Seismic cone analysis using digital signal processing for dynamic site characterization

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Received October 10, 1990

Accepted February 11, 1992

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 (UBC) 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, which has recently been incorporated into the analysis procedure. Comparisons of these two methods are presented and discussed. It has been found useful to isolate the main shear wave before further calculations, and the effects of this procedure are provided. A summary of findings concerning the characteristics of the measured signals is also included.

Key words: seismic, cone penetrometer, sources, receivers, accelerometers, shear wave, velocity, downhole, digital, signal processing.

La mesure *in situ* des caractéristiques dynamiques des sols de surface est de plus en plus courante dans la pratique géotechnique pour prédire les mouvements de la surface des sols lors de sollicitations par tremblements de terre, et pour évaluer les fondations de machines produisant des vibrations. Des techniques pour faire ces mesures ont été développées à l'Université de Colombie-Britannique (UBC) depuis 1980. Cet article présente plusieurs considérations pratiques en rapport avec l'équipement (sources, récepteurs, déclencheur, etc.) et les procédures qui peuvent influencer l'interprétation et l'analyse des résultats du cône sismique. L'on passe brièvement en revue la méthode *cross-over* telle qu'utilisée à UBC pour déterminer les intervalles des temps de transmission des ondes de cisaillement des essais au cône sismique réalisés en fond de forages. L'on fournit une description plus détaillée de la technique de *cross-correlation* utilisée dans la plage de fréquence qui a été incorporée récemment dans la procédure d'analyse. Des comparaisons de ces deux méthodes sont présentées et discutées. Il a été trouvé utile d'isoler la principale onde de cisaillement avant tout autre calcul, et les effets de cette procédure sont présentés. L'on inclut également un sommaire des constatations concernant les caractéristiques des signaux mesurés.

Mots clés : sismique, pénétromètre au cône, sources, récepteurs, accéléromètres, onde de cisaillement, vélocité, en fond de forage, digital, traitement de signal.

[Traduit par la rédaction]

Can. Geotech. J. **29**, 477–486 (1992)

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 cross-hole testing, for which two of three boreholes are required. Robertson *et al.* (1986) described the development of the seismic cone penetration test (SCPT), which requires only one rapid cone penetration test (CPT) and provides CPT data for stratigraphic logging and soil property estimates (Robertson and Campanella 1983*a*, 1983*b*) 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 cross-hole methods in both sand and clay sites in Canada, the United States, and Norway.

Equipment

Detailed discussions of the seismic cone equipment used at the University of British Columbia (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 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-kg sledgehammer. 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 support. The forward, most heavily loaded pad is now used as the shear beam. At the present time an adjustable height swing hammer weighing 12 kg is used to provide a highly repeatable and calibrated source for shear waves. In a study of the factors contributing to optimal shear sources (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

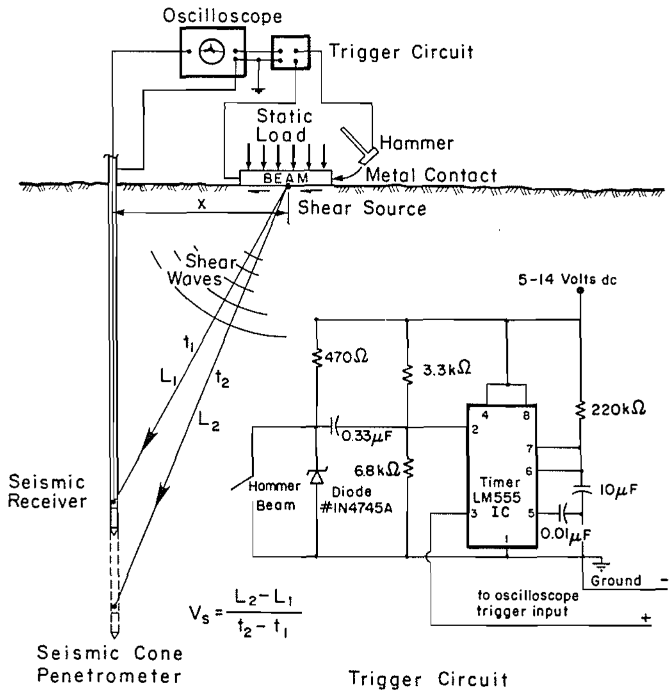

FIG. 1. Schematic of downhole seismic cone arrangement including trigger circuit.

it uniformly to obtain a good response. It should be noted that a friction reducer (with an area 1.5 times greater than the area of the cone and rods) is used just above the cone to decouple the rods from the soil.

A vertical hammer strike on a plate has also been used to produce dominant compression or P-waves with limited success. A vertically oriented receiver in the cone can give erroneously very high P-wave velocity measurements (>6000 m/s), possibly caused by a poor response to soil motion due to rod stiffness in the vertical direction and a compression wave traveling down the steel rods. A horizontally oriented receiver is not in the direction of P-wave particle motion and therefore gives very low signal-to-noise response and is usually not effective below a few metres depth. Recently a heavy 136-kg drop weight that is raised on a winch on the side of the UBC cone truck to fall heights of 1.5 m has been developed. It appears that P-waves from drop weights are measured by a horizontally oriented receiver to depths of at least 15 m. The use of heavy drop weights is currently being studied.

A "point" source that has been routinely used for several years is the "Buffalo gun" (Pullan and MacAulay 1987), which provides an alternative to small explosive cap sources. A Buffalo gun is used to fire a 12-gauge shotgun shell beneath the ground surface. A length of water pipe with fittings to hold the shotgun shell is placed in a narrow augured hole about 0.7 m deep and flooded with water. The shell is fired by dropping a pointed rod into the pipe. Results of S-wave velocity measurements with the Buffalo gun are usually in close agreement with the shear beam results. Generally it is also possible to detect P-waves to a depth of at least 10 m with the Buffalo gun, especially where a high water table is present. Above the water table, the difference in travel time between P-wave and S-wave velocities is reduced, making it sometimes difficult to separate the two events.

