DIGITAL FILTERING TECHNIQUES FOR INTERPRETING SEISMIC CONE DATA

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ABSTRACT: Seismic cone penetration testing (SCPT), a relatively new in situ technique, records the arrival of seismic waves generated at the surface using velocity or acceleration transducers installed in an electric piezocone. To distinguish the different seismic arrivals, instruments with fast response times are required, i.e., accelerometers. The fast response time of an accelerometer results in a very sensitive instrument with corresponding noisy time-domain characteristics. One way to separate events is to apply digital filters, which characterize the signal frequencies and then isolate frequency spectrums of interest. The digital filter introduced in this paper is based on frequency-domain filtering using cross-correlation algorithms. The cross-correlation filter concepts are synthesized by a computer program referred to as PS CrossCor, whose performance was evaluated by interpreting both synthetic and real data. Data from three sites is presented to compare the PS CrossCor and the established crossover method. The results from the analysis indicate that PS CrossCor is an accurate and reliable tool that greatly assists in determining seismic velocities, and has potential for determining other seismic parameters.

INTRODUCTION

This paper introduces a processing technique to be used for determining velocities and accuracy estimates from data obtained during seismic cone penetration testing (SCPT). This test was first investigated at the University of British Columbia (UBC) by Campanella and Robertson (1984) and Rice (1984). Rice found that the application of the technique could provide a rapid and accurate method for carrying out a downhole shear-wave velocity survey. Rice worked predominantly with geophones, which generally have a slower response time compared to an accelerometer. From his work with geophones, Rice concluded that below 20 m the strength of individual shear-wave excursions were not always identifiable.

The application of the seismic cone in situ test was later evaluated by Laing (1985). Laing arrived at the same conclusion as Rice with respect to the use of the geophone as a seismic receiver. She also states, "accelerometers tend to show a response which more closely represents the response of the soil. Thus, damping characteristics of soil should theoretically be attainable from accelerometer responses."

The dynamics behind source wavelet generation and final velocity determination is first summarized. A source, such as a hammer blow or explosive seismic cap, generates potentials at the surface that correspond to shear (i.e., SV and SH) and compression (i.e., P) waves. SV waves are polarized such that the particle motion is perpendicular to the surface of the ground, while SH waves are polarized such that the particle motion is parallel to the surface of the ground. For practical purposes, these initial potentials are usually assumed to be impulses having a broad frequency spectra.

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As these waves propagate through the earth, their frequency spectra are band limited (i.e., higher frequencies are attenuated). This is due to the earth acting as a low-pass analogue filter. At a certain depth, the generated signals are recorded with the three earth-filtered seismic waves (i.e., SV, SH, and P) and noise being superimposed. The recorded signals are difficult to analyze due to the superposition of many signals. Therefore, a digital filter is applied so one can focus on a specific wavelet (e.g., SH). Once filtering is applied, the time offset between two similar waves (e.g., SH) recorded at successive depths is determined and interval velocities are calculated.

The major contribution of this paper was to develop data handling and digital filter algorithms for automatically generating reliable estimates of the seismic velocity. These data-processing algorithms are required to give clear signals without distorting the original signal in terms of time shifts and amplitudes.

The prior technique used in estimating shear wave arrival times was the reverse polarity technique (Rice 1984), which is a visual-inspection technique and is highly susceptible to human bias. The reverse polarity technique is expanded upon later. The filtering algorithm presented in this paper (outlined later) proved to be a substantial improvement over the reverse polarity technique in that almost all human bias is removed, specific seismic events are isolated from geophone and accelerometer data, all the information in the seismic trace is used to derive velocity estimates (as opposed to one reference point in the reverse polarity technique), realistic error estimates are given, and more velocity estimates at a greater accuracy per downhole seismic profile are provided.

DESCRIPTION OF PHYSICAL PROBLEM

Details of the seismic cone, the downhole test procedures, and comparisons with crosshole results at several sites, have been described previously by Campanella et al. (1986), so that only a brief review is given here.

The seismic cone is advanced to the depth of interest using a high reactionary force such as the UBC Geotechnical Research Vehicle. Horizontally polarized shear waves (SH) were generated in the following two ways:

1. Using a hammer blow applied laterally to the pads of the research vehicle.
2. By the use of a Buffalo gun or 12-gauge shot gun fired in the ground (Pullan and MacAulay 1984).

Both methods also produce a compressional wave that can be monitored and analyzed to provide P wave velocity data. By striking the ends of the pad it is possible to generate two oppositely polarized SH wavelets. The accelerometer response is recorded on a Nicolet 4094 digital oscilloscope with CRT screen and floppy disk storage capability. Typical frequency spectra for the shear waves generated by the two sources are shown in Fig. 1.

For the hammer-beam source, the dominant shear wave response is around 50 Hz [Fig. 1(*a*)]. The point source (Buffalo gun) generates a seismic trace having a more variable spectral range with the dominant response being between 50 Hz and 200 Hz [Fig. 1(*b*)]. However, the actual frequency spectrum will depend on soil and equipment characteristics as well as wave source and test procedure. A typical complete spectrum showing P and S wave response as well as instrument resonance is shown in Fig. 2.

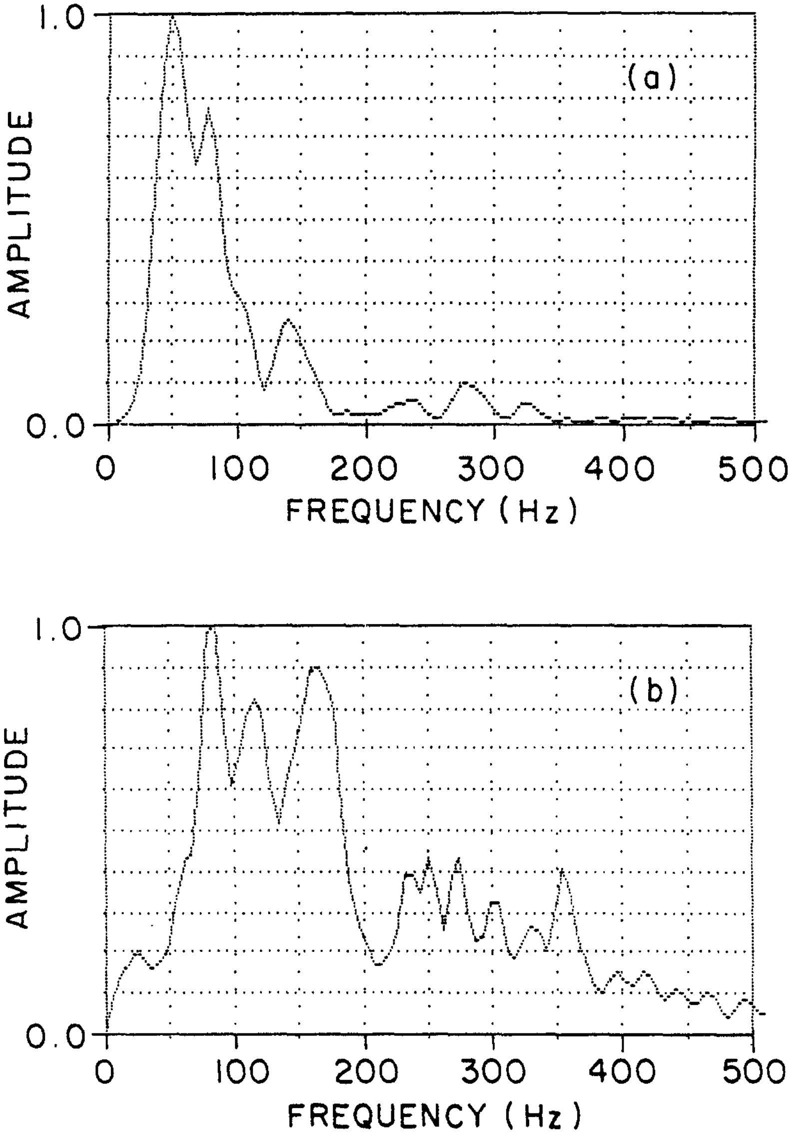


FIG. 1. Characteristics of Frequency Spectra for (*a*) Hammer-Beam Source; and (*b*) Buffalo Gun Source

