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Interpretation of seismic cone data using digital filtering techniques

Interprétation des données sismiques du pénétromètre utilisant des techniques digitales de filtration

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SYNOPSIS: 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 (Campanella & Robertson, 1984). To distinguish between different arrivals, instruments with fast response times are required , i.e., accelerometers. This sensitivity generally corresponds to noisy time domain characteristics. One method of separating the events is to characterize the signal frequencies and remove unwanted "noise." Digital filtering is ideal for this application and is a new and exciting approach in analyzing in situ SCPT data. A crosscorrelation program P-S CROSSCOR, is described which allows accurate and reliable velocity determinations for both polarized and nonpolarized waves. P-S CROSSCOR has been evaluated using both synthetic and real data. Data from two sites is presented to compare the P-S CROSSCOR and crossover methods.

1 INTRODUCTION

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) and only a brief review is given here.

The seismic cone is advanced to the depth of interest using the UBC geotechnical research vehicle. Horizontally polarized shear waves (SH) were generated in two ways: using a hammer blow applied laterally to the pads of the truck and by the use of a Buffalo gun or 12 gauge shot gun shell fired in the ground (Pullan and MacAulay, 1984). Both methods also produce a compressional wave which 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. The 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. 1a). 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. 1b). 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.

Shear wave velocities using the hammer beam were determined by the pseudo interval technique using the second crossover point of the two oppositely polarized SH waves at two consecutive depths (Rice, 1984; Laing, 1985). By performing downhole seismic tests at one meter intervals, a velocity profile can be determined. Ideal signal traces for this method of interpretation are shown in Fig. 3.

Unfortunately, not all sites present signal

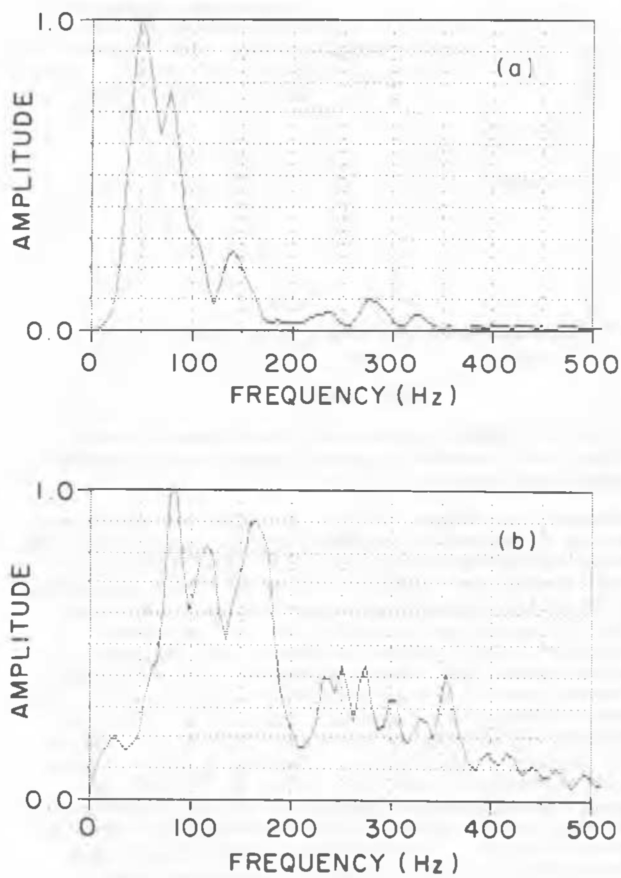

Figure 1. Characteristics of frequency spectra for (a) hammer-beam source, and (b) point source

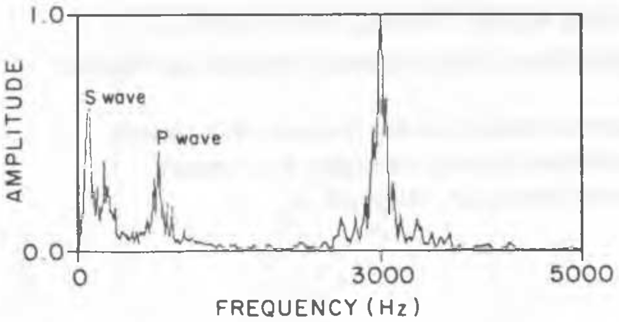

Figure 2. Typical frequency spectrum from shear source illustrating accelerometer resonance at 3000 Hz

