear wave velocities measured?

The simplistic answer is that shear waves are collected and measured just like P-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. Shear waves travel slower than P-waves and thus will be imbedded in the complex wavetrain somewhere after the first arrival.

In a normal refraction survey, identification of the P-waves is simple since they arrive first in the record. After the "first arrivals", many other waves will be buried in the later part of the seismic record. In addition to the shear waves, there are P waves

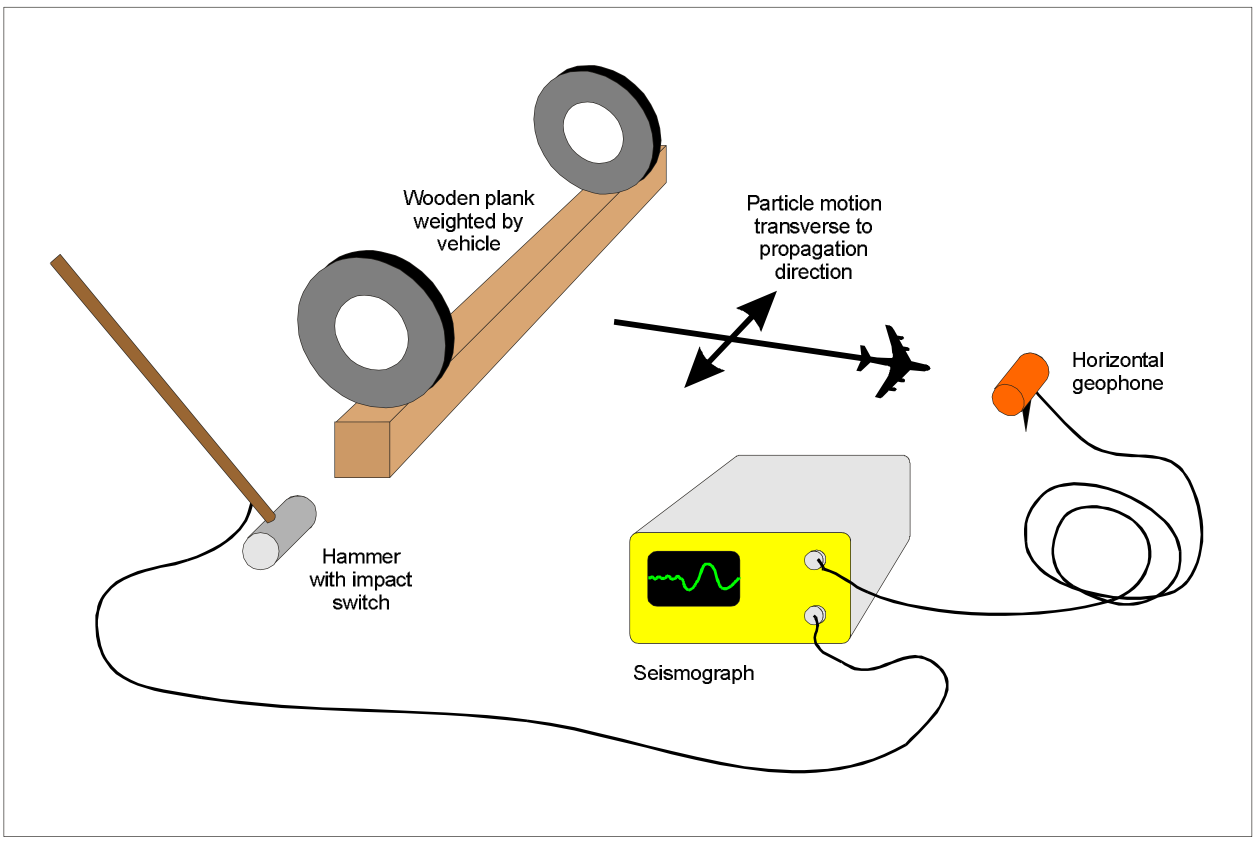



Figure 2. Basic field procedure for recording clean shear-wave records.

with different refraction paths, reflections, surface waves and various converted waves. Occasionally, you will see examples of composite records with alleged 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 sensitive to 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.

Geophones are available with different sensitive axes, usually horizontal or vertical. In this illustration, we are using a horizontal geophone (Horizontal geophones are often mistakenly called "shear phones" because they are commonly used for shear-wave surveys, but shear waves can be oriented in any direction depending on the polarization of the source). The geophone is oriented parallel to the plank, in the same axis as the particle motion. It will be quite sensitive to the shear waves, and relatively insensitive to any compressive waves.

The seismic record from this survey will resemble an ordinary seismic record and an illustrative example is shown in Figure 3A. There is a classic zero-phase wavelet with a strong first arrival followed by larger excursions which die down after a few cycles. In a properly done survey, a good shear wave record will be less complex than refraction data, because we aren't dealing with mode conversions and because the survey geometry is chosen to minimize multiple arrivals. 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 of one record, or with a computer plotting program.