Rice (1984) and Laing (1985) determined shear wave velocities using the hammer beam by the pseudo interval technique. They used the second crossover point of the two oppositely polarized SH waves at two consecutive depths. The pseudo interval technique used at UBC relates to the procedure of lowering the seismic cone at 1-m intervals and comparing arrival times, as opposed to the true interval technique, which has two receivers installed 1 m apart in the seismic cone and estimates arrivals times at each event generation. By performing downhole seismic tests at 1-m intervals, a velocity

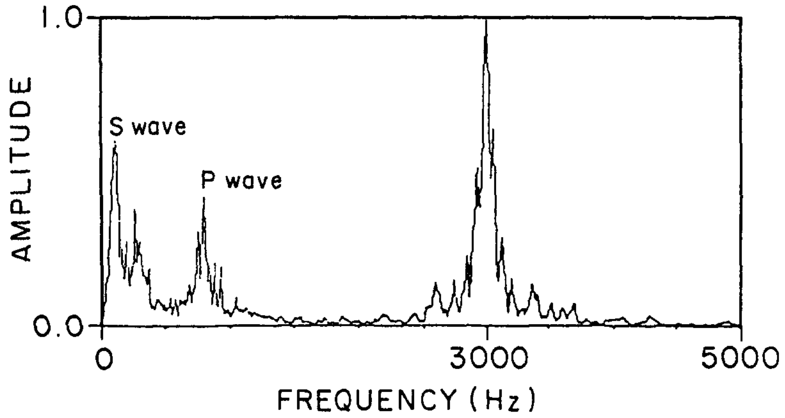


FIG. 2. Typical Frequency Spectrum from Shear Source Illustrating Accelerometer Resonance at 3000 Hz

profile can be determined. Idealized signal traces for this method of interpretation are shown in Fig. 3.

Unfortunately, not all sites present signal traces similar to those illustrated in Fig. 3. Ground response may be affected by stratigraphic conditions and velocity characteristics such that the crossover technique cannot provide arrival times for calculating wave velocities. Fig. 4 shows data obtained at the Lulu Island Pile Research (LIPR) site in the Lower Mainland, B.C., where variable low frequency noise masks the ideal response. The geotechnical properties of this site are presented later. In many cases P waves also corrupt the SH wavelet trace. The method generally used for this type of data applies an analogue low-pass filter to remove the higher frequencies. Stokoe and Hoar (1978) have suggested that this form of filtering should be minimized since it can significantly distort the true signal and lead to erroneous arrival times. Furthermore, they state that electronic filters usually introduce time delays that vary with input signal frequency and are susceptible to temperature and other environmental changes. For the trace in Fig. 4, the signals are difficult to analyze due to the superposition of many signals. Digital filtering techniques allow one to band-pass a desired frequency range without distortion and phase shift and thus can be used to focus on a specific wavelength (i.e., SH or P wave). The treated data can then be crosscorrelated using the entire waveform to determine the time offset, which provides for more reliable and consistent evaluation of interval velocity. The cross-correlation filter concepts are applied by a computer program referred to as PS CrossCor (Baziw 1988), which has been evaluated by analysis of synthetic and real data.

The results of the analysis indicate that PS CrossCor is an accurate algorithm that facilitates the interpretation of seismic data generated by the downhole method to produce reliable and consistent shear wave velocities.

DATA PROCESSING CONSIDERATIONS IN FORMULATION OF CROSS-CORRELATION FILTER FOR IN SITU DATA INTERPRETATION

In the development of the in situ data handling and interpretation algorithm, PS CrossCor, there were important aspects of digital filtering to consider. The field of digital filtering consists of a large set of mathematical

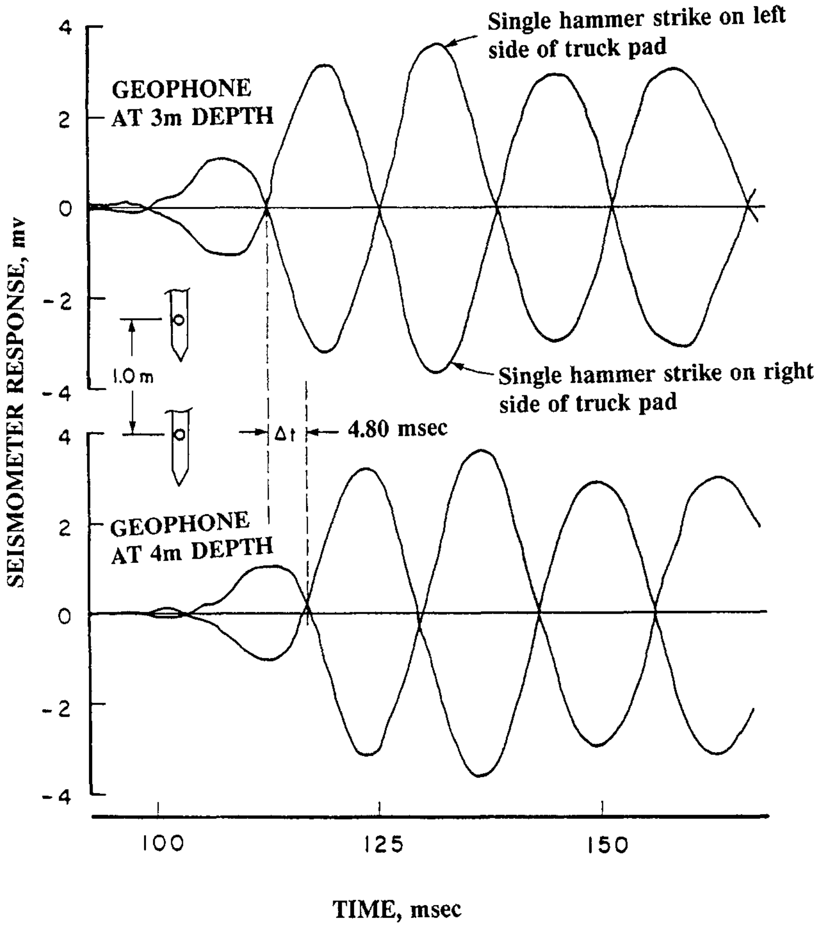


FIG. 3. **Ideal Polarized Shear Wave Signal Traces at 1-m Interval Depth Using Hammer-Beam Shear Source**

tools that must be formulated properly in order to solve the problem at hand and obtain accurate and repeatable results. Since the data to be processed consist of short bursts of high-frequency, noisy data, the cross-correlated data need to be properly conditioned. The important aspects of digital filtering to be considered in the implementation of PS CrossCor are the following: sampling rate (aliasing), Gibbs' phenomenon and Hamming window, Butterworth-type filter, bilinear Z transform, cross-correlation function, DC shift removal, error analysis, band-pass selection, and travel-path corrections.