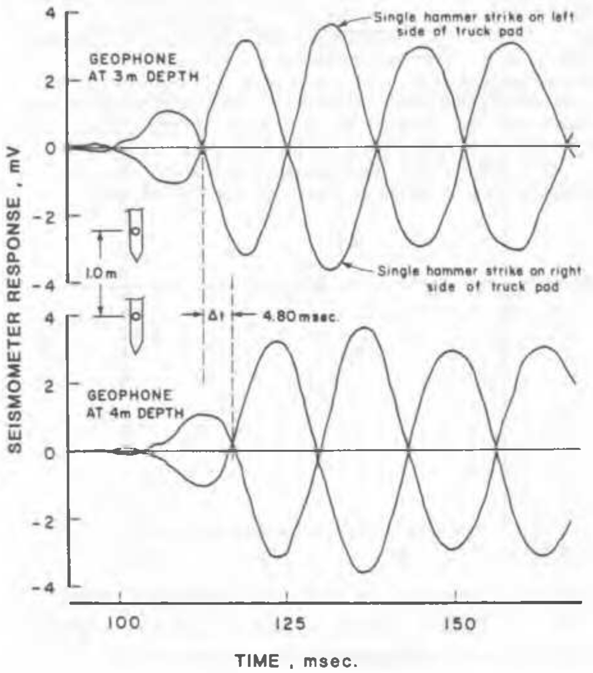

Figure 3. Ideal polarized shear wave signal traces at 1 meter interval depth using hammer-beam shear source

traces like those in Fig. 3. Ground response may be affected by stratigraphic conditions and velocity characteristics such that the cross-over technique cannot provide arrival times for calculating wave velocities. Figure 4 shows data obtained at a sand site in the Lower Mainland, B.C. where variable low frequency noise masks the ideal response. 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 & 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 which vary with input signal frequency. 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 wavelet, 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 a more reliable and consistent evaluation of internal velocity. The crosscorrelation filter concepts are applied by a program referred to as P-S CROSSCOR (Baziw, 1988) which has been evaluated by analysis of synthetic and real data. The results of the analysis indicate that P-S CROSSCOR is an accurate algorithm which facilitates the interpretation of seismic data generated by the downhole method to produce reliable and consistent shear wave velocities.

2 FORMULATION OF CROSSCORRELATION FILTER

The relevant aspects of the digital filtering employed in the P-S CROSSCOR program will be very briefly reviewed. A detailed discussion of the program and its important aspects are presented by Baziw (1988). In essence, the procedure followed to obtain the required seismic velocity can be summarized as follows:

- record in situ downhole seismic data at two depths for crosscorrelating
- using the average of the integrated waveform, remove any d.c. shift from records to avoid erroneous interval time estimation
- taper time domain data to eliminate discontinuities in records and possibly "ringing" in frequency domain
- apply Fast Fourier Transform (FFT) to obtain frequency spectra
- pick frequency range to be passed for enhancement of wavelet to be analyzed
- apply Butterworth type filter (band-pass). The advantage of using this type of filter is that the treated signal does not undergo a phase shift and the transfer functions are smooth
- take inverse FFT
- crosscorrelate filtered time-domain signals
- determine time offset to obtain travel time over internal depth
- determine seismic wave (SH or P) velocity.

