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ABSTRACT

In-situ measurement of the dynamic characteristics of surficial soils is becoming more common in geotechnical practice for prediction of ground surface motions from earthquake excitation and to evaluate foundations for vibrating equipment. Techniques for these measurements have been under development at the University of British Columbia (U.B.C.) since 1980.

The paper discusses many practical considerations with respect to equipment (sources, receivers, trigger, etc.) and procedures that can affect the interpretation and analysis of seismic cone results. A brief review is given of the cross-over method as used at UBC to determine interval shear velocity travel times from downhole seismic cone testing. A more detailed description is provided for the cross-correlation technique used in the frequency domain that has recently been incorporated into the analysis procedure. Comparisons of these two methods are presented and discussed.

INTRODUCTION

A number of authors have presented papers on the determination of wave velocities in surficial soils from in-situ measurements (Davis, 1989, Woods and Stokoe, 1985 and Tonouchi et al, 1983). The main emphasis of most authors has been on crosshole testing, for which two or three boreholes are required. Robertson et al(1986) described the development of the seismic cone penetration test (SCPT), which requires only 1 rapid cone penetration test, and provides CPT data for stratigraphic logging and soil property estimates (Robertson and Campanella, 1983) as well as seismic signals. Furthermore, Robertson et al (1986) show that the more economical seismic cone test gives the same shear velocity profiles as crosshole methods in both sand and clay sites in Canada, the U.S.A. and Norway.

EQUIPMENT

Detailed discussions of the seismic cone equipment used at UBC up to 1985 are given by Rice(1984) and Laing(1985). A schematic diagram showing the layout of the usual seismic downhole test procedure to measure interval velocity travel times is shown in Fig. 1 along with a step trigger circuit. The horizontally oriented seismic receiver is embedded into the cone body which is pushed vertically through the soil resulting in exceptionally good coupling between low level soil vibrations and the receiver.

Sources

The primary source of shear waves has been a weighted beam struck horizontally with a hammer. Such a source can produce very clean shear or S-waves with essentially no compression or P-waves. Initially a heavy wooden beam with steel ends, weighted with a van, was struck with a 7 Kgf sledge hammer. It was subsequently found that the full width rectangular steel pads supporting the UBC cone truck could be struck, if suitably reinforced, without damaging the truck supports. The forward, most heavily loaded pad is now used as the shear beam. At the present time an adjustable height swing hammer weighing 12 Kgf is used to provide a highly repeatable and calibrated source for shear waves. In a study of the factors contributing to optimal shear sources (M. Robertson, 1986), it was found that a very high normal load on the shear beam was absolutely essential. The high load maintains coupling with the ground so no energy is lost due to slippage when the beam is struck. The wooden beam with steel ends is portable and easily used with a drill rig, but careful consideration must be given to adequately loading it uniformly to obtain a good response.