For offshore work from land-fast ice sheets over water depths to 8 m, seismic caps have been exploded at different locations in the water between the ice and the mud line. The limited number of tests suggested that the in-water seismic cap source signals contain both P- and S-wave components when traveling through the soil and, although difficult to interpret, gave reasonable average results (Campanella *et al.* 1987).

Receivers

A variety of receivers have been used in the research at UBC, including geophones and accelerometers of both the piezoceramic and piezoresistive type. An important requirement of the receivers is that they fit within the cone to be used. The geophones used, manufactured by Geospace Corporation, are 17 mm in diameter and have a natural frequency of 28 Hz. Although it is recognized that it is desirable to use receivers with damping of about 70% of critical damping to reduce resonant effects, the geophone characteristics did not allow damping in excess of 48% (short-circuited) and were typically used with 30% damping. 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 50 m. However, with the explosive sources it was found that the geophone response was activated into resonance by primary and reflecting P-wave arrivals that overlapped with and obscured the S-wave and its arrival. Furthermore 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 12.7 mm square and had a natural frequency of about 3000 Hz. Resonance of the undamped receiver caused noise on the signals and required digital filtering. Two models of piezo-resistive accelerometers have also been used, and these have the advantage that they can be calibrated statically, since they have a flat frequency response from 0 Hz. The first, manufactured by Kulite Semiconductor Products, has a range of ±10 g, is 9.5 × 3.9 mm, has a natural frequency of about 550 Hz, and is also undamped, causing noise on the signals.

However, the second type, a model 3021 manufactured by IC Sensors, Milpitas, Calif., has a range of ±2 g, is a 15 mm square by 4.7 mm thick wafer, weighs less than 1 gm, has a typical sensitivity of 20 mV/g at a supply voltage of 5 V direct current (DC), has a natural frequency of about 600 Hz, and is critically damped at 70%, giving a flat frequency response from 0 to 500 Hz. 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 inexpensive accelerometers have been successfully used since 1989 and are as close to ideal as possible at this time. Unless indicated, all seismic data are taken with IC Sensors accelerometers.

Sensors with the active axis oriented horizontally have been used singly, or in pairs separated along the cone rod by a distance of 1 m. Velocities measured by a separated pair of sensors responding to a single impulse have been referred to as true interval measurements, since interval tim-

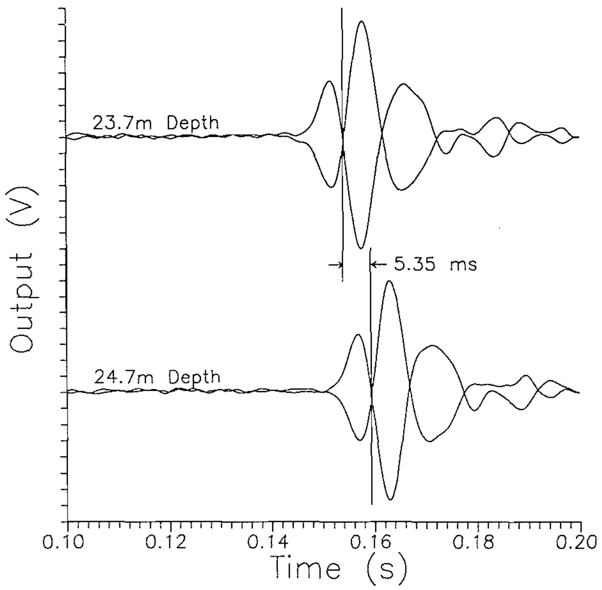

FIG. 2. Cross-over method for time interval (C77-89-5).

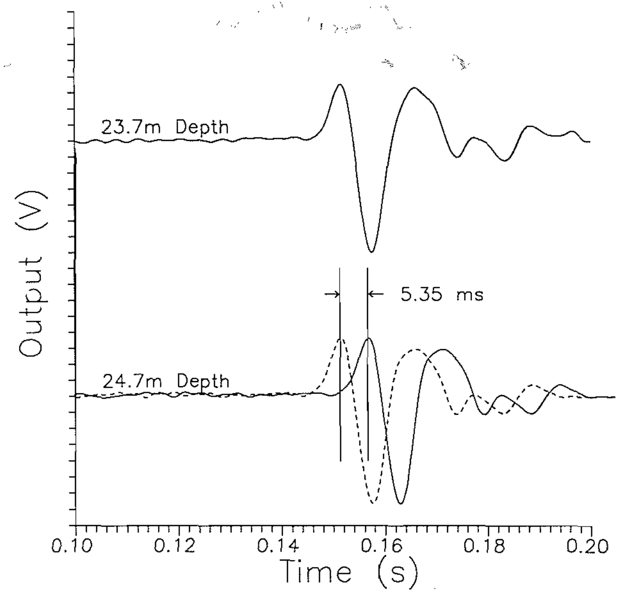

FIG. 3. Cross-correlation method for time interval (C77-89-5).

ing 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 (0.3 ± 0.05 ms) before the oscilloscope was triggered. Only an accelerometer with resonance above 500 Hz 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 module to generate an output pulse of about 90% of the voltage source for about 2.4-s duration. This duration negates the possible effects of bounces of the hammer. The rise time of the pulse is typically 100 ns. 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.

Signal recorder

The primary recording device used at UBC is a Nicolet 4094 digital oscilloscope with a cathode ray tube (CRT) screen and floppy disk storage. The unit has 15-bit A/D resolution and, in the two-channel mode, a time resolution down to 0.01 ms. This scope has been satisfactorily used for over 10 years. It should be noted that the recorder is typically operated in the AC-coupled mode to eliminate baseline shifts.