Of course this same vehicle-on-a-plank source can be used with multiple geophones in a line on the surface (i.e. a refraction survey) and the refraction formulas can be used to analyze the data. The problem is that refraction analysis relies on the assumption that the wave velocities increase with depth. In those situations where determining the shear wave

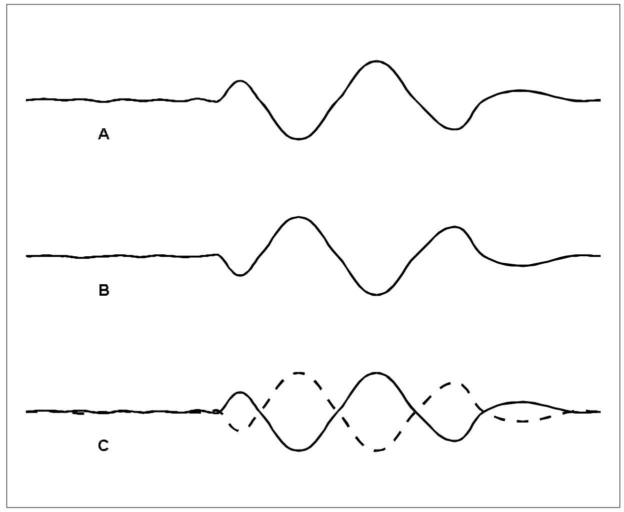



Figure 3. Shear waves reverse polarity when the source polarity is reversed.

velocities is an important objective of the survey, it is more common for this assumption to be invalid. 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 generally used for analysis of layered alluvial materials, or any other situation where there is likely to be a low-velocity layer sandwiched between high-velocity layers (i.e. a velocity inversion).

## 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 down hole.

The cross-hole survey is shown in Figure 4. Two (or three) holes are drilled side-by-side, typically with 10 foot (3 m) spacing. A vertical geophone is clamped in one hole at some depth. A down-hole shear-wave hammer is clamped at the same depth in the adjacent hole. The hammer is a special tool with a sliding 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.