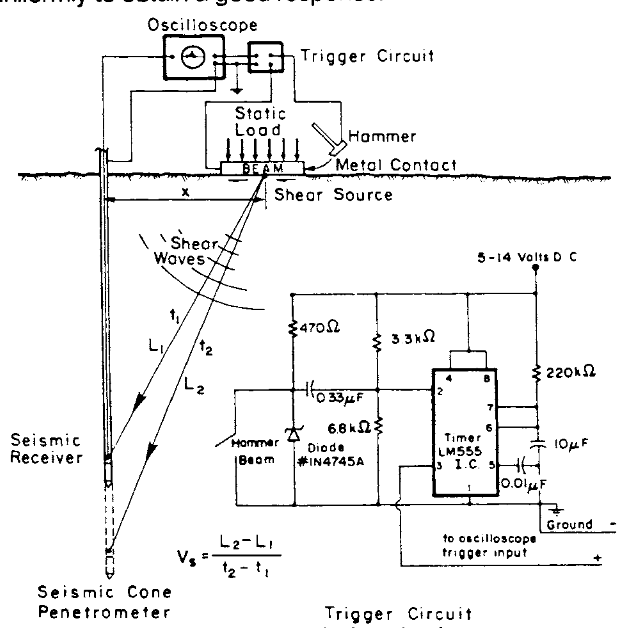

Fig. 1. Schematic of downhole seismic cone arrangement including trigger circuit

Receivers

A variety of receivers have been used in the research at UBC, including geophones and accelerometers of the piezoceramic and piezoresistive types. An important requirement of the receivers is that they fit within the cone to be used. The geophones used, manufactured by Geospace Corporation, are 1.7cm in diameter and have a natural frequency of 28Hz. In the 15 cm^2 cone a triaxial package was used, and in the 10 cm^2 cone a single horizontal geophone was used. When used with the shear beam source, they produced clear signals to depths in excess of 50m. However, in recent studies aimed at measuring material damping in-situ, the natural frequency of the geophone was in the range of the shear wave of interest making it difficult to separate soil response from instrument response. For these reasons the use of accelerometers having natural frequencies from 300 to 3 kHz was pursued.

The piezoceramic bender units, manufactured by Piezo Electric Products, were 1.27cm square and had a natural frequency of about 3000Hz. Resonance of the undamped receiver caused noise on the signals and required digital filtering after data acquisition. Two models of piezo-resistive accelerometers have also been used and these have the advantage that they can be calibrated statically. The first, manufactured by Kulite Semiconductor Products, has a range of +/- 10g, is 0.95cm by 0.39cm, has a natural frequency of about 550 Hz and is also undamped causing noise on the signals. The second type, manufactured by IC Sensors, has a range of +/- 2g, is a 1.5cm square wafer, has a natural frequency of about 600Hz but is at critical damping. A clever air damping mechanism is employed which does not affect the sensitivity and acts as an acceleration limiter preventing damage due to shock. These have been successfully used for about a year.

A single sensor with active axis oriented horizontally has been used alone or in pairs separated along the cone rod by a distance of 1m. Velocities measured by a separated pair of sensors responding to a single impulse have been referred to as true interval measurements since interval timing is independent of the trigger. Velocities measured by an advancing single receiver recording separate impulses have been referred to as pseudo interval measurements since interval timing is referenced to the trigger. A detailed analysis by Rice (1984) showed that a comparison of pseudo to true time interval methods gave a standard deviation less than 1.5% of the mean indicating that the methods are equivalent with a repeatable trigger.

Trigger

For velocity measurements that depend on separate impulses, the single most important factor is a repeatable trigger to begin the recording of signals. A variety of triggers have been studied; a receiver located in the soil near the source, an inertially activated switch also near the source and an electrical step trigger of the type suggested by Hoar and Stokoe (1978). For the receiver in the ground, especially a geophone, it was found that the rise time was both considerable and variable. The inertial switch itself had a smaller rise time but there was a longer and variable delay (0.3ms+/-0.05ms) before the oscilloscope was triggered. Only an accelerometer with resonance above 500Hz proved to be an acceptable trigger when embedded in the soil near the source. However, when an electrical step trigger can be fitted to the source it provides the simplest and most reliable trigger signal.

A schematic diagram of the electrical step trigger used at UBC is shown in Fig. 1. When the hammer makes contact with the metal pad on the shear beam, it completes an electrical circuit, allowing the discharge of a capacitor. This discharge causes the timer IC module to generate an output pulse of about 90% of the voltage source for about 2.4s duration. This duration negates the possible effects of bounces of the hammer. The rise time of the pulse is typically 100ns. Once the pulse has finished, the circuit is automatically rearmed for another event. This trigger system has been used for several years with very good results. It is both repeatable and reliable.

The primary recording device used at UBC is a Nicolet 4094 digital oscilloscope with a CRT screen and floppy disk storage. The unit has a 15 bit A/D resolution and, in the 2-channel mode, a time resolution down to 0.01ms. This scope has been satisfactorily used for over eight years.

ANALYSIS OF SIGNALS

All dynamic signal processing and presentation has been done using the IBM-PC program VU-POINT V. 1.21. This versatile, easy to use and macro driven program is available from S-CUBED, La Jolla, Calif.