Analysis of signals

Most of the dynamic signal processing and presentation has been done using the IBM-PC program VU-POINT enhanced version 1.21. This versatile, easy to use, menu-driven program has full macro support and is available from S-CUBED, La Jolla, California. Although the 5.25 in. high-density disk in the Nicolet digital scope is IBM-PC compatible, it is written in a proprietary format, which can be read by the enhanced version of VU-POINT.

Cross-over method

Signals are normally recorded at depth intervals of 1 m (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 inverting 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 300 Hz) for clarity of presentation. Previously, traveltime measurements were made by estimating the arrival time of the shear wave from a single trace. However, the arrival time of the shear wave was not always clear and often required much judgment. 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 distance interval is calculated from the difference between the sloping distances from the source to the receiver locations, assuming a straight-line ray path, as shown in Fig. 1. The interval shear velocity V_s is given by the distance interval ($L_2 - L_1$) divided by the time interval

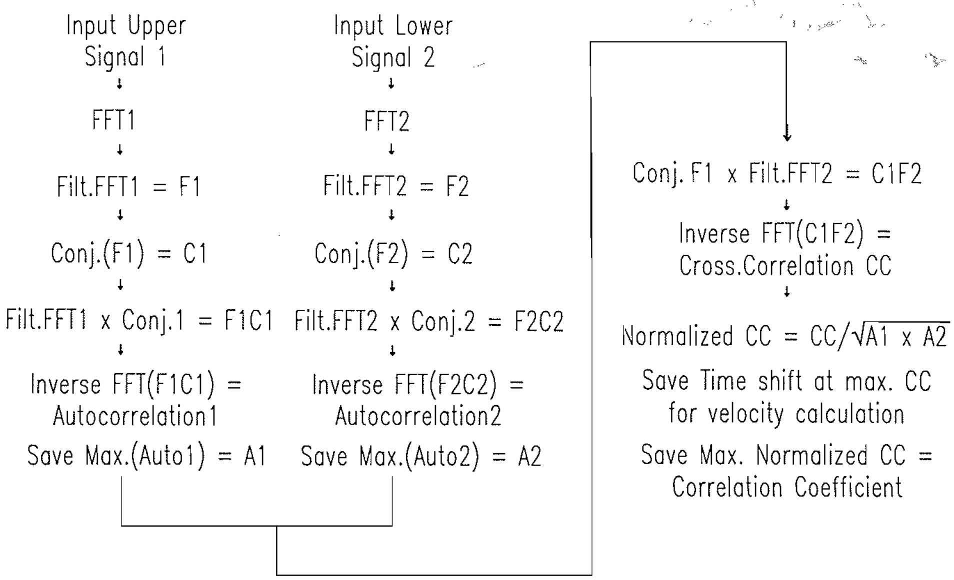

FIG. 4. Flow chart of normalized cross-correlation calculation procedure in the frequency domain. Filt., filter; Conj., conjugate; CC, cross-correlation.

$(t_2 - t_1)$. The effects of ray path bending due to changing shear wave velocities were studied by Stewart (1992), who found that velocities differed by less than 3% when comparing straight and bent ray paths. Thus, the assumption of straight ray paths is reasonable.

The cross-over method is described in detail by Robertson *et al.* (1986), who also presented data from sites in Norway, the United States, and Canada which show that the seismic cone down-hole method gives essentially the same results as the more costly cross-hole method.

Cross-correlation method

In some cases, the cross-over time for shear waves can be shifted if the signal is perturbed near the cross-over location. This can result from interference between the direct shear arrival and other events, particularly 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 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 2000 or 2048 points requires about 10 min on a 386 PC (25 MHz) with a 387 coprocessor if the cross-correlation is done in the time domain.

An alternate method of calculation of the time shift 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 FFT is a series of complex numbers associated with each frequency step and can be represented by the real and imaginary parts or, more commonly, the magnitude and phase. Typically, the magnitude is plotted as a function of frequency and is referred to as the transform FFT or spectrum of the signal. The complex conjugate of the upper signal FFT is calculated (by multiplying the imaginary part at each frequency by -1) and multiplied by the lower signal FFT. The inverse FFT of the resultant is the cross-correlation of the signals. This calculation requires only about 20 s on the same

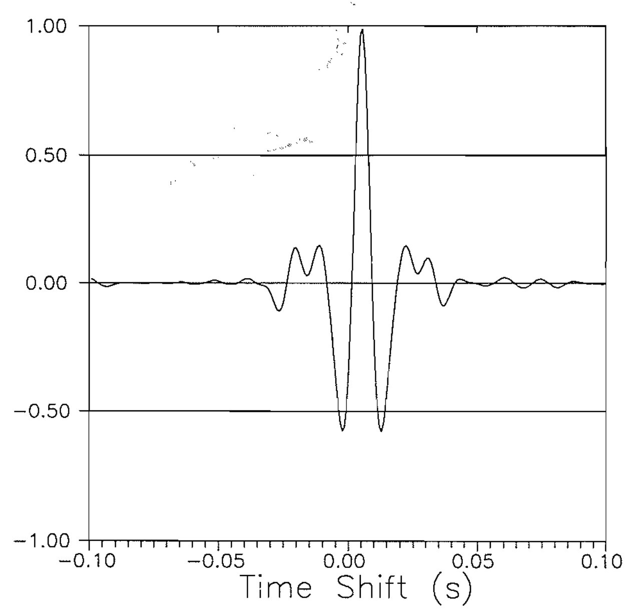

FIG. 5. Typical output of cross-correlation calculation in the frequency domain (SCPT C77-89-5, cross-correlation at 23.7 and 24.7 m depths, 300-Hz low-pass filter). Maximum normalized cross-relation = 0.993; time shift at maximum cross-correlation = 5.35 ms; distance interval = 0.999 m; interval velocity = 189 m/s.