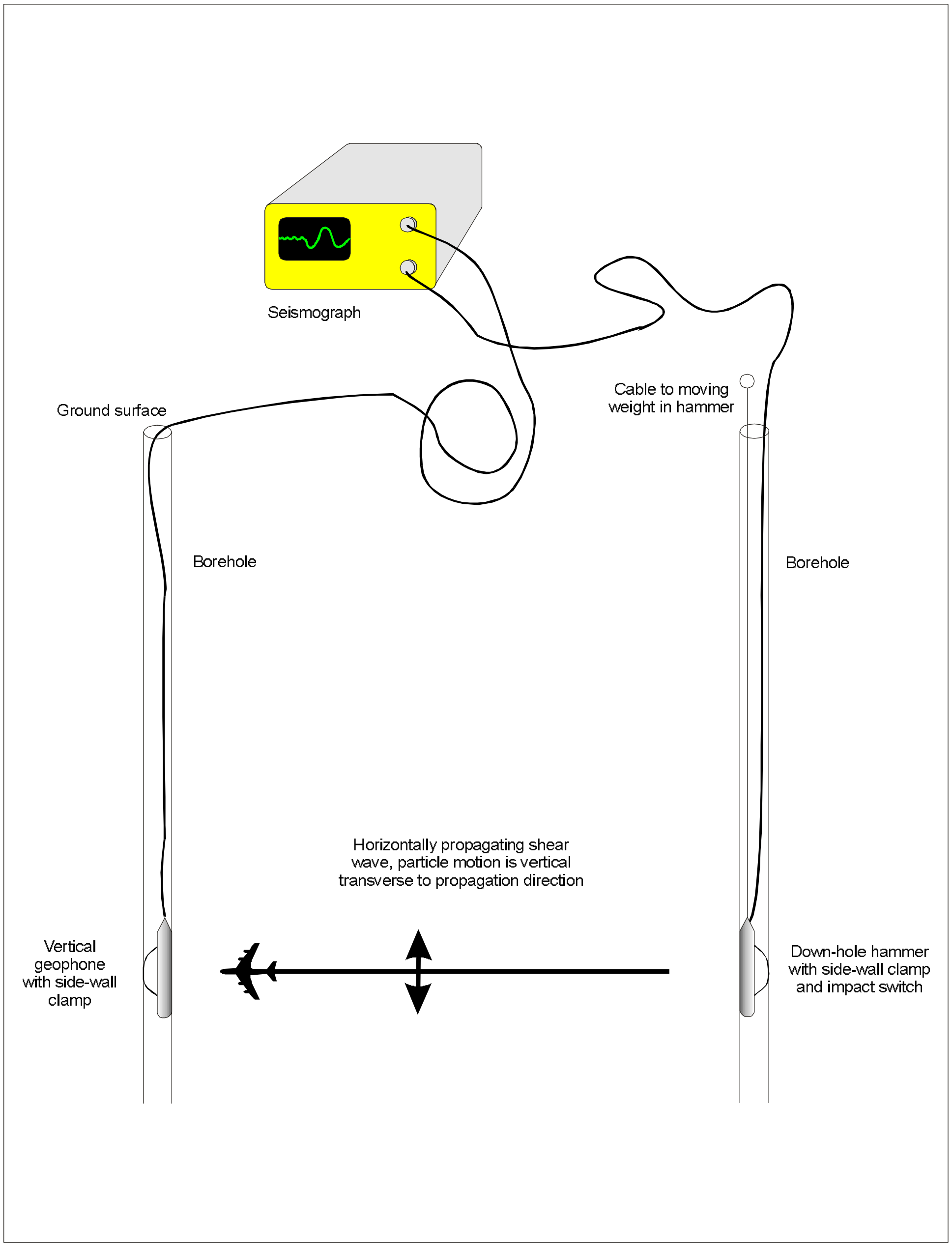



Figure 4, Cross hole shear wave measurements.

collecting records from impacts on both ends of the plank. A third record of P-wave velocity data is collected by hitting a striker plate on the ground surface to generate compressive waves (which is detected and recorded from a vertical geophone). The tri-axial geophone package is moved a short distance and the whole sequence repeated until records have been obtained at intervals from the surface to the depth of interest.

There are significant logistic and technical differences between the two methods. Typically, practitioners will have a strong preference for one method over the other, often approaching a religious fervor.

The cross-hole method was popularized earlier than down hole, and is an ASTM standard[1], 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 anisotropy, since cross-hole surveys measures $Vs_v$ (the velocity of a vertically polarized shear wave) and down hole surveys measure $Vs_h$ (the velocity of a horizontally polarized shear wave). There are advantages and disadvantages to either method:

Down hole 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 tri-axial geophone) and the data is acquired by

1 The ASTM standard is D4428/D4428M-00 Standard Test Methods for Crosshole Seismic Testing. It can be purchased and downloaded from the ASTM web site at http://www.astm.org

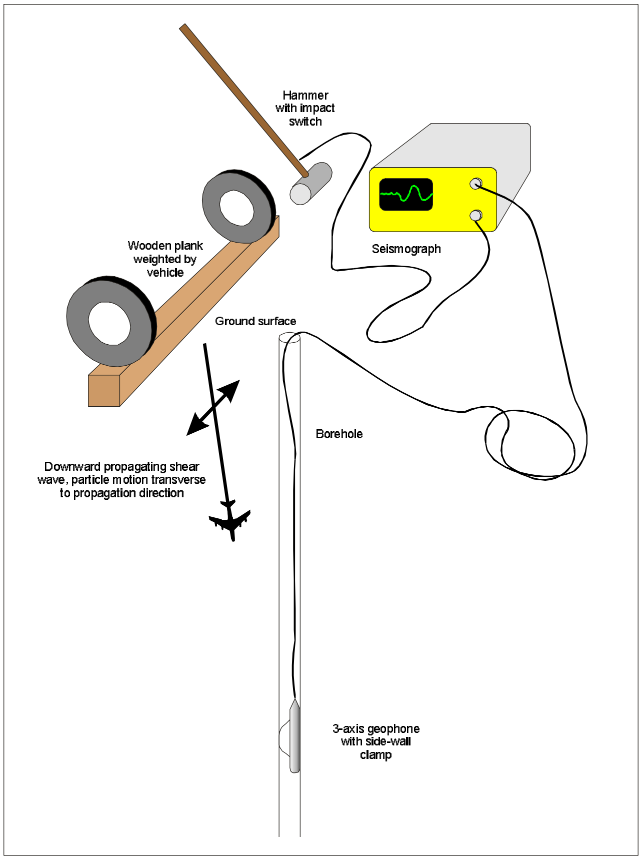



Figure 5, Down-hole shear wave configuration

Cross-hole surveys require two (or three) boreholes instead of one, and the holes must be surveyed to determine the distance between them at each depth. Depending on your driller, the holes can deviate from vertical (or rather, equal spacing) by a substantial distance. A not-uncommon variation of 1 meter in spacing between two boreholes 3 meters apart can affect your results enough to make field interpretation and quality control difficult.

A down-hole hammer is required for cross hole; an extra piece of equipment which is not widely available. There are practical limits to the maximum depth the weight-and-cable hammer mechanisms can be used, and most require dry holes.

Shear waves traveling horizontally between boreholes can refract down (or up) and travel through adjacent, 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. The refraction problem is the reason that cross-hole surveys must be conducted with small distances between boreholes.

