

Near-surface, downhole shear-wave surveys: A primer

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Downhole shear-wave surveys may be used for a wide variety of applications that include determining the shear-wave velocity function with depth for static corrections or time-to-depth conversions for petroleum surveys involving shear-wave reflections. However, the principal nonpetroleum application is for investigations of engineering sites.

Shear-wave velocities are one of the more useful engineering properties of soil and rock because they are closely related to the shear strength of a material, and shear strength is what supports structures. Compressional-wave velocities are not a reliable indicator of material types or foundation quality.

The interest in these surveys expanded because the 1997 edition of the Uniform Building Code (UBC) and the 2000 edition of the International Building Code (IBC) prescribed use of the average value of the shear-wave velocity in the top 30 m (100 ft) of Earth materials to categorize building sites. The position where the V_{30} (metric) or V_{100} (English) velocity falls in the table determines how resistant a structure must be to withstand earthquakes, which affects major design decisions.

This paper describes the downhole method commonly used to measure shear-wave velocities. The details of this technique are seldom covered in textbooks or papers, the former because it's too esoteric and the latter because it's common knowledge. Geophysicists who have actually conducted a downhole shear-wave survey are few and widely scattered.

Reasonable values for shear-wave velocities are listed in Figure 1. While there will be wide variations, the shear-wave velocity tells us a lot about the character of the material in-situ. Shear-wave velocities are dependent on the shear strength of the material. Empirical studies by OYO Corporation in 1976 showed that shear-wave velocity correlates well with N-values (blow counts), one of engineering geology's well-established measurements.

Given 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.

Material	Vp m/s (ft/s)	Vs m/s (ft/s)
Saturated gravels (clean)	1500 (5000)	300 (1000)
Saturated gravels (dirty)	1500 (5000)	600 (2000)
Clay deposits	1500 (5000)	900 (3000)
Weathered rock	1500 (5000)	6-900 (2-3000)

Figure 1. Reasonable values for P- and S-wave velocities.

Bulk modulus is also termed the modulus of incompressibility.

- 4) Poisson's ratio (σ) 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:

$$\text{Poisson's ratio } \sigma_p = \frac{(V_p/V_s)^2 - 2}{2(V_p/V_s)^2 - 2}$$

$$\text{Shear modulus } G = dV_s^2$$

$$\text{Young's modulus } E = 2G(1 + \sigma_p)$$

$$\text{Bulk modulus } K = \frac{1}{3} \cdot \frac{E}{1 - 2\sigma_p}$$

where V_p = P-wave velocity, V_s = shear-wave velocity, and d = density.

These are, of course, elastic linear dynamic characteristics and are not always applicable to performance of the foundation material when subjected to large static or dynamic loads, but these are the principal parameters used to predict ground spectral amplification ratios for earthquake site response.

Shear waves are generally measured using a seismic energy source that generates mostly shear waves and vibration sensors sensitive to shear waves. Figure 2 illustrates the basic field deployment.

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 velocities is an objective of the survey, it is 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.

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: crosshole and downhole.

The crosshole survey is shown in Figure 3. Two (or three) holes are drilled side-by-side, typically with 10-ft (3-m) spacing. A vertical geophone is clamped in one hole at some depth. A downhole 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, each with different first motions of the source mass as illustrated in Figure 4. 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 traveltime.

Downhole is a simple extension of a surface survey, 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 triaxial geophone) and the data acquired by 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 compressional waves (detected and recorded from a vertical geophone). The triaxial 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 as shown in Figures 6 and 7.

There are significant logistic and technical differences between the two methods.

The crosshole method was popularized earlier than downhole, and has been an ASTM standard, so it will often be specified on bid documents. More recently, an ASTM standard for downhole shear wave-testing has been published, and there may be some choice of methods. There are advantages and disadvantages to either method.