Cross-over method

Signals are normally recorded at depth intervals of 1m (the length of the cone rods). A significant advantage in using a shear beam source is that the polarized shear wave signals can be reversed when the opposite end of the beam is struck, i.e., the initial particle motion is reversed, thus reversing the amplitude of the measured signal. A fairly typical pair of signals is shown in Fig. 2. These signals were recorded with an accelerometer and digitally filtered (low pass at 300Hz) for clarity of presentation. Previously, travel time measurements were made by estimating the arrival time of the shear wave from a single trace. However, the arrival

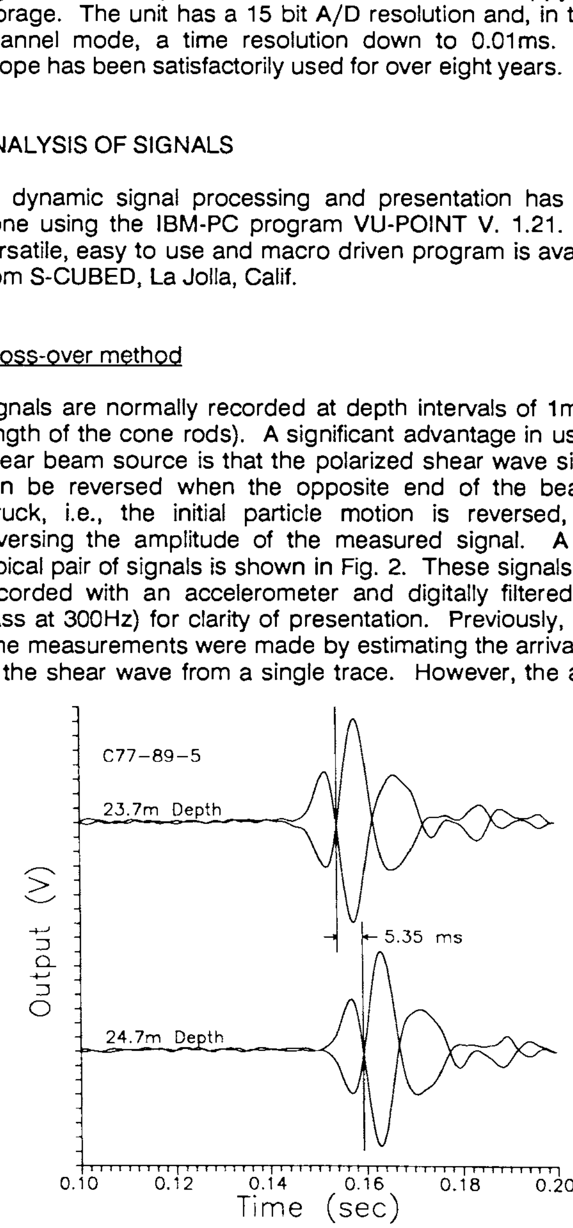

Fig. 2 Cross-over method for time interval

time of the shear wave was not always clear and often required much judgement. Generally the time of the first cross-over of the two signals is clearly defined as in Fig. 2. The time interval between two depths is found by subtracting the cross-over time at the lower depth from that at the greater depth. The depth interval is calculated from the difference between the sloping distances from the source to the receiver locations, as shown in Fig. 1. The interval shear velocity, V_S, is given by the depth interval, $(L_2\text{-}L_1)$,divided by the time interval, $(t_2\text{-}t_1)$.

The cross-over method is described in detail by Robertson et al (1986), who also show that the seismic cone downhole method gives essentially the same results as the more costly cross-hole method.

Cross-correlation method

With some signals, the cross-over time for shear waves can be shifted if the signal is perturbed near the cross-over location which can result from interaction from reflections in layered soil. The cross-over method only utilizes the time information in the signal at a single point. An alternate approach to determine the time interval which utilizes all of the time information in the signals is the cross-correlation technique. In principle, the cross-correlation of signals at adjacent depths is determined by shifting the lower signal, relative to the upper signal, in steps equal to the time interval between the digitized points of the signals. At each shift, the sum of the products of the signal amplitudes at each interval gives the cross-correlation for that shift. After shifting through all of the time intervals, the cross-correlation can be plotted versus the time shift, and the time shift giving the greatest sum is taken as the time shift interval used to calculate the interval velocity. This process is shown schematically in Fig. 3, where the lower signal has been shifted to the left and to the position giving the maximum correlation. The cross-correlation calculation can be done as outlined here, in the time domain, but it is very inefficient. A typical calculation for signals of nominally 2k, (2048), points requires about 10 minutes on a 386 PC (25 MHz) with 387 coprocessor if the cross-correlation is done in the time domain.