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 nearly vertically, there are fewer ambiguities about the path. The main disadvantage of downhole surveys is that attenuation and natural filtering by the earth rounds off the seismic arrivals so that it can be difficult to pick the first breaks with the necessary precision.

## Data Analysis and Interpretation

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).

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 geologic 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

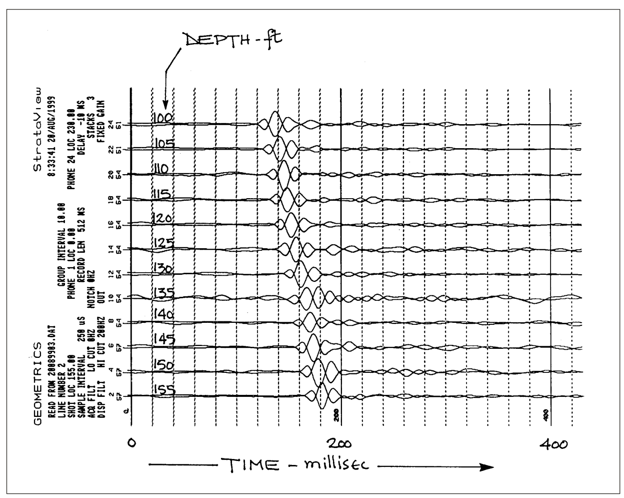



Figure 6, Sample shear wave data showing stacked traces with opposite polarities.

serve and the structure, and also depends on the quality of the downhole signals. Waveforms contaminated by noise or interference may preclude computing reliable interval velocities.

Cross-hole data is relatively simple to interpret and display, since there is only one record at each depth, and the velocity, Vs, 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 orientation is off the azimuth of the plank, then the shear wave data will appear on both horizontal geophones. Worst case is 70% of the waveform amplitude, and 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.

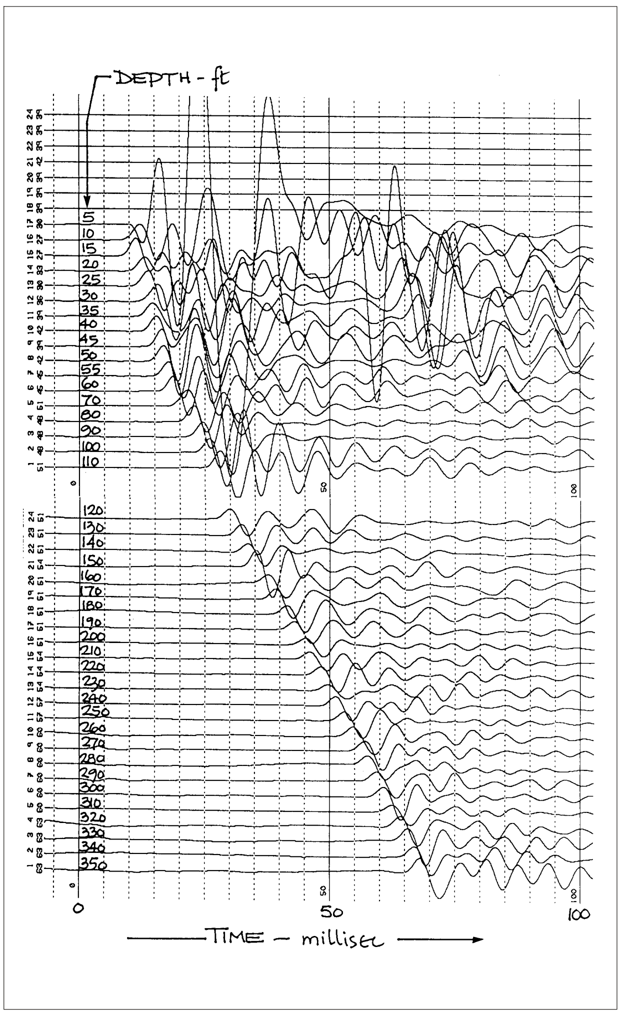



Figure 7, Composite down hole P-wave section

## Equipment

### The Seismograph

Modern exploration seismographs are ideal for shear-wave surveys. They offer precise time synchronization with the hammer switch, fast data sampling, and summing of multiple hammer blows to allow surveys to greater depths and in the presence of cultural noise. Floating point amplifiers (or 24-bit systems) eliminate the need for operator gain adjustments regardless of the distance between the