Crosshole surveys require two (or three) boreholes instead

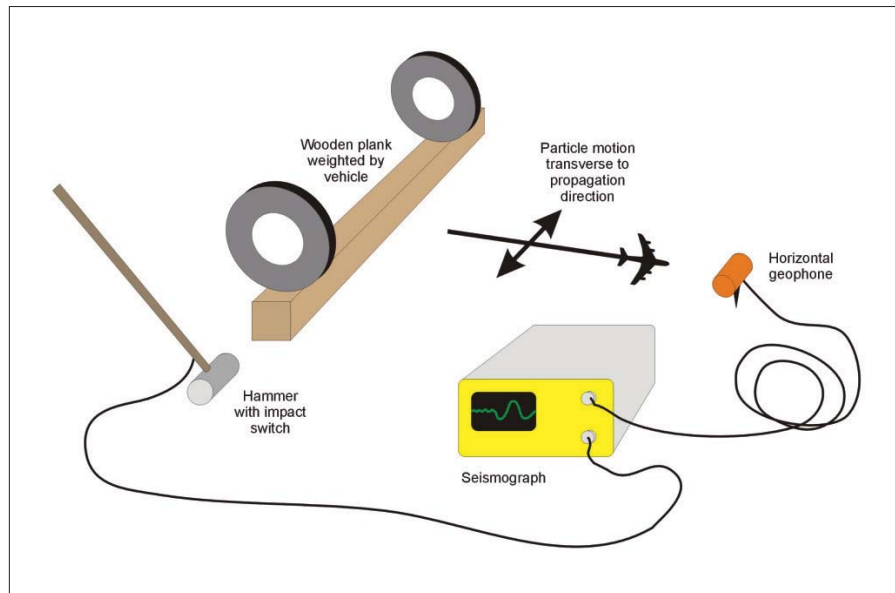


Figure 2. Basic field procedure for recording clean shear-wave records.

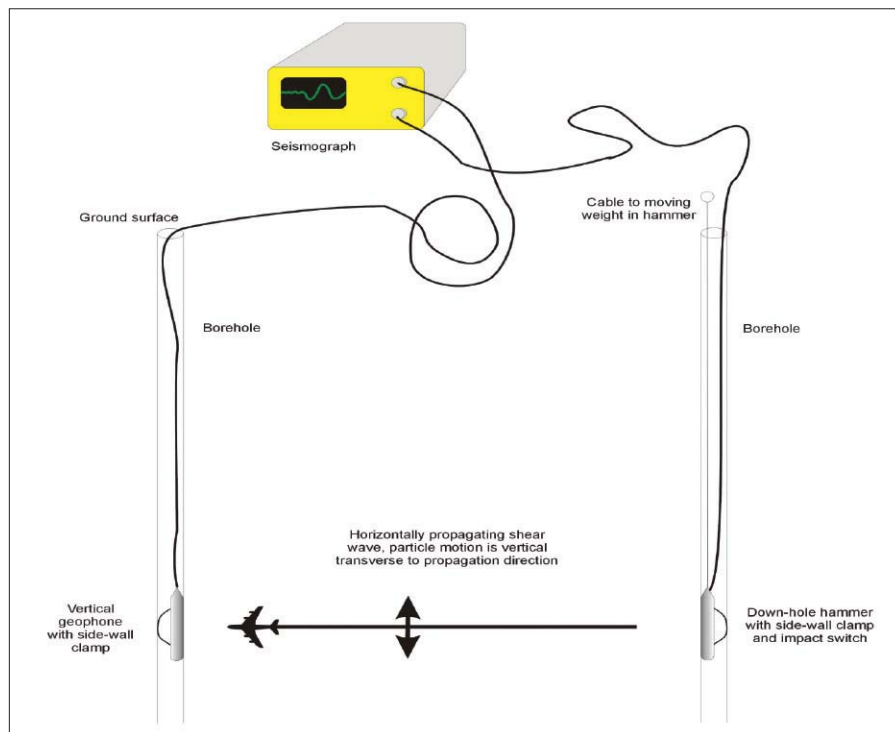


Figure 3. Method for crosshole shear-wave measurements.

of one, and the holes must be surveyed to determine the distance between them at each depth. The holes can deviate from vertical (or rather, equal spacing) by a substantial distance. A variation of 1 m in spacing between two boreholes 3 m apart is not uncommon and can make your results erroneous.