Sampling Rate

The sampling theorem defines the minimum sampling interval over which one can apply data acquisition without losing a wavelet's identity (aliasing). In general, no information is lost by regular sampling, provided that the sampling frequency is greater than twice the highest frequency component

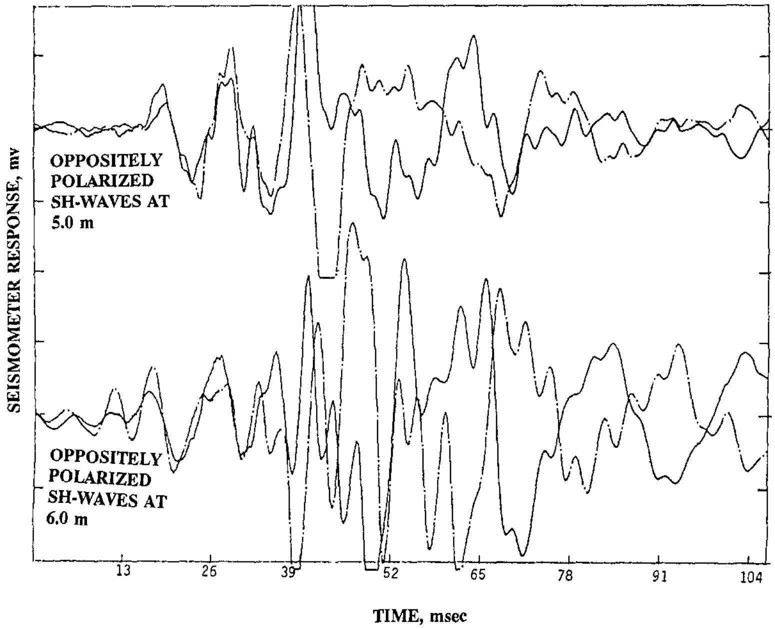


FIG. 4. Seismic Data Illustrating Difficulty in Obtaining Crossovers Due to Signals Being Masked by Many Low Frequencies

in the waveform being sampled. The data-handling algorithm must be designed to be compatible with the measured data requirements.

Gibbs' Phenomenon and Hamming Window

The Gibbs' phenomenon and Hamming window consider the distortions that occur at discontinuities that may be present within filtered signals, and can be conceptualized more readily in the time domain. A signal truncated due to a short recording time is analogous to multiplying the signal with a boxcar function in the time domain that results in distortions or "leakage" in the frequency domain. The boxcar function represents a function that has amplitude 1.0 until it reaches the end of the singles recording time, at which point the function has amplitude 0.0. As the signal recording time increases "leakage" becomes less prevalent because more information of the signal is retained. This concept is illustrated in Fig. 5(*a*), where a 100-Hz cosine signal is being multiplied with a boxcar function, which is defined as 1.0 for $0.0 \leq$ time (milliseconds) ≤ 100.0 and 0.0 for $100.0 <$ time (milliseconds). Fig. 5(*b*) illustrates the "leakage" effect in the frequency domain.

Another variable which gives rise to "leakage" is the signals sampling rate. A smaller sampling rate for a particular sampling time would decrease the "leakage" effect because more signal information would be available. If the sampling rate in the signal illustrated in Fig. 5(*a*) were decreased from 1 ms to 0.5 ms, the frequency spectrum shown in Fig. 5(*b*) would have a corresponding decrease in "leakage."

In order to minimize Gibbs' phenomenon (i.e., "leakage" effect) the data needs to be tapered. The time series can be tapered by a pair of

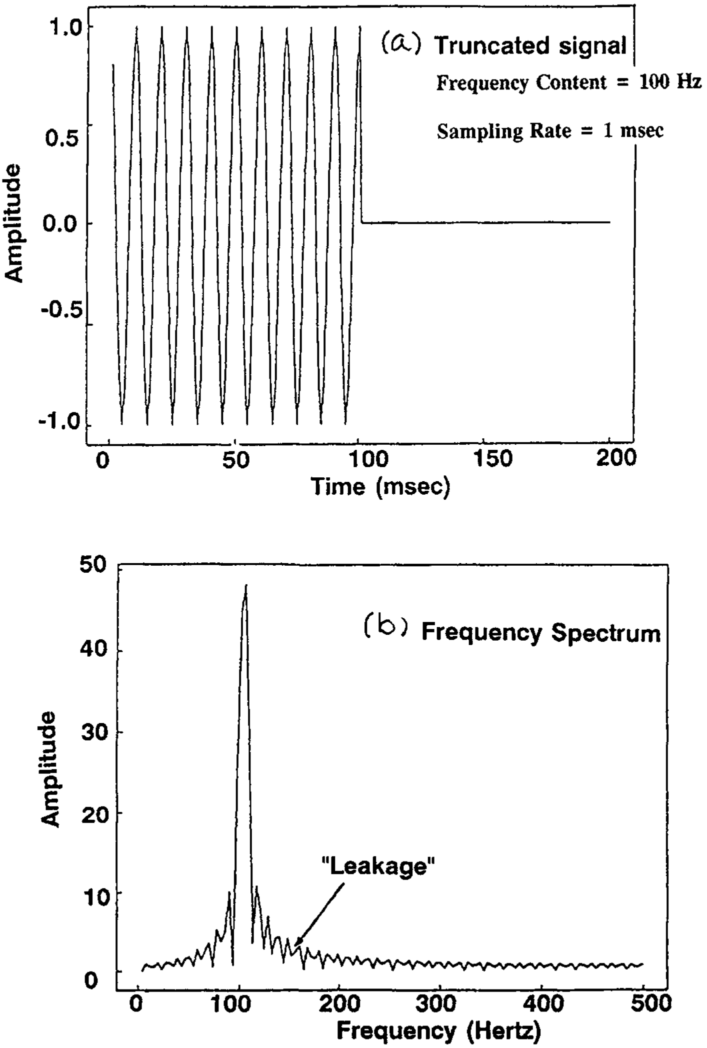
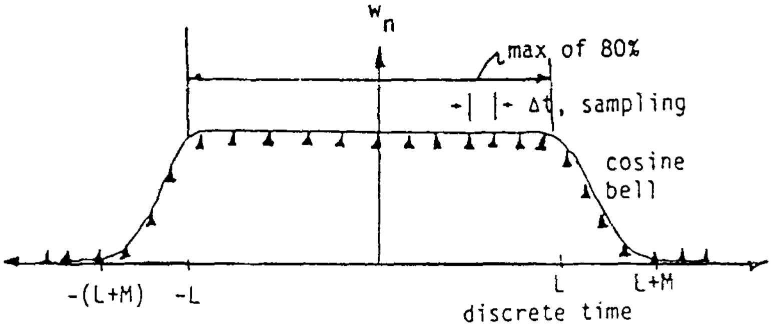


FIG. 5. Illustration of Gibbs' Phenomenon

cosine bells, where the first and last points of the trace approach the mean value of the series, which is usually zero. Fig. 6 illustrates the tapering Hamming window. The Hamming window is similar to the Hanning window, which consists of a truncated cosine wave with a DC shift as it approaches zero without discontinuities (Kanasewich 1981). Alternatively these windows are known as cosine bells. In Fig. 6, M determines the period of the cosine bell (i.e., roll-off of the window), and 2 L is 80% of the length of the time series. Hamming (1977) recommends that M be about 10% of the existing data with 80% in the flat part of the window. The data can then be padded with zeros. In this way, there are no discontinuities to initiate transients (i.e., Gibbs' phenomenon) during the Fourier transform.