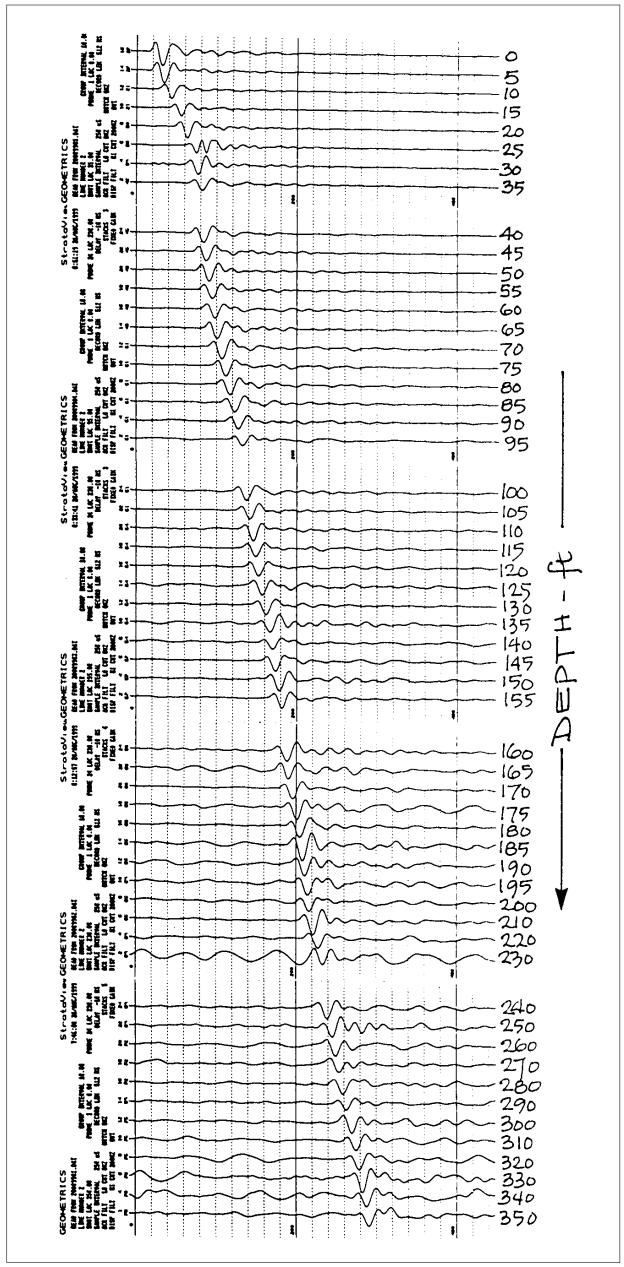



Figure 8, Composite down hole shear wave section, in same borehole as Figure 7 (time scale on record is changed).

hammer and geophone, ensuring maximum resolution of the signal. Analog and digital filters reduce or eliminate cultural and system related noise. Digital recording in PC compatible media allows later playback, analysis or processing. Digital plotters with precise time scales allow control of the display parameters and appearance for record comparison.

### Hammer

There is nothing special 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 20 lbs. (9 Kg). Different users prefer different weights and the best choice is not obvious. 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, down hole 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[2]. 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 down-hole 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.

### 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 weigh it down. The ground should be prepared by scraping the surface with a flat shovel to expose bare, undisturbed soil to provide a good friction contact. It is not necessary or desirable to excavate and backfill the site because that will tends to spread the energy and convert the shear stress into compressive stress.

Some users like to enhance their plank. One improvement is to put metal plates on the ends to reduce the wear and tear from extended pounding. Another improvement is to bolt short pieces of channel iron to the bottom of the plank, transverse to the long axis, to provide a better gripping surface. For air-mobility, buy a fencepost at a local hardware store and nail metal joint brackets to the bottom.[2]

Typically the plank is located some distance from the hole, 5 to 10 feet (2 to 3 meters). This offset must be corrected for when computing travel times for shallow depths, and the separation between the plank and the borehole should be kept small enough to allow accurate measurement of near-surface arrival times. Some practitioners locate the plank away from the borehole as much as 1/3 the total depth of the borehole, presumably to avoid tube waves. The author disagrees strongly with this approach, since it destroys your ability to measure near-surface interval velocities[3] The best offset distance seems to be determined by the distance between the vehicle's wheels and the adjacent bumper, which should be clear of the top of the borehole to provide access.

### Geophones

The basic sensing element is the geophone, chosen with a frequency low enough to capture the signals. Shear waves frequencies are lower than those of

2 Other types of shear-wave energy source mechanisms are possible, though few can match the simplicity and effectiveness of the weighted plank and hammer. Because the plank and hammer provide particularly clear shear wave arrivals, this is the preferred source for less-experienced users and the choice of experts. One substitute–hammering the side of a trench–is particularly challenging for the uninitiated, because the plastic deformation of the trench wall produces strong P waves that make proper identification of the shear wave arrivals difficult.

P-waves. 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 will be tilt sensitive and may have spurious resonances in the bandpass of interest. 28-Hz sensors may lose some of the information but have the advantage of operating in any position, such as in horizontal drill holes. Higher frequency geophones are not desirable except for tomographic applications in rock.