A downhole hammer, an extra piece of equipment which is not as easily available as the wooden plank, is required for a crosshole survey. 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

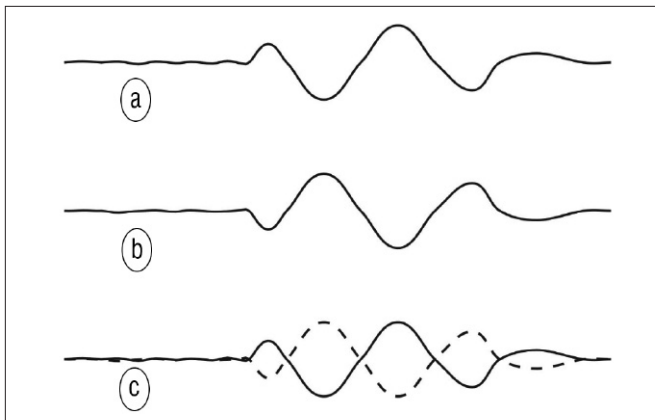


Figure 4. Shear waves reverse polarity when the energy source polarity is reversed.

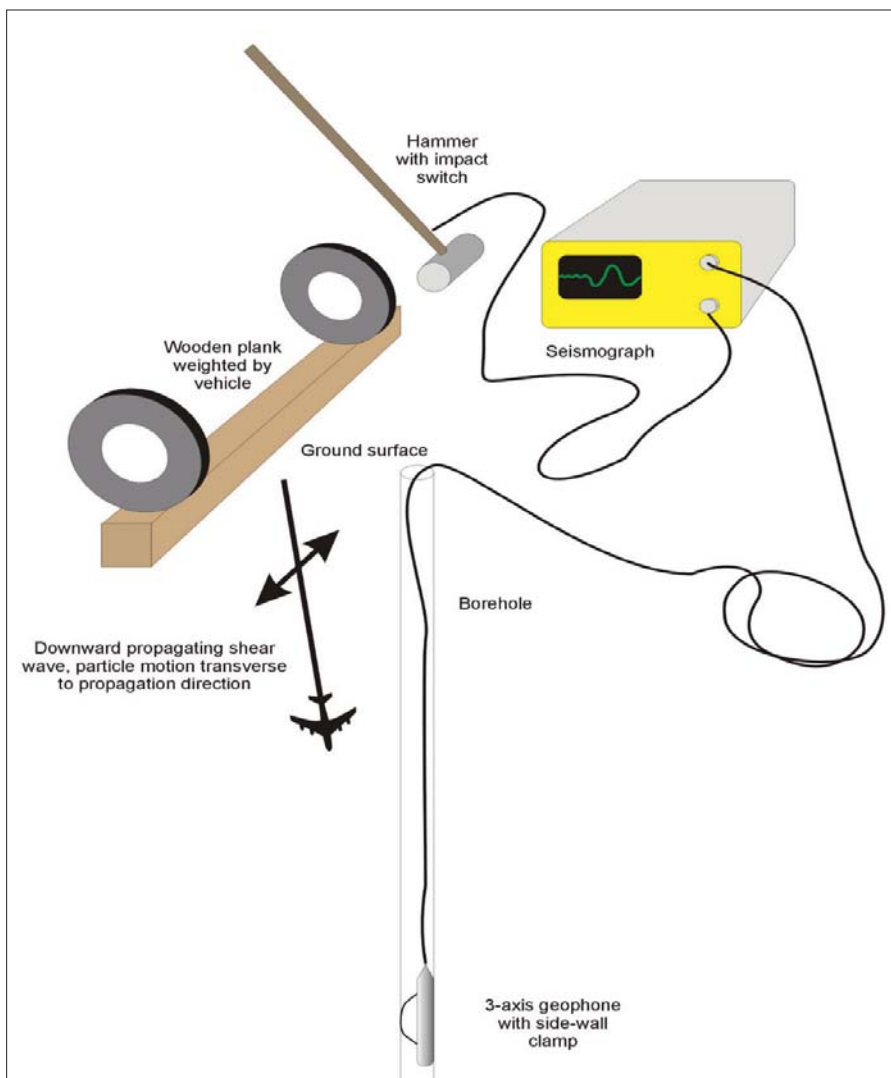


Figure 5. Downhole shear-wave configuration.