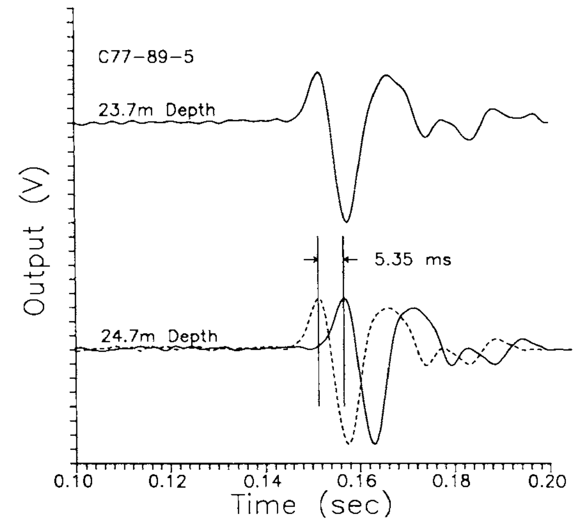

Fig. 3. Cross-correlation method for time interval

An alternate method of calculation makes use of the frequency domain. In this procedure, which is outlined in Fig. 4, a Fast Fourier Transform (FFT) is used to convert each signal to the frequency domain. The complex conjugate of the upper signal FFT is calculated and multiplied by the lower signal FFT. The inverse FFT of the resultant is the cross-correlation of the signal. This calculation requires only about 20 seconds on the same 386 PC. The signals can be conveniently filtered before the multiplication, using a zero phase shift digital (cosine) filter. The resulting cross-correlation can also be normalized by dividing by the square root of the product of the autocorrelation of each signal. The autocorrelation can be evaluated as the cross-correlation of a signal with itself, and has a maximum at a shift of zero.

The above procedure has been automated using a macro (automated sequence of keystrokes for a menu-driven program) with the commercially-available program called VU-POINT. A flow chart of the macro is shown in Fig. 4 and a typical output is shown in Fig. 5, which gives a maximum correlation coefficient of 0.993 for a time shift of 5.35ms over a distance of 0.999m for a shear velocity of 189m/s.

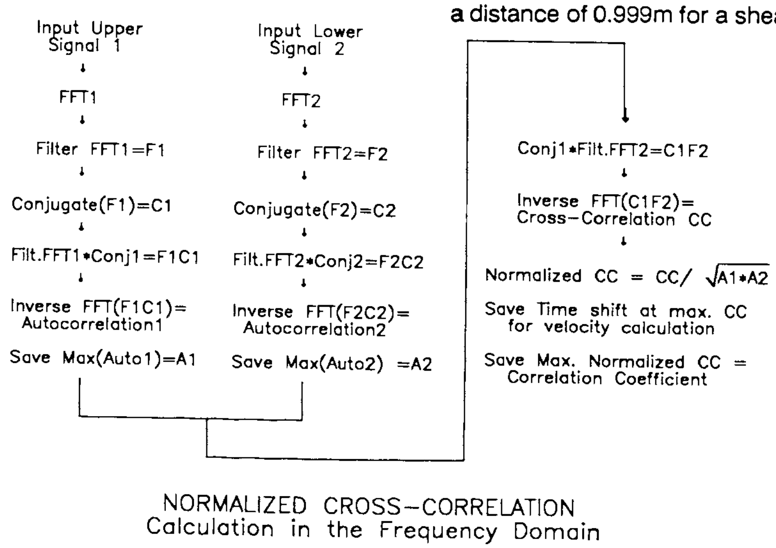

Fig. 4. Flow chart of normalized cross-correlation calculation procedure in the frequency domain