M = period of cosine bells (approximately 10 percent of the existing data).

2L = 80 percent of the length of the time series.

FIG. 6. Data Window Used to Taper Discrete Function

Butterworth-Type Filter

The Butterworth Filter is a common form of a low-pass filter, and it can be defined by the expression:

$$|G(w)| = \frac{1}{\left[1 + \left(\frac{w}{w_0}\right)^{2N}\right]} \quad \text{(1a)}$$

$$w = \text{circular frequency} \quad \text{(1b)}$$

where w_0 is the "cutoff" circular frequency and N determines the sharpness of the cutoff. Characteristics of $|G(w)|$ for various values of N are shown in Fig. 7. Kanasewich (1981) states that "it is recommended that the Butterworth function, which yields an optimum filter when the signal and noise are clearly separated in bands, be used whenever simple low-pass, high-pass, or band-pass filtering is required." Since this was found to be the case in SCPT testing, the Butterworth-type filter was chosen. The advantages associated with the Butterworth Filter are as follows:

- Their transfer functions are smooth and maximally flat both inside and outside the passband.
- The squared filter (i.e., the input is filtered twice so that amplitude response is $|G(w)|^2$) produces zero shift and its power is 3 dB (factor of one-half) at the cutoff frequency. The cutoff frequency determines that half-power point of the filter.

The high-pass Butterworth-type filter is the inverse of the low-pass filter [(1)] and the band-pass filter used in this application is a combination of both the high- and low-pass filters. Referring to Fig. 7, the value of N specifies the rate of attenuation where a larger value of N gives a greater rate of attenuation and "leakage" effect and demands more computation and processing. The order of the filter (i.e., N) was chosen (from trial and

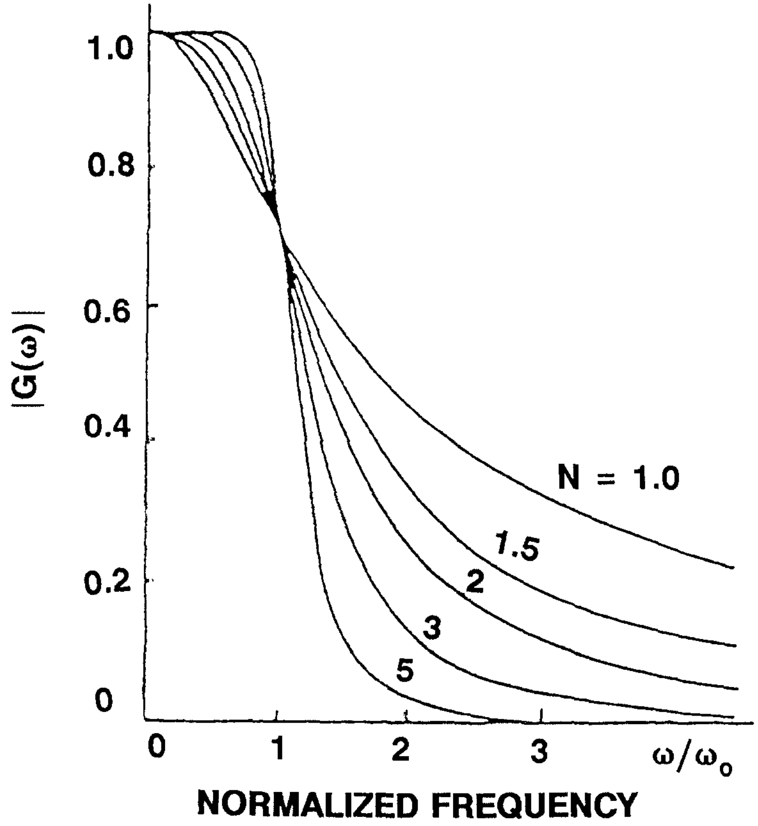


FIG. 7. Amplitude Response of Butterworth Filter

error) as four in order to optimize computation time and frequency isolation for the SCPT application.

Bilinear Z Transform

In order to use the continuous transfer function given in (1), it is first necessary to modify it so it can be used on sampled data and aliasing problems are removed. Aliasing arises when the Butterworth filter attempts to filter frequencies higher than the Nyquist frequency within the sampled data. The bilinear *Z* transform is applied to the continuous angular frequencies, *w*, in (1) in order to convert them to sampled or discrete values and keeps the highest filtered frequency component within the Nyquist frequency of the sampled data.

Cross-Correlation Function

The first step in determining the interval times, once seismic wavelets are adequately filtered, is to apply the cross-correlation function. The cross-correlation of the successively recorded wavelets is defined as