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 crosshole surveys must

be conducted with small distances between boreholes.

Downhole surveys eliminate most of these problems. Only one hole is needed, the energy source is the surface plank-hammer combination, and because 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

Analysis of the vertically 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 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.

Crosshole data are relatively simple to interpret and display, because there is only one record at each depth, and the velocity, V_s , is calculated from the arrival time and source-to-receiver separation.

In the case of downhole data, there will be two horizontal geophones that may be oriented in a random azimuth. If the geophone orientation is off the azimuth of the plank, then the shear-wave data will appear on both horizontal geophones. The worst case will still result in 70% of the waveform amplitude, and at least one will have an interpretable signal. The reverse polarity test (by recording data from the other end of the plank) must be made before the geophone is repositioned so that valid comparisons can be made.

Equipment

The seismograph. Modern exploration seismographs offer precise time synchronization with the hammer switch, fast data sampling, and summing of multiple hammer blows to allow surveys to extend to greater depths and to be successful in the presence of cul-

tural noise. Digital recording allows later playback, analysis or processing. Precise time scales allow control of the display parameters and appearance for record comparison.

Hammer. A standard sledgehammer with a transducer or closure switch is commonly used as the directional energy

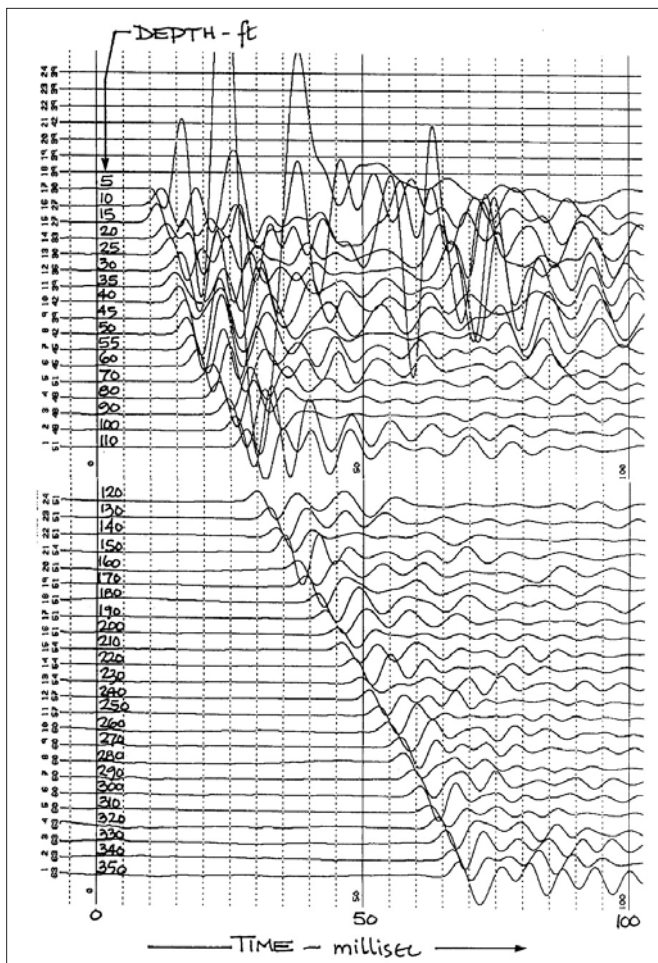


Figure 6. Composite downhole P-wave section.

source for downhole shear-wave surveys. They are available in different weights from 4 lbs (2 kg) to 20 lbs (9 kg). 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).

Downhole hammer. Crosshole surveys require a downhole 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. An impact switch or geophone is attached to the body of the downhole source 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 3-m (10-ft) separations between holes in an ASTM crosshole survey. Falling-weight hammers don't work well underwater, so wet holes must be pumped dry before the survey.

Plank. The plank can be an ordinary fence post or railroad tie. The ground is prepared by scraping the surface to expose bare, undisturbed soil providing a good friction contact.

Other types of shear-wave energy source mechanisms are possible, though few can match the simplicity and effectiveness of the weighted plank and hammer.