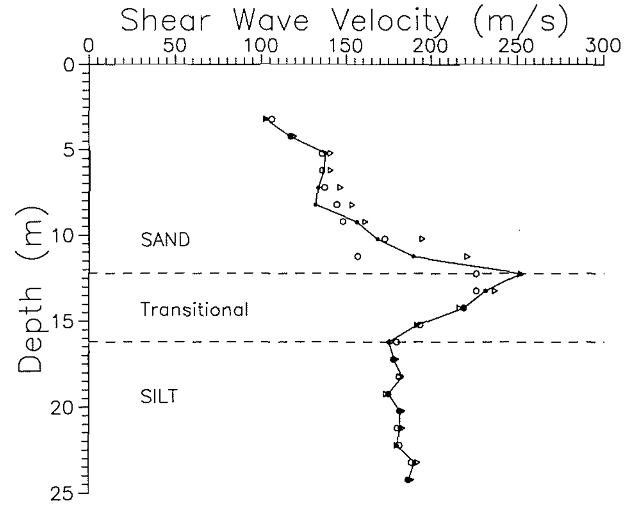

FIG. 6. Comparison of shear wave velocities from cross-correlation and cross-over methods (McDonald farm site, C77-89-5, 40 to 100 Hz). ▷ and •—•, full and windowed signals, both by cross-correlation method; ○, cross-over method.

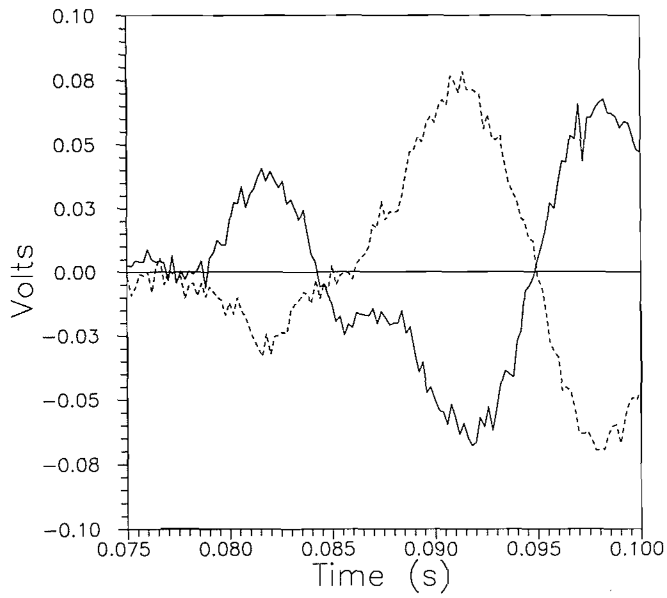

FIG. 7. Signals from left and right hits showing "step" effect on cross-over point at 10.7 m depth (McDonald farm site, SCPT C77-89-5).

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 value at zero shift for 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 key strokes 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 at a time shift of 5.35 ms over a distance of 0.999 m for a shear velocity of 189 m/s.

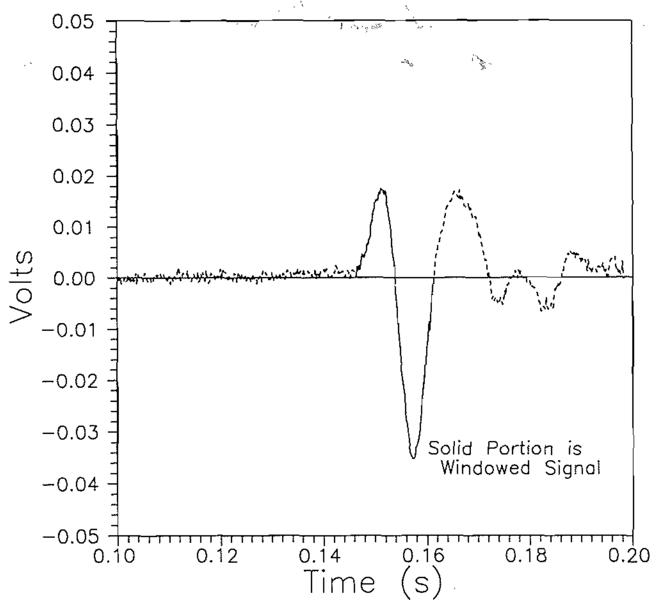

FIG. 8. Windowed portion of full signal (SCPT C77-89-5, 23.7 m).

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

However, a detailed study of the measured signals showed that the portions of the signal other than the main shear wave can strongly affect the FFT of the signal, and that these portions are not simple reflections of the shear wave (Stewart 1992). It is therefore desirable to remove those parts of the signal that are extraneous to the measurement, and this can be done by windowing the signal.