$$\Phi_{xy}(\tau) = \sum_{k} X_k Y_{k+\tau} \quad \text{.....} \quad (2)$$

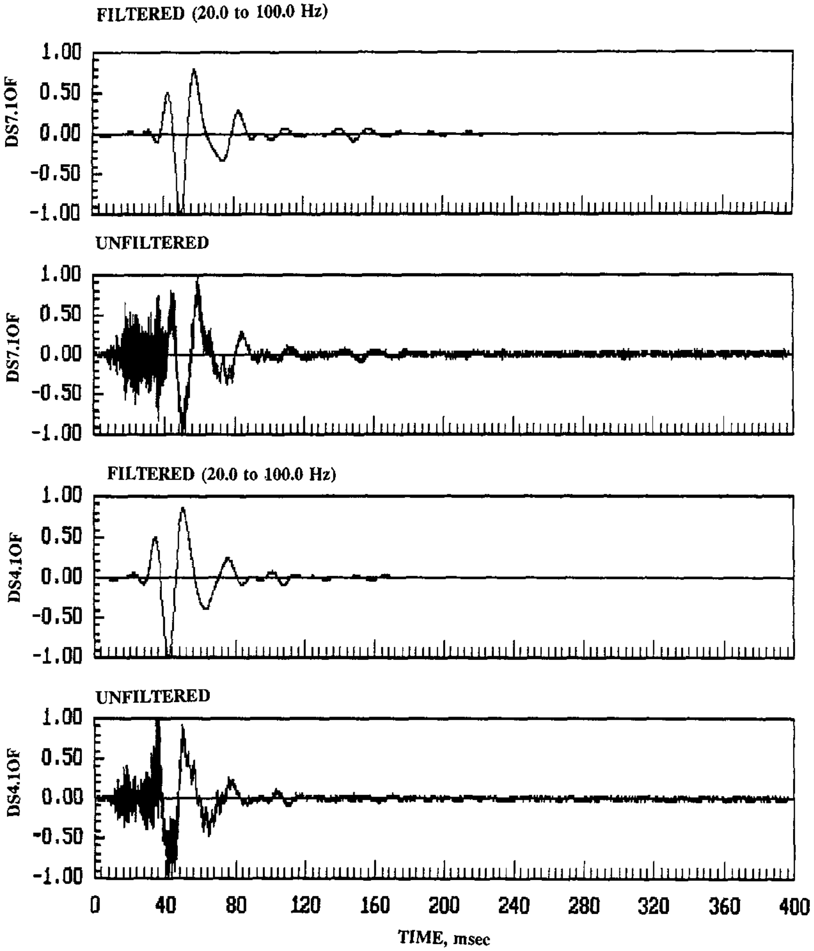


FIG. 8. Unfiltered and Filtered (20–100 Hz) Seismic Traces from Lower Langley

TABLE 1. Illustrating Frequency Band-Pass Sensitivity and Accuracy

Band-pass (Hz) (1)	Velocity (2)	Accuracy (3)
10–3,500	101.91	0.920
10–150	103.91	0.970
20–100	103.16	0.986
30–80	104.43	0.992
40–70	104.43	0.998

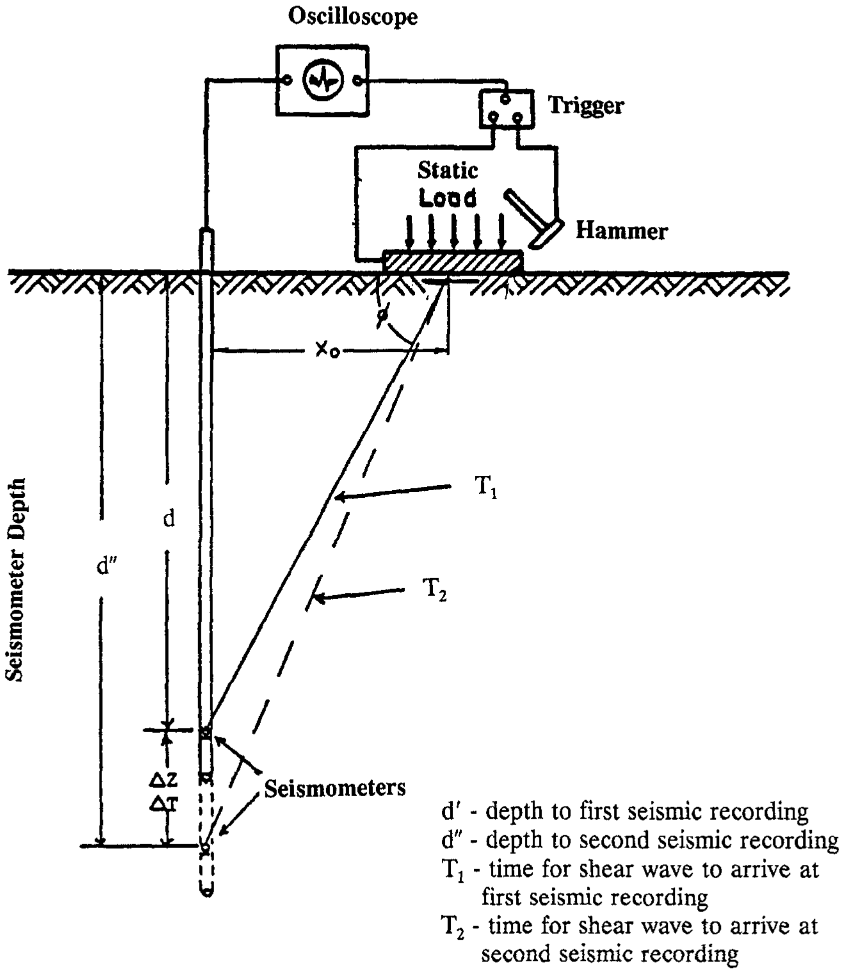


FIG. 9. Schematic of Seismic Transmission Profile, Illustrating Travel-Time Corrections

where $\Phi_{xy}(\tau)$ = the cross-correlation function; Y_k = the sampled data at depth 1, at sample time k; X_k = the sampled data at depth 2, at sample time k; and τ = the time shift between the two sets of recorded wavelets.

The cross-correlation provides information between the wavelets. In this case we are looking for the arrival time differences between the dominant responses of the recorded wavelets. With this consideration, when the value of Φ in (2) is maximum, we have a time shift that is representative of the time interval ΔT between successive wavelets.

As stated previously, τ = the value that represents the difference in the arrival times of the wavelets. Therefore, their cross-correlation amplitude, Φ, is maximum at the best arrival time difference, τ.

DC Shifts

An important aspect to consider when applying crosscorrelations to seismic wavelets is DC shift. DC shift occurs when the recorded signal is not centered

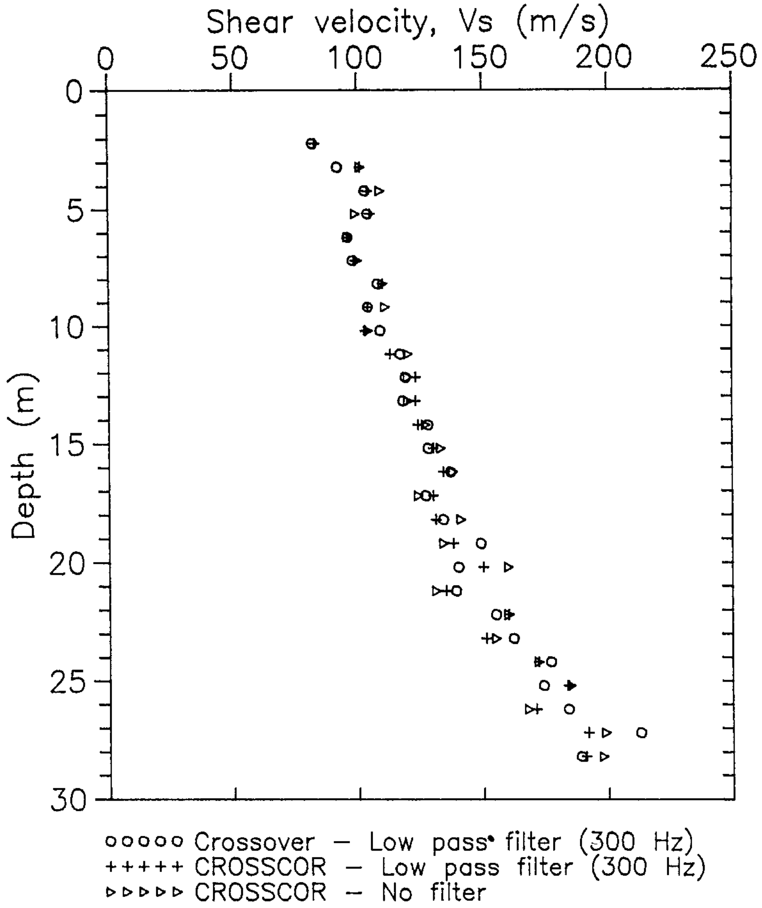


FIG. 10. Velocity Profile from Lower 232 Street Site Comparing Filtered and Unfiltered Seismic Data Generated Using Hammer-Beam Source

at zero mean. By manipulating (2) the DC shift can be illustrated. An offset can be represented by shifting one signal relative to the other, that is $X'_k = X_k + C$ where C is an arbitrary constant. In this case (2) becomes

$$\Phi_{xy}(\tau)' = \sum_k X'_k Y_{k+\tau} = \sum_k (X_k + C)Y_{k+\tau} \quad (3a)$$

$$\Phi_{xy}(\tau)' = \Phi_{xy}(\tau) + \sum_k CY_{k+\tau} \quad (3b)$$

Eq. (3) clearly shows that the DC shift would result in a misrepresentative cross-correlation value.