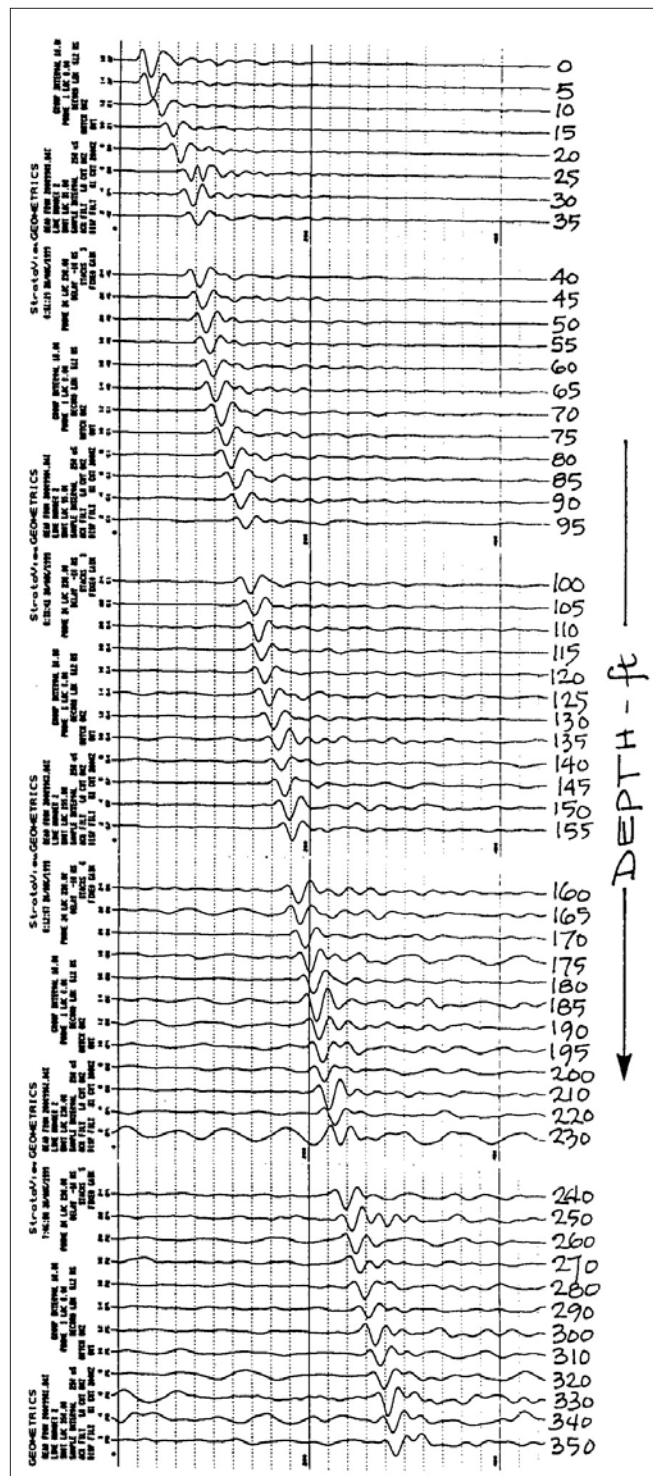


Figure 7. Composite downhole shear-wave section, in same borehole as Figure 6 (time scale was changed).

Geophones. A downhole 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, are homemade or purchased from a commercial source. The clamping device must be on just one side of the geophone so that the housing is firmly pressed directly against the wall and

must be 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 reposition, 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 downhole, three-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 reposition.

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 well unless there are washed-out segments where the tool can't make mechanical contact with the borehole wall.

Boreholes used for velocity logging in near-surface applications are usually cased with PVC pipe. The annular space must be backfilled with pea gravel or low-strength grout to ensure that the pipe transfers the motions of the adjacent soil exactly. Bad data are normally caused by bad backfilling in an otherwise properly conducted survey.

Field procedures

Crosshole surveys don't require much discussion beyond that already mentioned.

As discussed earlier, data should be collected from impacts in both directions (downhole 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.

Downhole 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 strong attenuation and even reflections when traveling through a high-impedance contrast interface, such as glacial till over limestone. Excellent data can be acquired as deep as 600 ft (200 m) or more by stacking enough hammer blows.