A windowed signal is formed along the same time scale as the original signal, and a scale factor ranging from 0 to 1 is assigned at each time step. Windowing is simply the operation of multiplying the original signal by the window signal. A rectangle window has a value of 1 for the duration of the main pulse only and 0 before and after. Applying the rectangle window gives the windowed signal in Fig. 8. Figure 9 presents the FFT's of the full and windowed signals. It can be seen that the FFT of the windowed signal is much smoother. A variety of other window types has been studied (Stewart 1992). The bulk of the energy of the signals measured with the SCPT falls in a range of less than 200 Hz. For this range it was observed that the signal windowed with the rectangle is closest to the original (has the closest peak frequency and highest correlation with the original signal). It is therefore concluded that the rectangular window is the best window type to isolate the shear waves in the data in this search. This is convenient, as the windowing operation can be done by simply replacing the signals before and after a full cycle of the shear wave with zeros. Velocities calculated

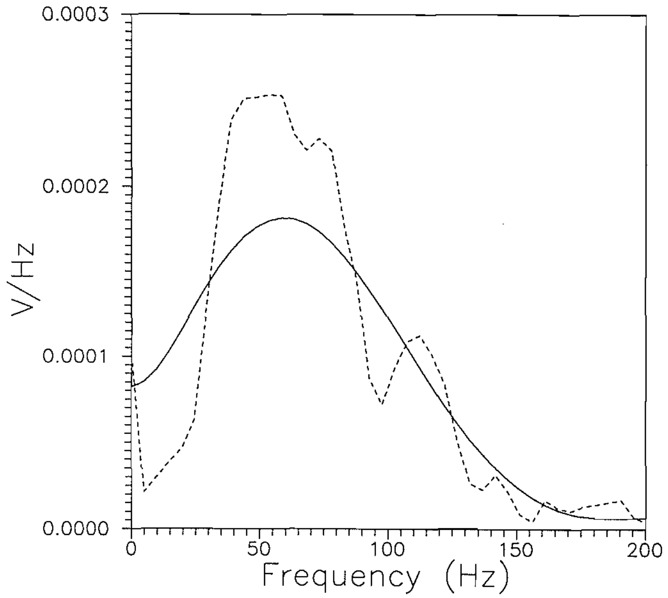

FIG. 9. FFT's of full and windowed signals at 23.7 m depth (SCPT C77-89-5). - - -, full signals; —, windowed signals.

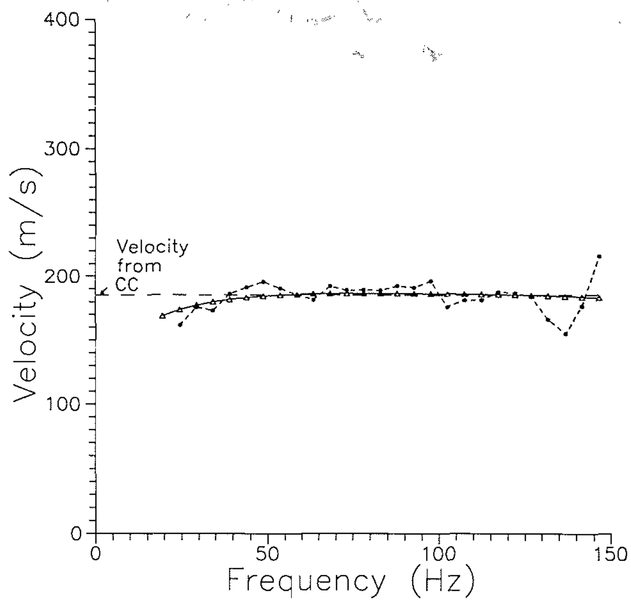

FIG. 10. Velocity variation with frequency (SCPT C77-89-5, using 23.7- and 24.7-m signals). Δ, windowed signals; ●, full signals; CC, cross-correlation.

by the cross-correlation method using windowed signals are also shown in Fig. 6. This approach is considered by the authors to be the best methodology, as it allows the use of multiple points (typically 100–300), as opposed to a single point, to define the time shift, while excluding the other parts of the signal that are not related to the main shear wave.

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

[1] $t(f) = \text{phase}(^\circ)/(360^\circ \cdot f)$

where $t(f)$ = time as a function of frequency, f, and the velocity from

[2] $v(f) = \text{distance}/t(f)$

A typical plot of the above calculations is shown in Fig. 10 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).

Filtering

Filtering of signals is often desirable to clarify the signals and to remove the effects of noise and, sometimes, the resonance of instruments (if not critically damped). Analog filters introduce a phase shift that varies with frequency. Laing (1985) reported a delay of about 2 ms in shear wave arrival caused by the use of a low-pass analog filter at a cutoff frequency of 100 Hz, compared with using 1000 Hz. This is very significant, since interval times are typically 4–8 ms.

Digital filtering in the frequency domain can be calculated to give zero phase shift and thus can be used without affecting the results. There is usually a choice of low-pass, high-pass, band-pass, and band-reject types of filter. However, it is necessary to use judgment when specifying the filter frequency characteristics to be used. Table 1 shows the effect of band width in applying a band-pass filter in the cross-correlations for both full and windowed signals. The very wide band width of 5–5000 Hz is equivalent to no filtering. The correlation coefficients for the deeper 23.7- to 24.7-m interval increased, and the time interval was essentially constant with a decreasing band width of band-pass filter. However, at the shallower depth the correlation coefficients for the 6.7- to 7.7-m interval varied for the full signals and increased for the windowed signals, and the time interval decreased for both full and windowed signals, with a decreasing band width. (It can be noted that neither of these

TABLE 1. Effect of width of band-pass filter on velocities by cross-correlation

23.7–24.7 m			6.7–7.7 m		
Filter	CC coef.	t(ms)	Filter	CC coef.	dt(ms)
		Full signals			
5–5000	0.9811	5.35	5–5000	0.8928	6.80
5–120	0.9958	5.30	5–200	0.9465	6.80
10–110	0.9963	5.30	30–170	0.9386	6.80
20–100	0.9971	5.30	50–150	0.9797	6.75
30–90	0.9978	5.30	70–130	0.9051	6.60
40–80	0.9987	5.30	80–120	0.9556	6.55
50–70	0.9989	5.30	90–110	0.9875	6.55
		Windowed signals			
5–5000	0.9963	5.40	5–5000	0.9074	7.10
5–120	0.9985	5.40	5–200	0.9145	7.10
10–110	0.9987	5.35	30–170	0.9207	7.10
20–100	0.9989	5.40	50–150	0.9255	7.00
30–90	0.9991	5.35	70–130	0.9509	6.80
40–80	0.9993	5.40	80–120	0.9729	6.70
50–70	0.9993	5.35	90–110	0.9924	6.60

NOTE: SCPT C77-89-5 accelerometer receiver, time steps in 0.05-ms increments. CC coef., cross-correlation coefficient; dt, time shift.