Figure 9. Typical mechanical wall-lock geophone

A down-hole geophone is constructed with three geophone elements in an X-Y-Z orthogonal configuration sealed in a 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 and must be located near the center of the assembly.

Home-constructed systems usually employ a bicycle inner tube attached to the geophone package. Pressure tubing is run to the surface, where a bicycle pump or gas cylinder is used to inflate the bladder. 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, and are easy and quick to re-position. Battery-powered units are easier to handle 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 PVC pipe. The space between the outside of the pipe must be backfilled with pea gravel or low-strength grout 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. Do not backfill the hole with pure concrete or cement. The preferred recipe is 10 gallons of water per bag of cement, diluted with 5 to 10% bentonite by volume.

3 When the plank is an appreciable distance from the borehole, at shallow geophone depths, the shear waves will travel nearly horizontally toward the geophone. That means that the waves will arrive at the borehole at virtually the same time for the first few locations (the reader should sketch the geometry to see the problem). Since the interval times will be close to zero, it will not be possible to calculate velocities. Even worse, it is likely that waves will refract down, across, and back up to the geophone location. The interval velocities will be negative. Even at appreciably deeper locations, the waves will tend to refract rather than taking a direct path, distorting the velocities.

If preparing a new borehole, 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) to interfere with movement of the tool. Have a piece of foam rubber to stick in the top of the hole to keep the sound of the hammer from going down the pipe.

## Field procedures

Cross-hole surveys don't require much discussion beyond that already mentioned. The only common problem encountered is not with the shear waves, but with the P-waves. In a good system, the energy that radiates normal to the down-hole hammer is practically free of compressive waves. The compressive waves radiate vertically from the source (straight up and down). So, even though your horizontal geophones will point directly at the source, the signal may be very small or even undetectable. One solution is to use a source rich in compressive waves, such as a blasting cap. Some users suggest changing the depth of either the source or receiver so that some fraction of the vertically radiating compressive waves propagates between them. A field procedure could be developed collecting data between sequential repositioning of the tools.

As discussed earlier, data should be collected from impacts in both directions (down-hole hammer or ends 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.

For down-hole surveys, start with the geophone near 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 tape the records onto the side of your truck, stacked vertically, 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, especially in the learning period.

After you gain some skill, experience, and confidence (preferably in that sequence), 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—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. When starting at the bottom, the records won't be as clean and easily picked. For that reason, take a few test shots on the way down the hole to confirm that things are working properly and your data is pickable.

Down hole surveys can be conducted to considerable depths. Shear waves are body waves which travel a relatively direct path between source and receiver. Thus, they don't suffer the attenuation characteristic of waves that must refract down, across and back up as in the refraction method. You may see some attenuation when traveling through a high-impedance contrast interface, such as glacial till over limestone. Shear waves are generally fairly low in frequency, and suffer less from the high-cut filtering that the earth applies to seismic waves. Excellent data can be acquired as deep as 600 feet

(200 meters) or more by stacking just a few hammer blows.

Shear-wave stacking, can theoretically 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. Despite the theoretical benefits of this procedure, shear wave stacking is not widely practiced because there are no obvious benefits and because the added complexity leads to confusion and errors. Some have been known to hit one end of the plank, reverse the polarity of the geophone, and hit the same end of the plank under the mistaken idea that this constitutes a shear wave reversal.

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.

## Measurement Intervals

The depth intervals at which the geophone is positioned in the borehole is a matter of judgement and of site conditions.  Closer intervals will result in better resolution of the subsurface layers and more accurate velocities, but will require more time to conduct the survey. When in doubt as to the most appropriate measurement interval, it is better to use smaller intervals always. As an example, if a survey is required to a depth of 220 ft (70 m), a reasonable and prudent sequence would be 3 ft (1 m) intervals from the surface to a depth of 100 ft (30 m) and 5 ft (2 m) intervals below that depth.

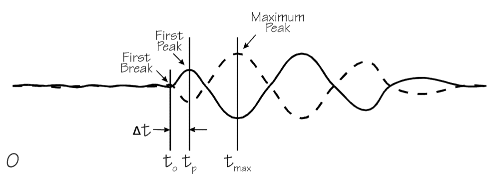
## Picking arrival times

Arrival times (or transit times) are plotted against their respective depths. The data points will generally plot as a sequence of nearly straight-line segments representing the various subsurface layers, and the velocities are the slopes of the least-square or visual straight-line fits to these segments.

The first breaks from down-hole 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.