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 are a matter of judgment 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.

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-squares or visual straight-line fits to these segments.

The first breaks from downhole shear waves are 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 traveltime 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 (Figure 8):

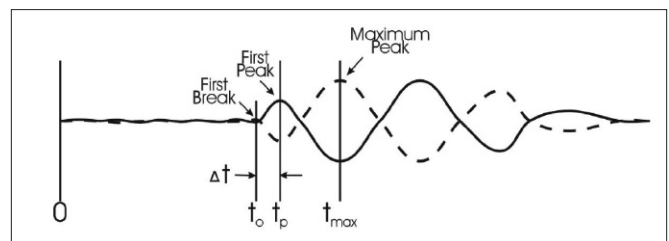


Figure 8. Procedure for cosine correction.

$$T_{\text{vert}} = t_o \cos \theta$$

$$T_{\text{vert}} = (t_p - \Delta t) \cos \theta$$

where Δt is determined from the near-surface records where the first 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 Δt , then the near-surface velocities will be too low.

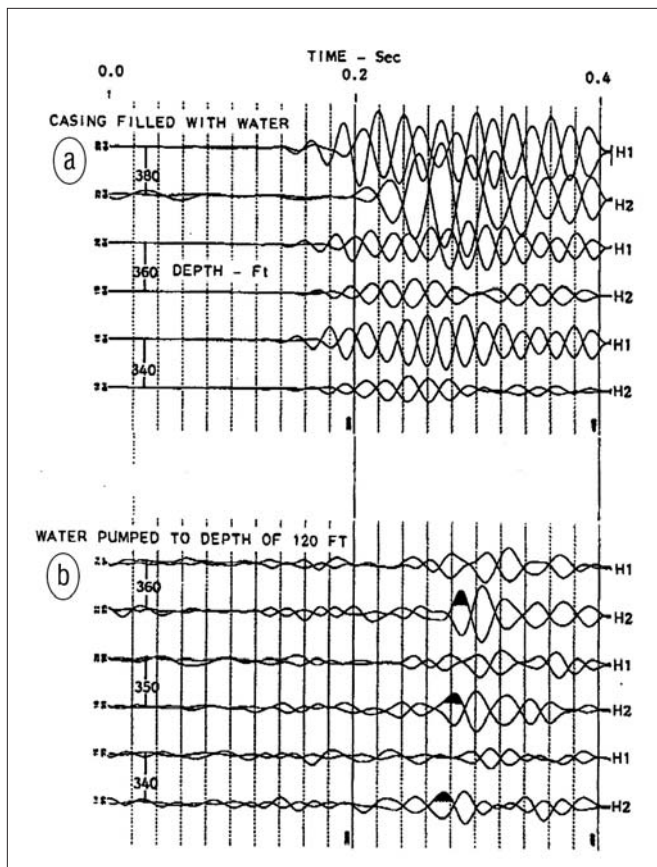


Figure 9. Comparison of tube waves in wet and dry boreholes.

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

$$T_{\text{correct}} = [(t_p - \Delta t) \cos \theta] + \Delta t$$

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 time difference in the arrivals can be more precisely measured. Because they record the vibrations from a single hammer blow, any time break 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 nonrotating mechanism such as a motorcycle chain. The near-surface interval times must still be corrected for the offset as discussed earlier.

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.

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 possible to purchase 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 9a. 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 9b shows data from the same depth as in Figure 9a with the water pumped out down to a depth of 120 ft. 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 10. The first arrivals are the P-waves. The tube waves intersect the P-waves at a depth of about 60 ft, the depth of the water inside the PVC casing.