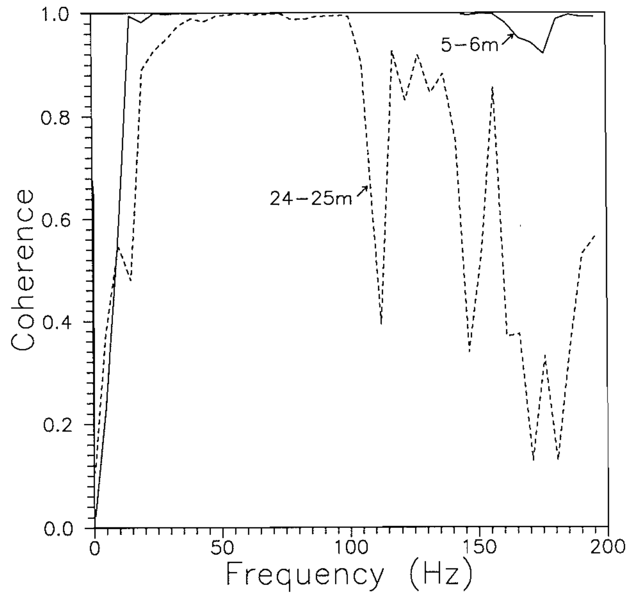

FIG. 11. Coherence function calculated for four hits at each successive depth, 5–6 m and 24–25 m (SCPT MF90SC5).

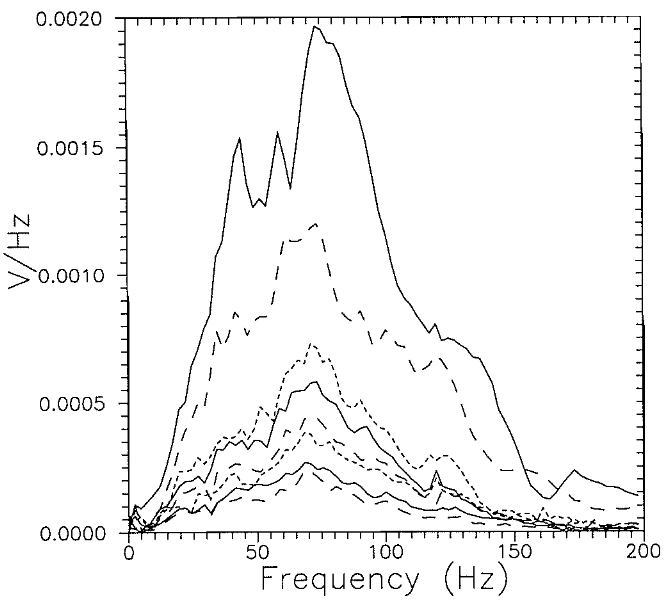

FIG. 12. Variations in full signal FFT spectra from 2.7 to 9.7 m depth in sandy soil (SCPT MF90SC2).

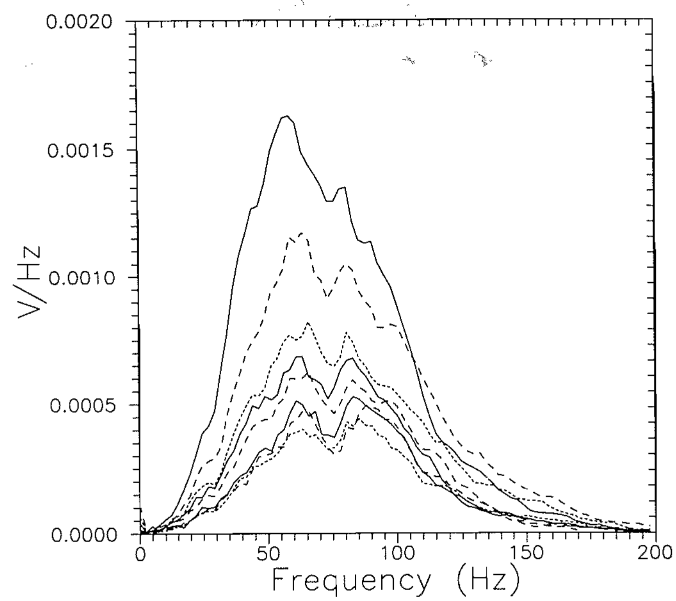

FIG. 13. Variations in full signal FFT spectra from 2.7 to 9.7 m depth in clayey soil (SCPT L290SC1).

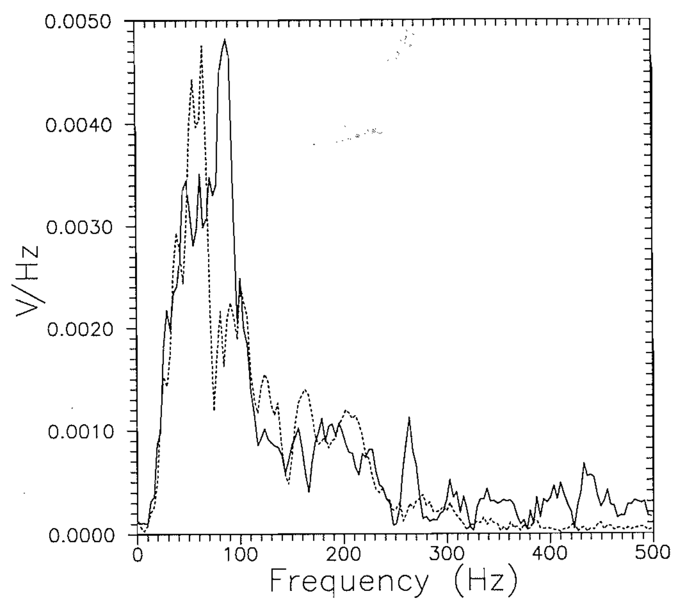

FIG. 14. Comparison of FFT's for shear-beam and Buffalo-gun sources at shallow depth (SCPT C77-89-5). —, shear beam (4.7 m); - - -, Buffalo gun (5.7 m).