At the shallower depths the times must be corrected for the horizontal offset of the energy source (plank) from the collar of the borehole. The signal travels along a slant path from the source to the receiver, and the travel time must be multiplied by the cosine of the angle between vertical (i.e. the borehole) and the slant path before plotting it against its corresponding depth. This is an approximate way of converting the time spent traveling along the slant path to the time the signal would have taken if it had traveled a vertical path down to the receiver. At some depth (typically about 10 times the offset) the cosine correction becomes insignificant and the raw times can be used.

If the onset of the signal is used (first break), then the cosine correction can be performed as just described. However, if a later portion of the signal is used, such as the first peak (and corresponding trough from the reverse blow on the plank), then the cosine correction must be performed as follows.




$$T_{vert} = t_o \cos 2$$

$$T_{vert} = (t_p - )t) \cos 2$$

Where )t is determined from the near-surface records where the frist breaks are easily picked. As previously mentioned, the onset of the shear wave, $t_o$, becomes increasingly obscure with increasing depth, but the first peak can be followed down with reasonable accuracy.  Whichever portion of the record is picked, it must be used from top to bottom, just as the same filters must be used from top to bottom, to maintain accurate time relationships, and the time difference between it and the first break used in the above equation. If the cosine correction is applied without taking account of )t, then the near surface velocities will be too low.

When picking later arrivals, we are only interested in the time difference between levels, and the equation for the correct time becomes:

$$T_{correct} = [\,(t_p - )t) \cos 2\,] + )t$$

The time interval and velocity from the ground surface to the first depth point are ignored.

Some users like to put multiple geophones in the hole. By having, say two geophones separated by a 10 ft (3 m) 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 non-rotating mechanism such as a motorcycle chain. The near-surface interval times must still be corrected for the offset as discussed earlier.

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. <u>So, if you use filters, use the same filter for the whole survey</u>.

## Orientation

There are two horizontal sensors in a down-hole 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 most seismographs have digital recording, it is not too difficult to make this calculation later and it is often done 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 anisotropy 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.

The issue of signal polarity is one that is seldom addressed in discussions of shear wave surveys, and yet it can be critically important in identification of the shear wave. The ability to maintain a consistent signal polarity, i.e. To know in which direction the seismograph trace will deflect for a given direction of hammer blow, has proven quite helpful in deep surveys. This issue has not been considered important because it was a moot point when using a randomly oriented downhole sensor. Aligning the sensor with the plank can be critically important in the presence of noise, interference, multiple signal paths or weak signals.

## Tube waves

A tube wave is a pressure pulse that propagates nearly unattenuated down (and up) the fluid column. The velocity of a tube wave is a function of the bulk Modulus of the fluid, the elastic Modulus of the casing, and the shear modulus of the surrounding material. They can 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 body 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

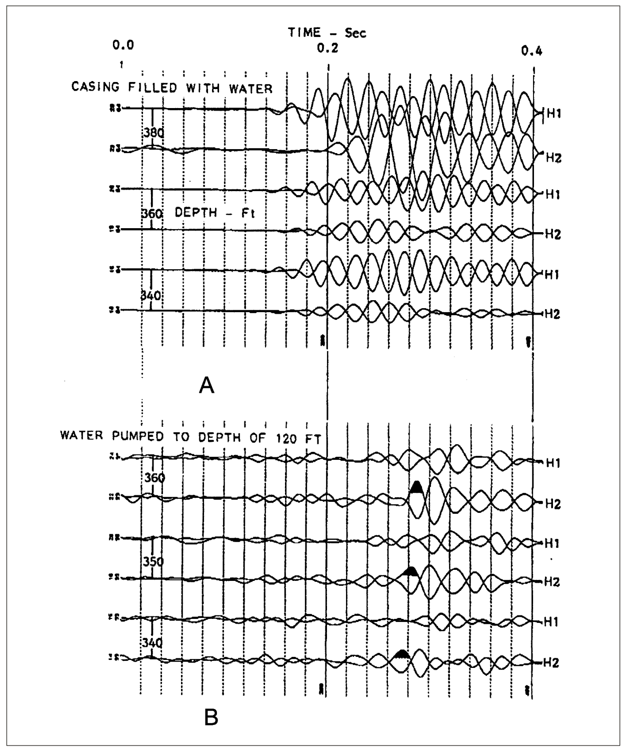



Figure 10, Comparison of tube waves in wet and dry borehole.