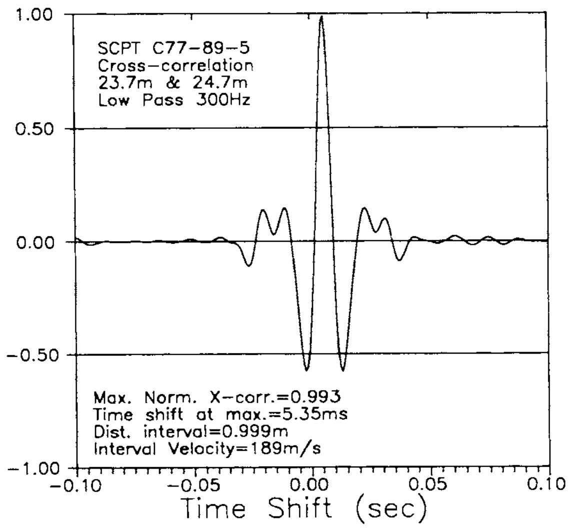

Fig. 5. Typical output of cross-correlation calculation in the frequency domain

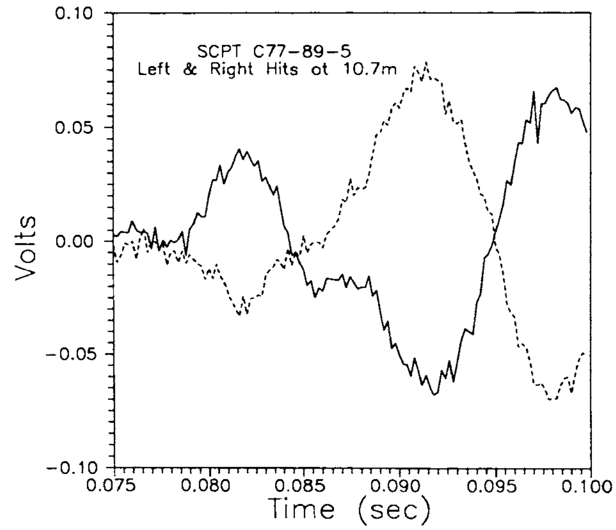

Fig. 7. Signals from left and right hits showing "step" effect on cross-over point, McDonald farm site at 10.7m depth

A shear wave velocity profile comparing the results from cross-over and cross-correlation methods is shown in Fig. 6. The velocities are in good agreement above 5m and below 14m. In between, the cross-over velocities are consistently less, within about 10%, except at 11m, where the difference is about 30% (depending on how one might select the cross-over point). The calculated cross-over velocity at this depth is affected by a "step" or distortion in the signal as shown in Fig. 7. The cross-correlation velocity is not affected by the localized step in the signal, but makes use of the entire wave traces at adjacent depths. The cross-correlation velocity is considered correct since it gives a value which better reflects average soil characteristics over the interval of depth.

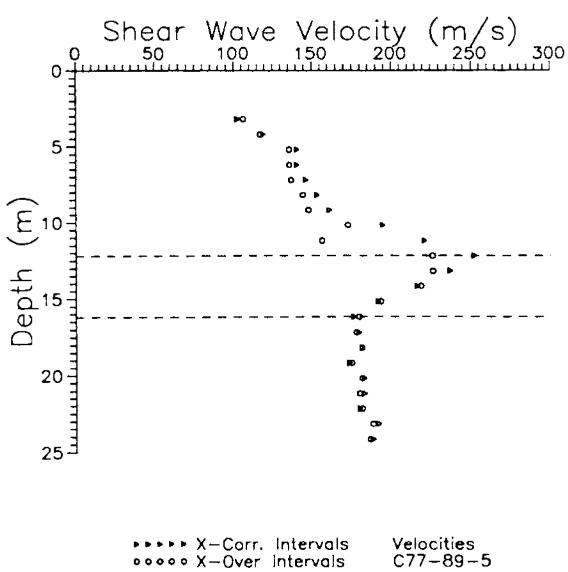

Fig. 6. Comparison of shear wave velocities from cross-correlation and cross-over methods, McDonald farm site

If desired, the cross-correlation approach can be extended to calculate the variation of velocity with frequency. Instead of computing the inverse FFT of the cross spectrum, the phase is calculated. Since the phase is periodic, it must be unwrapped (or stacked) to provide a continuous function. For each frequency, the time interval can be calculated from:

$$t(f) = phase(^{o}) / (360^{o} * f) \qquad (1)$$

where
t(f) = time as a function of frequency, f.

and the velocity from:

$$v(f) = distance / t(f) \qquad (2)$$

A typical plot of the above calculations is shown in Fig.8 of shear velocity versus frequency and it can be seen that the velocity determined by the cross-correlation has a reasonable average over the frequencies of interest, (40 to about 120 Hz).