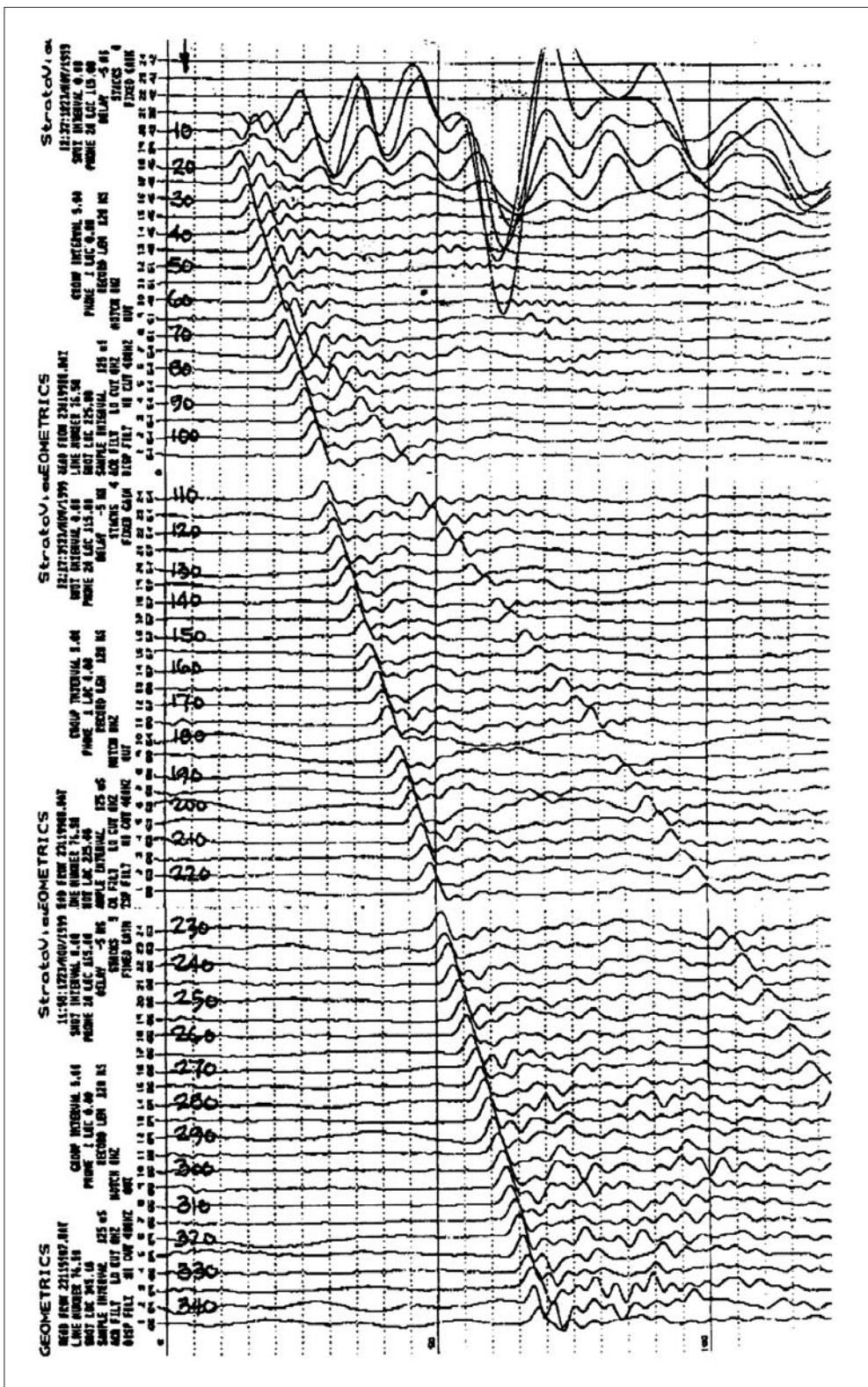
Anisotropy

Shear-wave velocities are often different in the vertical (S_v) and in the horizontal (S_h) plane. S_h 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. Anisotropy in alluvial-type deposits can be as high as 1.4X (e.g., an NS-polarized shear wave may have a velocity 40% greater than an EW polarized shear wave), although this would be exceptional. More typically 5–15% horizontal anisotropy will be observed. **TLE**

References

Imai, T., H. Fumoto, and K. Yokota, 1976, P- and S-wave Velocities in subsurface layers of ground in Japan: OYO Corporation, <http://www.oyo.co.jp/english/index.html>.

Figure 10. Composite downhole P-wave record showing tube waves.



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surveys is D7400-08 Standard Test Methods for Downhole Seismic Testing. Both can be purchased on the ASTM Web site at www.astm.org.

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