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, which was the depth of the water inside the PVC

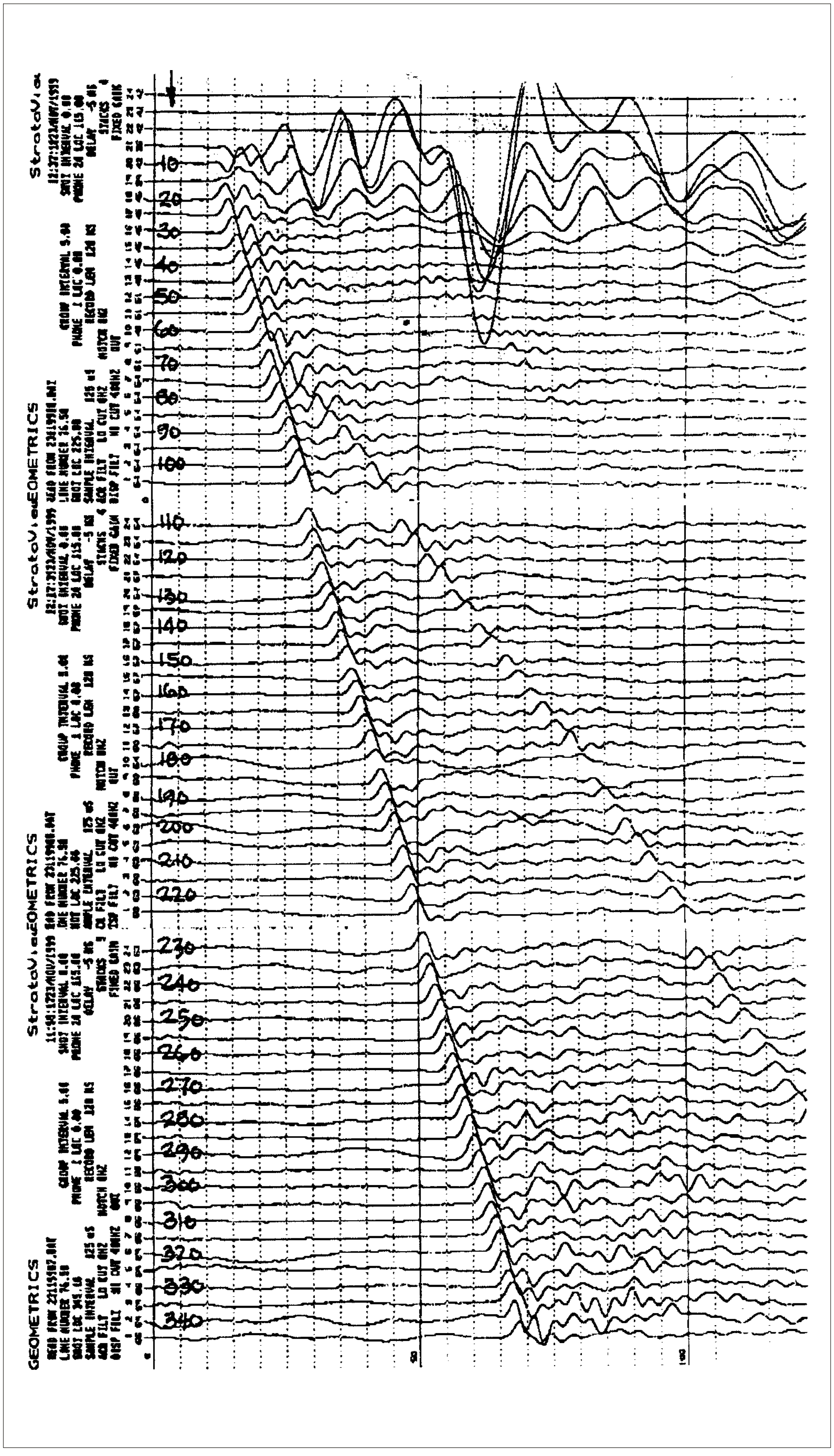



Figure 11, Composite downhole P wave record showing tube waves.

casing. 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—a shear wave record is similar to a common offset gather. Some users have written cross-correlation routines to get a more precise measurement of delta-time and thus interval velocity for sequential depths. F-K filters could be used to remove tube waves.

## Anisotropy

The shear wave velocities are seldom 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, local mass movement or special depositional situations. In this case, the ground spectral response will be different, depending on which way the plank and geophones are oriented. Anisotrophy in alluvial-type deposits can be as high as 1.4X (e.g. a N-S polarized shear wave may have a velocity 40% greater than an E-W polarized shear wave), although this would be exceptional. More typically 5 to 15% horizontal anisotrophy will be observed.

## 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 author suggests that the beginner try this alone before imposing his or her learning experience on a paying client. 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.

## Acknowledgment

All the data and most of the knowledge in this paper are the work of Bruce Redpath, who probably does more shear wave surveys than any practicing geophysicist and who provided insightful critique of the draft. Any one else who feels motivated to correct errors or bring further insight is encouraged to e-mail dcrice@georadar.com

[1] Imai, Tsuneo, Hideo Fumoto, and Koichiro Yokota, P- and S-Wave Velocities in Subsurface Layers of Ground in Japan, 1976 (available from OYO Corporation, http://www.oyo.co.jp/english/index.html)

[2] The only known commercial source for down hole hammers is from Bob Ballard (check with the SEG membership directory, http://www.seg.org)