Error Analysis and Band-Pass Selection

A quantitative indicator of the statistical relation between the seismic signals at depths 1 and 2 is given by the cross-correlation coefficient. The cross-correlation coefficient is calculated by dividing the maximum correlation value,

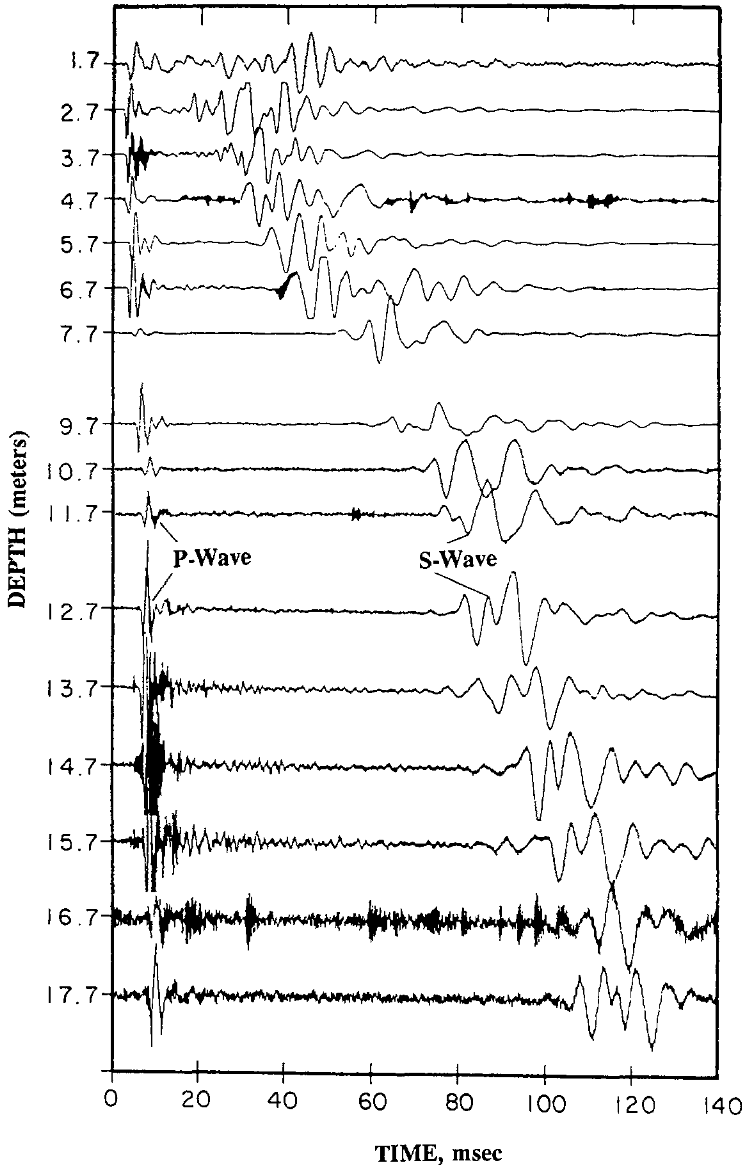


FIG. 11. Seismic Section from Lower 232 Street Using Point Source and Unfiltered Accelerometer

Φ_{max}, determined by (2), by the standard deviation of the two isolated wavelets at depths 1 and 2. This statistical parameter is used as an indicator of the accuracy of the calculated velocity estimated by the method proposed in this paper. The cross-correlation coefficient ranges in value from 0.0 to 1.0. A value of 0.0 would indicate that the waveforms are not correlated at all and any velocity estimated from these signals would be unreliable. A value near

TABLE 2. Comparison of Shear Wave Velocities at Lower 232 Street Site from Two Different Sources (Data from Fig. 11)

Average depth (m) (1)	V_s (m/s) from PS CrossCor Hammer beam (2)	 Buffalo gun (3)
3.2	101	106
4.2	109	94
5.2	99	90
6.2	96	96
11.2	120	114
12.2	120	120
13.2	120	101
14.2	127	108
15.2	133	155
16.2	138	133
17.2	124	122
18.2	141	165

1.0 would indicate that these signals are highly correlated and any velocity derived from these signals would be highly accurate.

Possible signal-processing errors such as frequencies selected for the band-pass filter, DC shift values, frequency content of the noise and signal to noise ratio are reflected in the cross-correlation coefficient. For instance, a signal with a high DC shift or low signal-to-noise ratio would have an increased standard deviation thus decreasing the coefficient value. The sensitivity of the frequency band-pass selected is determined by selecting band-pass frequencies and calculating corresponding changes in cross-correlation coefficient and velocity estimates.

When selecting the band-pass frequencies, one must consider that the shear and compression body waves are identified by their own band of frequencies as was illustrated in Fig. 1. From the extensive amount of seismic data processed in this research, it was found that in specifying the bandwidth in filtering the most important considerations are the following:

1. Include sufficient dominant frequencies characterizing wavelet, because too narrow a bandpass will remove wavelet characterizing frequencies, while too large a bandpass will include noise and other body wave frequencies.
2. The bandwidths specified must be consistent throughout the seismic profile in order that the cross-correlated dominant responses are similar in transient response specifications.

These discussions can be conceptualized by processing the seismic traces illustrated in Fig. 8. This data is from the Lower 232 Street site in Langley, B.C., whose geotechnical properties are presented later. Fig. 1 illustrated a typical frequency spectrum from the Lower Langley site, where the dominant shear wave response is identified at 50 Hz. Table 1 summarizes bandwidths and corresponding velocity and accuracy estimates. Referring to Table 1, it is noted that when a large bandwidth is applied (i.e., 10–3,500 Hz) the signal-to-noise ratio and accuracy are decreased. As one narrows on the dominant 50-Hz signal, the corresponding accuracy is increased and velocity estimate becomes consistent. Table 1 illustrates that when the band-