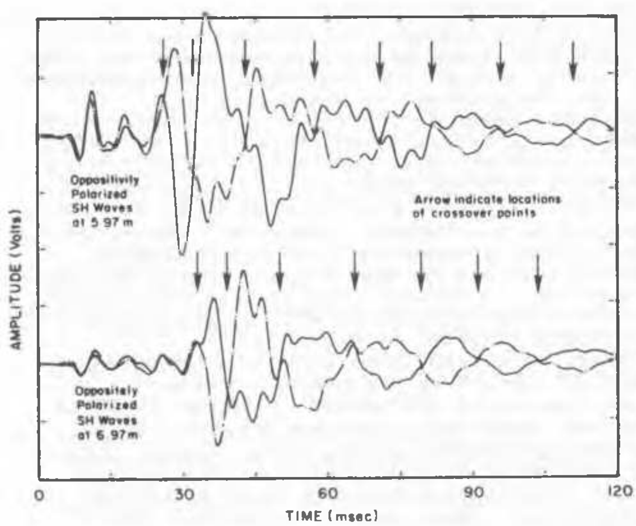

Figure 4. Seismic data illustrating difficulty of obtaining crossovers due to signal noise

3 FIELD PROGRAM AND RESULTS

The P-S CROSSCOR technique has been evaluated using data at several of the UBC research sites. Results obtained at Lower 232 Street in Langley, B.C. are presented here as they represent the most comprehensive seismic cone investigation performed to date. The signal traces recorded are of very good quality and allow a comparison to be made between the crossover interval time (reverse polarity method) and that obtained by analyzing the time series data with P-S 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 noise exists, additional data from the Laing Bridge South (LBS) site is 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 (1988).

The profile of shear wave velocity with depth (generated by the hammer source) for Lower 232 Street is shown in Fig. 5, which compares velocities from the reverse polarity method (RPM) and the P-S CROSSCOR evaluation, resulting in the following mean and standard deviation:

$$\frac{V_s \text{ (P-S CROSSCOR)}}{V_s \text{ (RPM)}} = 0.999 \pm 0.046 \qquad (1)$$

As mentioned previously, since P-S 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 of reverse polarity method, as in the case of Lower 232 Street. Also shown on the figure is the velocity profile obtained when no low-pass filter is used. All three profiles are remarkably consistent.

Figure 6 shows the seismic waves obtained using the point source and an unfiltered accelerometer. It is possible to clearly distinguish between the P and S wave arrivals. The P-S CROSSCOR comparison between the shear wave velocities obtained from the hammer and point sources gives (Table 1):

$$\frac{V_s \text{ (Hammer)}}{V_s \text{ (Buffalo gun)}} = 1.03 \pm 0.11 \qquad (2)$$

The scatter in the data is relatively large compared to that in (1) and has since 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 data suggests that the crosscorrelation program gives results in agreement with the crossover method. As outlined previously, a noisy signal may make velocity determination by the crossover method difficult. The data obtained at the Laing Bridge South site illustrates this problem in Fig. 7 which compares the two sets of velocity determinations. Noticeable differences in the calculated velocities occur at depths of 6.3 m, 10.3 m, 11.3 m and 13.1 m due to the fact that it was not possible to determine consistent crossover points at the mentioned depths because of signal noise. It is believed that the P-S CROSSCOR analysis yielded the correct velocities especially since the hammer beam results agreed with the P-plate source (impact on surface plate) at depths of 10.3 and 11.3 m in Fig. 7.

Table 1. Comparison of shear wave velocities at Lower 232 Street from two different sources (Data from Fig. 6)

Average Depth (m)	V_s (m/s) from P-S CROSSCOR	
	Hammer-beam	Buffalo gun
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
19.2	134	114