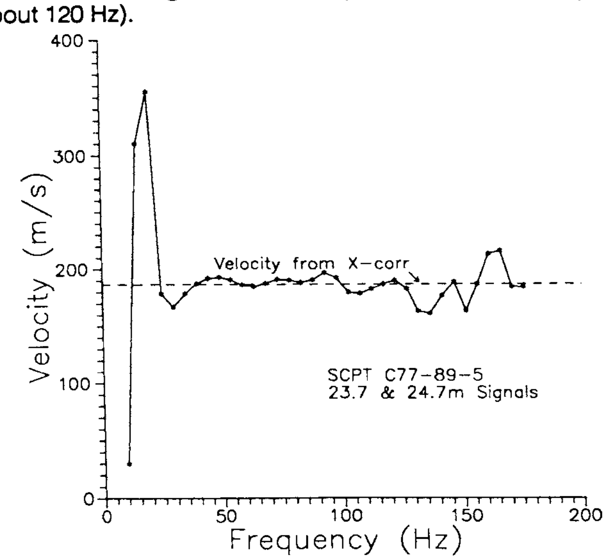

Fig. 8. Velocity variation with frequency

FILTERING

Filtering of signals is often desirable to clarify the signals and to remove the effects of higher frequency noise and the natural frequency of the receiver. Analog filters introduce a phase shift which varies with frequency. Laing(1985) reported a delay of about 2ms in shear wave arrival using a low-pass analog filter and a cutoff frequency of 100Hz, compared to using 1000Hz. This is very significant since interval times are typically 4 to 8ms.

TABLE 1

Effect of Width of Band-pass Filter on Velocities by Cross-correlation

SCPT C77-89-5 Accelerometer Receiver

Depth	23.7m-24.7m		Depth	6.7m-7.7m	
Filter	X-Corr	Time	Filter	X-Corr	Time
Hz	Coef.	ms	Hz	Coef.	ms
None	.976	5.35	None	.892	6.8
0-120	.995	5.3	0-200	.947	6.8
10-110	.996	5.3	10-190	.941	6.8
20-100	.997	5.3	20-180	.941	6.8
30-90	.997	5.3	30-170	.939	6.8
40-80	.998	5.3	40-160	.935	6.8
50-70	.998	5.3	50-150	.980	6.75
			60-140	.912	6.7
			70-130	.905	6.6
			80-120	.956	6.55
			90-110	.988	6.55

Digital filtering in the frequency domain can be calculated to give zero phase shift, and thus can be used without affecting the results. However, it is necessary to use judgement in applying the filter width. Table 1 shows the effect of band width on the cross-correlation. With a reasonably smooth FFT (see Fig. 9a) the correlation coefficients for the 23.7m to 24.7m interval increased and the time interval was constant with a decreasing band width of band-pass filter. With an irregular FFT (see Fig. 9b) the coefficients for the 6.7m to 7.7m interval varied and the time interval increased with a decreasing band width. The values of the cross-correlation coefficients shown are fairly typical; i.e. 0.99+ for fairly clean or smooth FFT's and 0.90+ for more irregular FFT's. In general, some care is required in the selection of the filter, and a reasonably wide band width is desirable to obtain sensible velocities. The FFT in Figs. 9a and 9b show that the dominant energy for this shear wave was between 40 and 120 Hz and corresponds to the frequency range of interest as mentioned previously. The authors consider the correct shear wave travel time from 23.7 to 24.7m to be 5.3ms and from 6.7 to 7.7m to be 6.75ms.

Coherence function

One method of determining a suitable filter band width is to use the coherence function. Use of this method requires repeated hits of the source at the same depth. Typically four hits at each depth have been recorded and used. The coherence function is defined as:

$$Coh = (G_{yx} \cdot G_{yx}^*) / (G_{xx} \cdot G_{yy}) \qquad (3)$$

where:

G_{yx}^* = Complex Conjugate of G_{yx}
G_{yx} = Average of Cross-Correlation Spectra
G_{xx} = Avg. of Autocorrelations of L_1 Signal
G_{yy} = Avg. of Autocorrelations of L_2 Signal