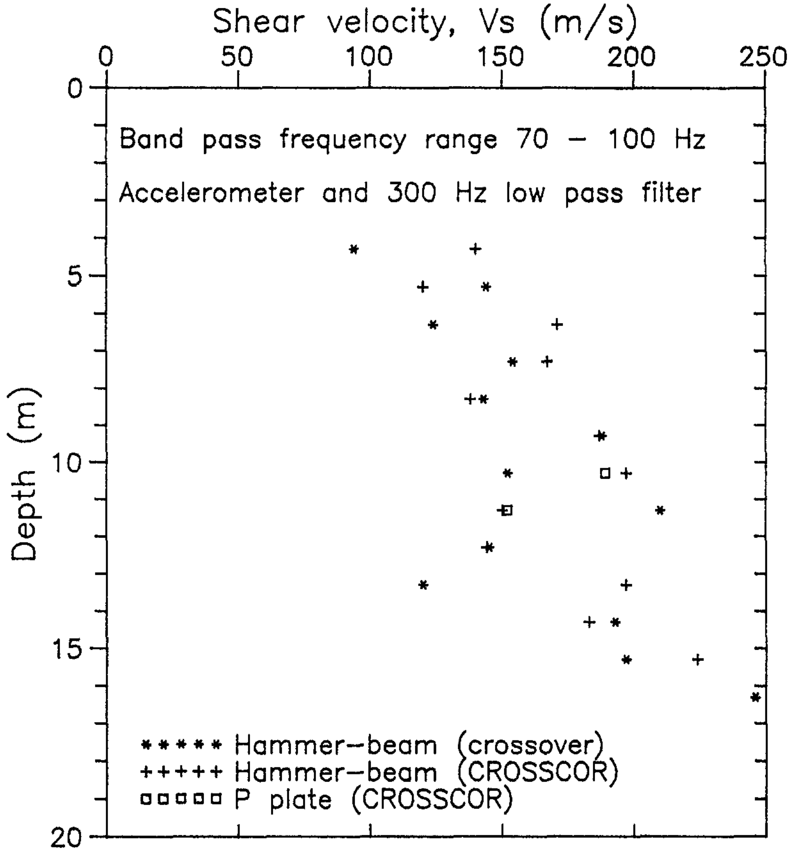


FIG. 12. Velocity Profile from Laing Bridge South Site

width is narrowed from 30–80 Hz to 40–70 Hz, the velocity estimate is repeatable and accuracy is the greatest at 0.998.

Travel Path Corrections

As stated previously, the seismic cone test records wavelets at 1-m interval depths. The wavelet is generated at the surface by a hammer blow or a seismic cap and received at the cone with either a geophone or an accelerometer. Fig. 9 illustrates the seismic cone transmission profile. In order to calculate accurate seismic velocities, it is necessary to make travel path corrections. Referring to Fig. 9, the seismic velocity is calculated as follows:

$$V = \frac{d''_{\text{corr}} - d'_{\text{corr}}}{T_2 - T_1}$$

where

$$d''_{\text{corr}} = \sqrt{x^2 + d''^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4a)$$

$$d'_{\text{corr}} = \sqrt{x^2 + d'^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4b)$$

and d', d'', T_1 and T_2 are defined in Fig. 9.

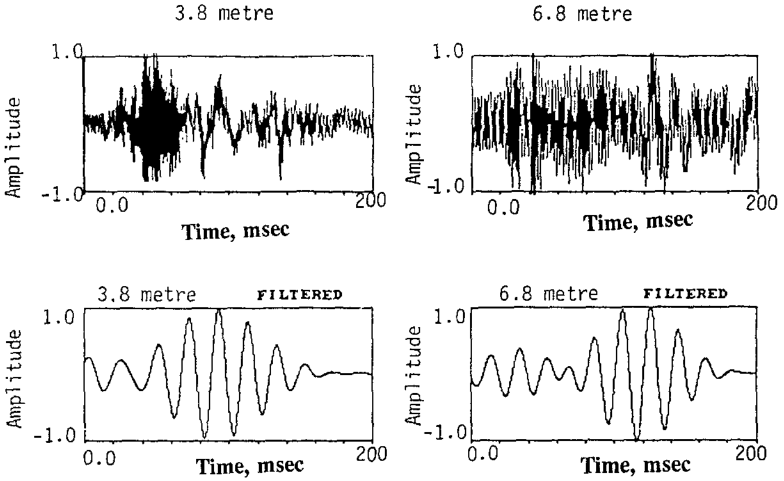


FIG. 13. Seismic Traces from Laing Bridge from Depths of 3.8 and 6.8 m; These Wavelets Are then Filtered with Bandpass of 80–120 Hz in Order to Extract Shear Wave

Proposed Algorithm

The procedure in obtaining the desired velocity profile can thus be summarized as follows:

1. Record in situ seismic data.
2. Remove any DC shifts in the recorded data.
3. Taper time-domain data with cosine bells.
4. Apply FFT to obtain frequency spectra.
5. Pick frequencies to be filtered (low and high in the passband).
6. Take inverse FFT.
7. Apply Butterworth-type filter.
8. Calculate cross-correlation coefficient of filtered time-domain signals; if not satisfied go to item 5, else continue.
9. From Φ_{max} determine the time offset, ΔT, between recorded data 1 m apart.
10. Make travel path, Δd, corrections to account for source location from receiver.
11. Compute velocities, $V = \Delta d/\Delta T$, at 1-m intervals throughout profile.

The program PS CrossCor was developed to perform these steps. PS CrossCor is a graphics interative IBM PC-compatible program that displays the frequency spectra, unfiltered and filtered traces, cross-correlation functions, and is driven by menus and windows. The performance of this algorithm using field data is discussed in the next section.

PERFORMANCE OF PROCESSING TECHNIQUE WITH FIELD DATA

The PS CrossCor in situ data-processing technique using the previously outlined bandwidth-selection method and error analysis has been evaluated using data from several of the UBC research sites. Results obtained at the

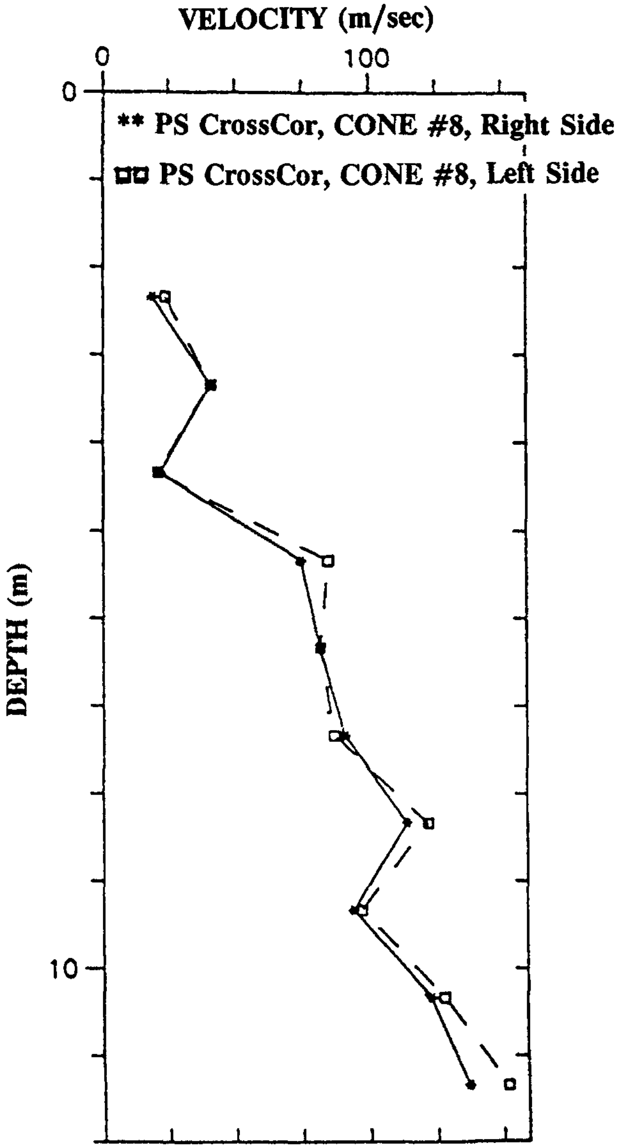


FIG. 14. Velocity Profile from LIBR Site, Where Velocities from Both Sides of Hydraulic Pads of Hammer Shear Source Are Compared

Lower 232 Street site in Langley, B.C., are presented here as they represent the most comprehensive seismic cone investigation performed to date (Baziw et al. 1989). The signal traces recorded are of very good quality and allow a comparison to be made between the crossover-interval time (reverse polarity method [RPM]) and that obtained by analyzing the time series data with PS CrossCor. Both filtered (analogue) and unfiltered reverse polarized shear waves generated by hammer blows to the truck pads were obtained.