intervals are near a major soil layer boundary at this site, and the signal/noise ratios only differed by a factor of about 1.6 between shallow and deep intervals, even though signal strength differed by a factor of 5.) The values of the cross-correlation coefficients shown are fairly typical, i.e., greater than 0.90 and often 0.99 and more. 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's of the signals show that the dominant energy for these shear waves was between 40 and 120 Hz and corresponds to the frequency range of interest as mentioned previously. The authors consider the most reasonable estimate of shear wave travel time from 23.7 to 24.7 m to be 5.4 ms and from 6.7 to 7.7 m to be about 7.0 ms, with emphasis given to the windowed signals for reasons previously given.

Also the relative stability of the interval times with band width attests to the consistently high quality of signals from the critically damped , flat response of the IC Sensors piezoresistive accelerometer.

Coherence function

Another method of determining a suitable filter band width is to use the coherence function. It is not possible to determine the signal/noise ratio of a signal directly, but the coherence function will be high (approaching 1) when the signal/noise ratio is high and low for a poor signal/noise ratio. Use of this method requires repeated hits of the source at the same depth. Typically four hits at each depth have

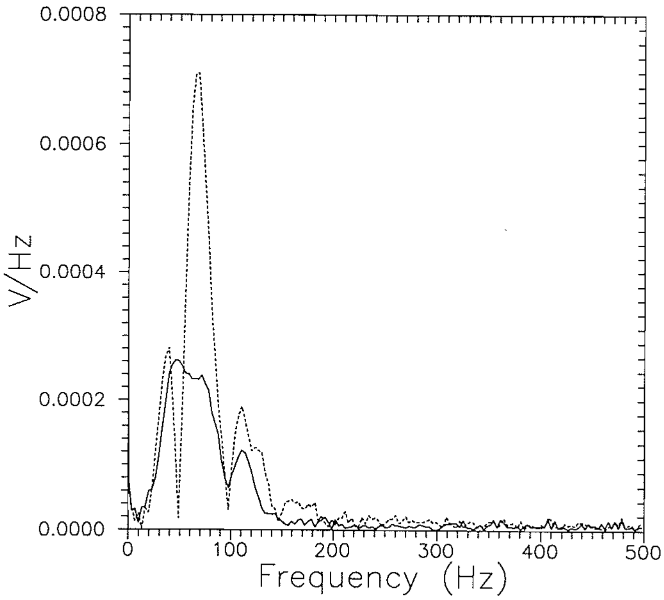

FIG. 15. Comparison of FFT's for shear-beam and Buffalo-gun sources at greater depths (SCPT C77-89-5). —, shear beam (23.7 m); - - -, Buffalo gun (24.7 m).

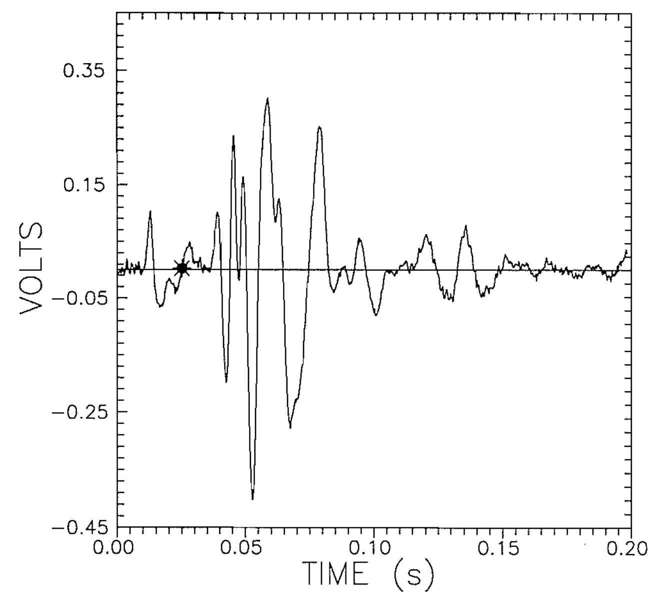

FIG. 16. Time record of Buffalo-gun signal at 5.7 m showing P-wave near start followed by S-wave (SCPT C77-89-5). ✷, 25.2 ms.

been recorded and used. The coherence function is defined as

$$[3] \quad \text{Coh} = \frac{G_{yx} \cdot G_{yx}^*}{G_{xx} \cdot G_{yy}}$$

where G_{yx} = average of cross-correlation spectra, G_{yx}^* = complex conjugate of G_{yx}, G_{xx} = average of autocorrelations of upper signals, and G_{yy} = average of autocorrelations of lower signals

A typical plot of the coherence function is shown in Fig. 11. For the signals at shallow depth, the coherence is constant at a value of essentially 1.00 about 30–150 Hz, whereas for the greater depth, the coherence is still very high