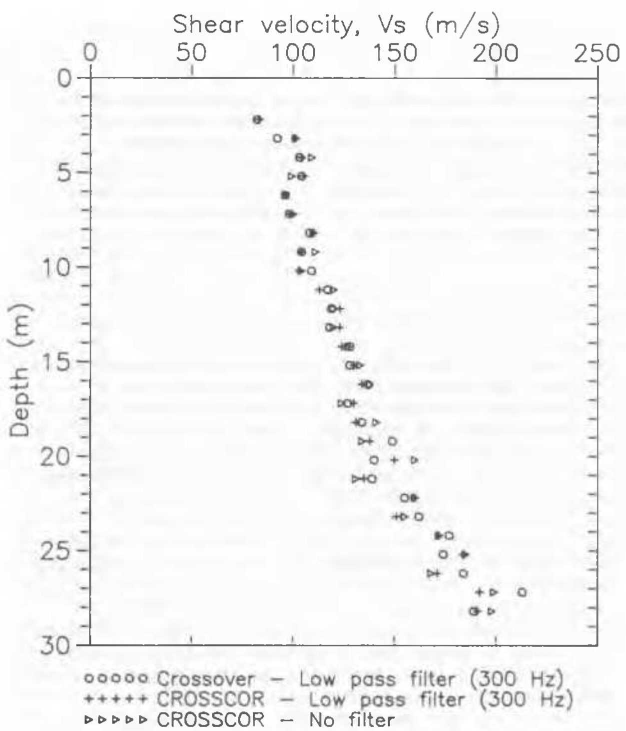

Figure 5. Velocity profile from Lower 232 Street comparing filtered and unfiltered seismic data generated using hammer-beam source

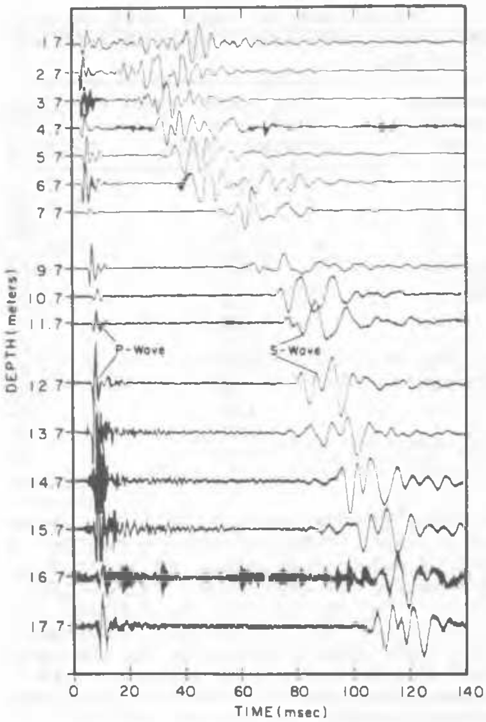

Figure 6. Seismic section from Lower 232 Street using a point source and unfiltered accelerometer

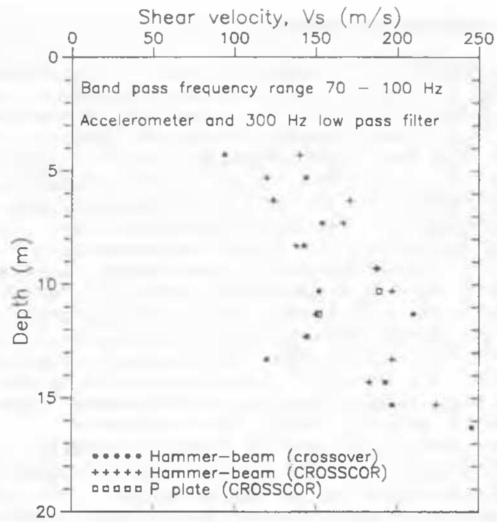

Figure 7. Velocity profile from Laing Bridge South site

4 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_o, small variations in V_s can result in appreciable errors in G_o:

$$G_o = \rho \, V_s^2 \qquad (3)$$

where ρ = mass density of soil horizon under consideration.

The use of digital filtering techniques such as those implemented in the program P-S CROSSCOR can reduce the sources of possible error and provide reliable and accurate velocity determinations for both shear and compressional wave sources. P-S CROSSCOR was found to be suitable for analyzing noisy accelerometer data where the crossover technique could not be used. Where good data exists and either method can be used, probably the most important function of P-S CROSSCOR is to reduce human bias. Furthermore, the crosscorrelation function in P-S CROSSCOR uses all of the signal information (averaging out irregularities and considering dominant responses) as opposed to the crossover or reverse polarity method which relies on a single reference crossover point to determine interval times. In addition, P-S CROSSCOR is more flexible and can obtain velocity estimates from non-polarized sources and is especially effective in offshore seismic studies.

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