INSTRUMENTATION CORRECTIONS TO WAVE VELOCITY DATA

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The detection of the arrival of seismic stress waves for a field measurement of wave velocity requires that the incoming signal be recorded and displayed by an instrument such as a seismograph. Filters, introduced into recording circuits to limit noise or to prevent aliasing in digital recording, can have significant effects on the observed arrival times and on the computation of wave velocity. Such filtration is often not taken into account in processing the data, but the example that follows indicates how the effects can be evaluated and the data corrected by simple techniques. The properties of electronic filters are, of course, well known to electrical engineers, and the following comments are concerned with an application in which their importance has not always been appreciated by those trained in other disciplines.

FILTER CHARACTERISTICS AND EFFECTS

One widely used recorder is the Bison Model 1580, the filter of which is composed of two first-order, low-pass, Butterworth filters cascaded in series, having cutoff frequencies of 160 Hz and 89 Hz, respectively. The ratio of the output voltage to the input voltage for a unit gain first-order, low-pass, Butterworth filter is

\[
\frac{E_o}{E_i} = \frac{1}{\sqrt{1 + \left(\frac{f}{f_c}\right)^2}} \tag{1}
\]

in which \(E_o\) = output voltage amplitude; \(E_i\) = input voltage amplitude; \(f\) = signal frequency in Hertz, \(f_c\) = filter cutoff frequency in Hertz. The phase angle, \(\theta\), is given by:

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4Geologist, Stone & Webster Engrg. Corp., Cherry Hill, N.J.
Note.—Discussion open until March 1, 1982. To extend the closing date one month, a written request must be filed with the Manager of Technical and Professional Publications, ASCE. Manuscript was submitted for review for possible publication on March 11, 1981. This paper is part of the Journal of the Geotechnical Engineering Division, Proceedings of the American Society of Civil Engineers, ©ASCE, Vol. 107, No. GT10, October, 1981. ISSN 0093-6405/81/0010-1419/$01.00.
\[ \tan \theta = \frac{f}{f_c} \]  

When two such filters are cascaded in series, the solution is the product of the solutions for the individual filters. For the Bison instrument with two filters, this gives an amplitude ratio

\[ \frac{E_o}{E_i} = \frac{1}{\sqrt{\left(1 + \left(\frac{f}{89}\right)^2\right)\left(1 + \left(\frac{f}{160}\right)^2\right)}} \]  

and a combined phase angle, \( \theta \), in radians:

\[ \theta = \arctan \left(\frac{f}{89}\right) + \arctan \left(\frac{f}{160}\right) \]

The phase angle, \( \theta \), causes a time lag, \( \Delta t \), which is equal to \( \theta / (2\pi f) \). The amplitude ratio from Eq. 3 and the lag from Eq. 4 are plotted in Fig. 1. It

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**FIG. 1.—Response of Filter to Steady State Sinusoidal Input**
will be seen that with increasing frequency there is a decrease of amplitude and an increase of phase angle. Because the time lag is equal to the phase angle divided by the frequency, Δt decreases as frequency increases. The waves measured in the example given below had a predominant frequency from 100 Hz to 200 Hz. For f = 100 Hz, the phase angle is 80.3°, and the time lag is 2.23 msec.

Transient Signals.—The signals transmitted in wave velocity measurements are not simple sinusoids. However, since the system is linear, it is possible to find the solution to transient signals by means of the Duhamel integral.

A typical result is shown in Fig. 2, where the time lag can be seen clearly. The shape of the wave form and its dominant frequency were varied to obtain the values of time lag for a range of transient signals as plotted in Fig. 3, which also shows the steady state time lag for comparison. The results between 100 Hz and 200 Hz indicate that time lags from 0.8–1.2 msec can be expected.

Example.—A recent field determination of shear wave velocity by cross-hole measurements in a competent rock was performed using three borings to a depth of over 300 ft. The energy was imparted to the walls of the holes by
a Bison Model 1465 hammer. The Bison 1580 seismograph was used to record all signals. The surface configuration of the holes is shown in Fig. 4, but evaluation of verticality indicated considerable horizontal drift in the positions of the holes at depth. Corrected horizontal distances were used in all calculations.

The shear wave velocity was originally computed by assuming no time lags in the seismograph and no delay in the trigger timing. The velocity appeared to increase for longer distances (Fig. 4), a result that indicated significant time delays may have been introduced by the seismograph. Therefore, at each depth a linear regression analysis was made of the travel time versus distance from all three legs of the triangle. The results showed that the mean of the zero distance intercepts computed at all elevations was 1.0 msec with a standard deviation of 0.3 msec. These values are consistent with those predicted from the filter analysis for a transient wave of similar form to that recorded in the field.

With the mean of 1.0 msec as an additional data point for each elevation, a new linear regression analysis was performed to compute the shear wave velocity profile plotted on the right in Fig. 4. Due to the high velocity of these materials, the difference between the corrected and uncorrected velocities is large. For soil sites, the influence of a 1 msec timing delay would be less significant.

The time lags calculated in the regression analysis of the field data also contain other effects such as errors in picking wave arrivals, delays in transmitting

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**FIG. 4.—Uncorrected and Corrected Shear Wave Velocities for Rock Site**

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energy to the soil, and errors in the trigger; but in this case, filtration is the major effect. The agreement between the predicted and calculated time delay induced by the filters lends confidence to the corrected shear wave velocities in Fig. 4. The computed shear wave velocities are affected by errors in the surveys by deviations of the boreholes from the vertical, especially at depths greater than 200 ft (61 m). However, since the values of corrected shear wave velocity show the anticipated gradual increase at depths below 125 ft (38.1 m), the errors in deviation surveys at large depths would seem to be less important than the filtration effects.

Conclusions

Two basic conclusions can be drawn from this work:

1. The characteristics of instrumentation can have important effects on the results of field geophysical tests. In particular, the effects of filtration should not be ignored.
2. Regression analysis of travel time versus distance is effective in determining timing error and correcting for it.

Final Comment.—There is a widespread belief that, if one utilizes a hammer with reversible polarity, shear wave arrivals in cross-hole seismic tests can be identified unambiguously because the direction of first motion in the shear wave reverses when the direction of the impact is reversed. The direction of first motion in the P-wave is assumed not to reverse. Unfortunately, shear wave sources such as the Bison hammer also produce P-waves of opposite polarity when the direction of impact changes.

The reason that P-waves reverse polarity is that a downward excitation of the hammer causes initial compression below the level of the hammer and initial tension above it. An upward excitation reverses this pattern so the P-waves must reverse polarity. A theoretical argument is that in a linearly elastic material, the superposition of equal and opposite upward and downward excitations gives a case of no net excitation. If the P-waves do not reverse polarity, they will not cancel, and there will be energy propagated with no input.

Non-reversing P-waves may be caused by several factors, including late arrivals of reflected or refracted waves and secondary dilatational effects near the source. However, this misconception probably arises because in the down-hole test, shear wave energy is often created by striking a horizontal beam or plate on the surface in opposite horizontal directions. There is almost certainly some downward component to the blow, which does not reverse when the beam is struck in the opposite horizontal direction. This unreversed vertical load causes an unreversing P-wave, which can be observed in field data.

Acknowledgments

Valuable assistance and criticism were provided by T. S. Coughlin, J. H. Mullin, and M. Gaa of Stone & Webster Engineering Corporation.