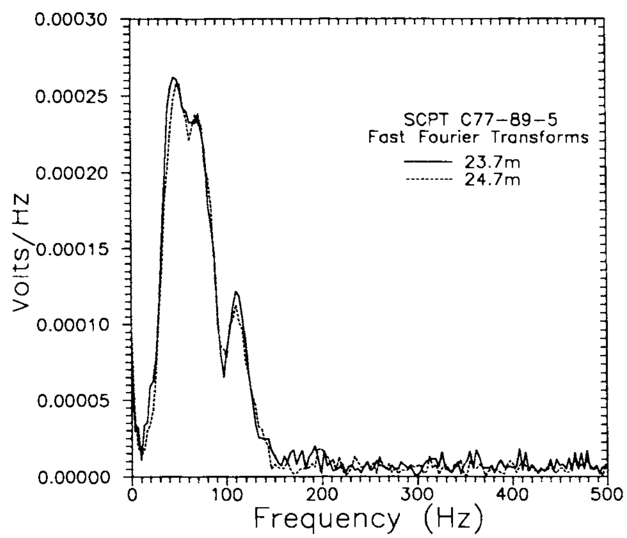

Fig. 9a. Variation in FFT for smooth spectra, McDonald farm site at 23.7 and 24.7m

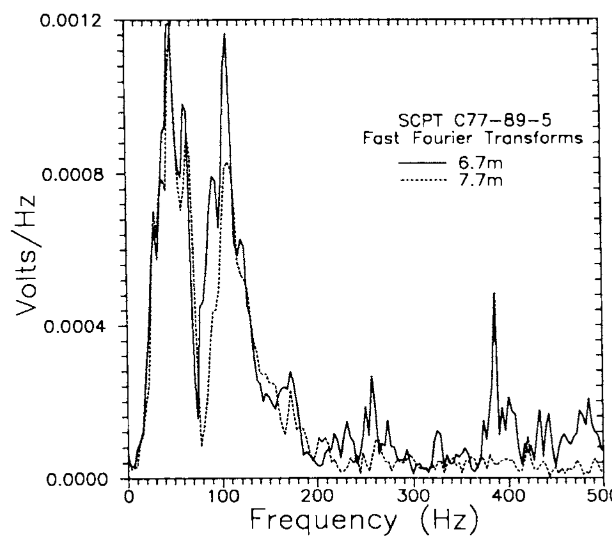

Fig. 9b. Variation in FFT for irregular spectra, McDonald farm site at 6.7 and 7.7m depth

A typical plot of the coherence function is shown in Fig.10. The coherence is high from about 20 Hz to 140 Hz except for a small dip at 120 Hz. This indicates that a maximum frequency band width of 20 to 140Hz could be reasonably used for calculation purposes.

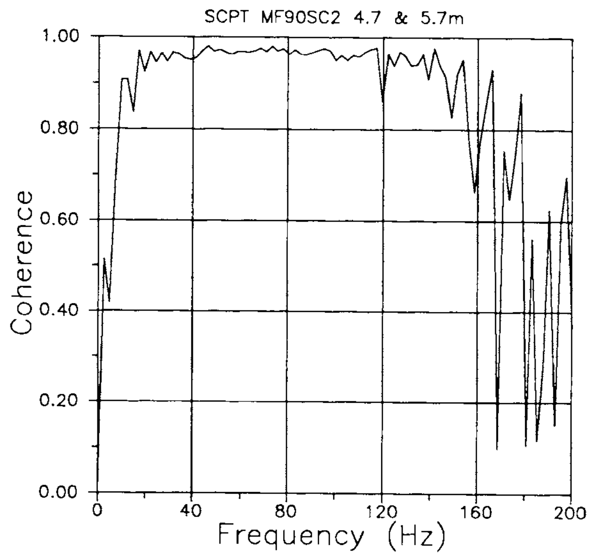

Fig. 10. Coherence function calculated for four hits at each successive depth, 4.7 and 5.7m

CONCLUSIONS

Experience with different types of seismic sources, receivers, procedures and analyses has been discussed and led to the following.

It is the authors' recommendation that the optimum determination of shear velocity can be obtained by using, whenever possible

1. a heavily loaded shear beam source,
2. a high sensitivity accelerometer receiver with resonance at 500Hz or higher, orient active axis in the horizontal direction and fix firmly into cone,
3. a cross-correlation method in the frequency domain to find the time shift and if filtering is required use only a zero phase shift digital filter over a band-pass width indicated by the FFT and use the same filter for all records in a soil layer or profile.

The cross-correlation method assumes no dispersion and/or distortion of the two signals over adjacent depths to obtain a correlation coefficient of 1.000. This has been found to be a very reasonable assumption over the usual 1m depth intervals but caution and judgement must be used at larger spacings.

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