In addition, a point source (Buffalo gun) was employed allowing both SH and P wave velocities to be evaluated (for this type of seismic data, the crossover technique cannot be applied since a single polarized signal is used). To illustrate the problems associated with the crossover technique when signal and instrument noise are present, additional data from the Laing Bridge South (LBS) site and Lulu Island Pile Research (LIPR) site are also presented and discussed.

The geotechnical characteristics of the soil at the Lower 232 Street site are those of a normally consolidated moderately sensitive marine clay with sand and silt interbedding (Campanella et al. 1989). The profile of shear wave velocity with depth generated by the hammer source is shown in Fig. 10, which compares RPM and the PS CrossCor evaluation, resulting in the following mean and standard deviation:

$$\frac{V_s\ (\text{PS CrossCor})}{V_s\ (\text{RPM})} = 0.999 \pm 0.045 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

As mentioned previously, since PS CrossCor correlates the complete signals rather than a single crossover point, it provides better estimates of the wave velocity. Only where excellent noise-free data is available can similar reliability result using the crossover or reverse polarity method, as is the case of Lower 232 Street site data. Also shown on this figure is the velocity profile obtained when no low-pass filter is used. All three profiles are remarkably consistent.

Fig. 11 shows a seismic wave profile obtained using the point source and an unfiltered accelerometer. It is possible to distinguish between the P and S wave arrivals. The PS CrossCor comparison between the shear wave velocities obtained from the hammer and point sources gives (Table 2):

$$\frac{V_s\ (\text{hammer})}{V_s\ (\text{Buffalo gun})} = 1.03 \pm 0.11 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

The scatter in data is relatively large compared to that given in (5) and has been traced to errors in the trigger mechanism. The trigger for the point source has subsequently been redesigned to avoid this problem in the future. Comparison of the Lower 232 Street site data suggest that the digital filtering techniques gives results in agreement with the crossover method. As outlined previously, noisy measurement data makes velocity determination by the crossover method difficult or impossible.

The data obtained at the Laing Bridge site illustrates the problem with the crossover method. Laing Bridge is located at the eastern end of Sea Island adjacent to Laing Bridge approach fill at Grant McConachie Way in Richmond, B.C. This site is located next to overpass embankments where extensive research has been conducted by Le Clair (1988) into predicting settlements. A typical stratigraphic profile of the Laing Bridge site is: 0–2 m extraneous soil, top soil, and silty clay; 2–20 m medium dense to very dense sands; 20–60 m normally consolidated clayey silt.

Fig. 12 compares two sets of velocity determinations from the Laing Bridge South site. Noticeable differences in the calculated velocities occur at depths of 6.3 m, 10.3 m, 11.3 m, and 13.3 m due to the fact it was not possible to determine consistent crossover points at the mentioned depths because of signal noise. It is more certain that the PS CrossCor analysis yielded the correct velocities especially since the hammer results agreed with the P-plate source (i.e., impact on surface plate) at depths of 10.3 and 11.3

m in Fig. 12. Fig. 13 illustrates seismic traces obtained from the P-plate source. From this figure, the difficulty in obtaining a crossover point is clearly illustrated. On the other hand, the filtered signals (80–120 Hz) show clean signals with the shear wave responses being prevalent.

The data from Lulu Island Pile Research site, where a noisy signal exists, further illustrates the difficulty of making velocity determination by the crossover method. The LIPR site is located on the extreme east end of Lulu Island, which is part of the Fraser River delta deposits in B.C. This research has been extensively investigated for geotechnical and geological parameters by Davies (1987). The surficial geology of the Lulu Island region is typical of a river deltaic deposit (i.e., deltaic distributary channel fill and marine sediments). The LIPR site has the following typical stratigraphy: 0–2 m sand fill; 2–15 m soft organic silty clay; 15–28 m medium dense sand with minor clay lenses; and 28–60 m normally consolidated clayey silt with thin sand layers.

At the LIPR site it was not possible to determine crossover points, as was illustrated in Fig. 4, because of noisy measurement traces recorded. These seismologically complex traces are most likely a result of the contrasting soil profile (i.e., resulting in reverberations and ground roll), fairly high attenuation characteristics of a soft organic silty clay, and sensitivity of the accelerometer (i.e., it magnifies any noise present). The profile of shear wave velocity with depth (generated from the hammer source) for LIPR site obtained using PS CrossCor is shown in Fig. 14. Two sets of velocity calculations are generated by analyzing data generated from both sides of the Hammer-Beam shear source (i.e., right and left). This allowed for greater confidence in the shear wave velocities obtained. Both profiles are remarkably consistent. The low shear wave velocities correspond to the previously researched geotechnical characteristics of the LIPR site.

CONCLUSIONS

The accurate determination of arrival times from in situ seismic time series is paramount to the evaluation of reliable shear wave velocities, V_s. Furthermore, since the shear wave velocity is squared to obtain the small strain shear modulus, G_0, small variations in V_s can result in appreciable errors in G_0, i.e.:

$$G_0 = \rho V_s^2 \quad \text{(7)}$$

where ρ = the mass density of soil profile under consideration.

The use of digital filtering techniques such as those implemented in the program PS CrossCor can reduce the sources of possible error and provide reliable and accurate velocity determination for both shear and compression wave sources. The performance of PS CrossCor is summarized in the following list of advantages with comparisons made to the crossover or reverse polarity method.

1. The PS CrossCor technique is capable of handling noisy accelerometer data to extract shear and compression wave information.
2. The cross-correlation function in PS CrossCor makes use of more information in the measured signals (e.g., averaging out irregularities and putting significance on dominant responses) as opposed to the reverse polarity method, which relies only on one crossover point to determine interval times.

3. The PS CrossCor technique works as well as the reverse polarity method when reducing clean signals, and PS CrossCor works better than the reverse polarity method with signals containing many dominant low frequencies (e.g., Fig. 4).

4. The PS CrossCor technique can obtain velocity estimates from nonpolarized sources (e.g., the Buffalo gun source and comparing one side of the hammer source to the other). Thus, PS CrossCor has greater flexibility than the reverse polarity method in working with different types of sources and giving more velocity estimates for a downhole seismic profile than the reverse polarity method. This characteristic of PS CrossCor would be especially effective in offshore seismic studies.

5. A very important advantage is that PS CrossCor considerably reduces human bias in determining velocity estimates.

6. The PS CrossCor technique can be used to give immediate results in the field; this prevents costly testing errors in cases where the data collection instruments have not been correctly calibrated or have defects.

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