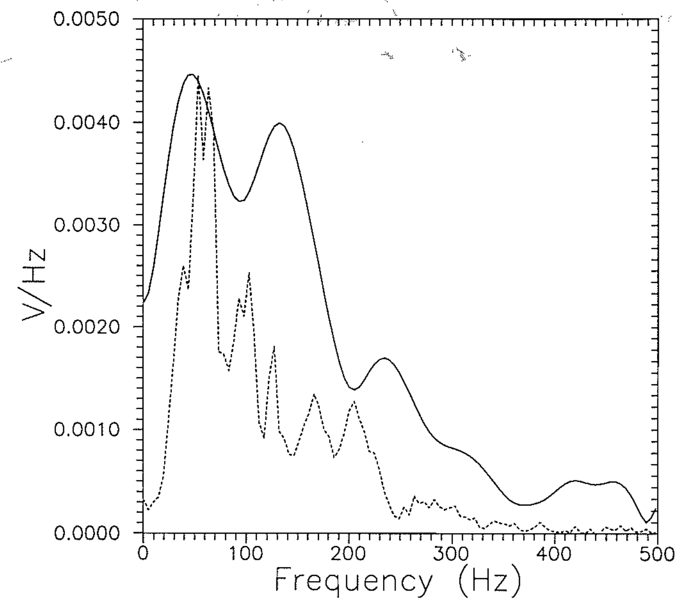

FIG. 17. Comparison of P- and S-wave FFT's from Buffalo-gun source at 5.7 m (scaled to same peak, SCPT C77-89-5). —, 0–25.2 ms portion; - - -, 25.2 ms to end.

from about 40 to 100 Hz. These frequency ranges are used to guide judgment in choosing the most appropriate band width for filtering for cross-correlation computations over the depth of the SCPT.

Measured signal characteristics

Investigations at a number of sites have allowed generalized observations of the frequency content of measured signals. The FFT's for the unfiltered full signal (from shear beam source and accelerometer receiver) shown in Fig. 12 (predominantly sand with silty sand and sandy silt) and Fig. 13 (predominantly clay with numerous sand and silt lenses) reveal the frequency variation of shear waves over the upper 10 m at each site. In Figs. 12 and 13 the top curve is for 2.7 m depth and progresses downward in 1-m increments to 9.7 m depth at the bottom. The results suggest that the predominant frequency of the shear wave where the amplitude is a maximum changes only slightly with depth, if at all, for both clayey and sandy soils. Furthermore, the predominant frequency for the shear wave appears to be about 75 Hz. When FFT's are analyzed for greater depths (to 20 or 30 m) the same trend continues with little variation in predominant frequency.

Similar comments can be made with respect to the variation of frequency content with source type. The majority of the investigations have been carried out with the hammer-on-beam or shear-beam source, but some investigations used the Buffalo gun. The results shown in Fig. 14 (about 5 m deep in mainly sand) and Fig. 15 (about 24 m deep in silt) compare the spectra of the signals measured from both sources and show that the frequency content is similar with the predominant frequency again in the order of 75 Hz.

Figure 16 shows the time record of a Buffalo-gun signal. It is possible to see the P-wave arrival at about 10 ms and the S-wave arrival at about 35 ms. If this record is divided at 25.2 ms into two signals, to isolate the P- and S-waves, the FFT's of the two signals are as shown in Fig. 17. Again, the frequency contents of the two spectra are similar.

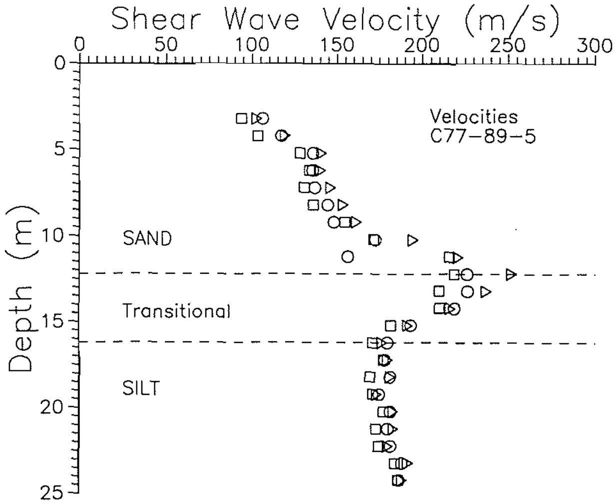

FIG. 18. Comparison of shear velocities using different measurement techniques, sources and calculation methods. ▷ and □, shear-beam and Buffalo-gun sources, respectively, calculated by cross-correlation method; ○, shear beam, calculated by cross-over interval method.

The technique of dividing the record of the time domain signal to separate the P- and S-wave portions of the soil response allows one to attempt to perform the cross-correlation method over a depth interval to determine the P- and S-wave velocities without one affecting the other. If the P- and S-waves are not well separated in time, as might happen at shallow depths especially in unsaturated soil, the authors know of no method to separate the two waves, especially since they have about the same frequency content. Sometimes it is necessary to use a Buffalo-gun or other point source where a shear-beam source is not feasible, for example, where the ground surface is below water and the separation of the P and S portions of the seismic wave is a first requirement.

Figure 18 summarizes the results of seismic cone shear wave velocity measurements to a depth of 25 m at the McDonald farm research site, where sand to 12 m overlies a soft plastic clay silt that starts at about 16 m and is separated by a sand to silt transition zone. The cross-correlation method is compared for the shear-beam and Buffalo-gun sources. Also compared are the results of using the simpler cross-over pseudo interval method. All give essentially the same results at this site except near soil-layer boundaries. The Buffalo gun gives slightly lower velocities.

Conclusions

To date the use of P- or compression-wave velocity measurements in foundation design for calculations of deformation and stability has had little application, especially in saturated soil where its value can be predicted with good accuracy compared with other properties. On the other hand, the shear wave velocity relates to shear modulus or stiffness of the soil skeleton which is used in calculations for deformation and stability where shearing stresses dominate soil behaviour. In addition, shear wave velocity is strongly affected by overburden or confinement stress, soil type, density, and strength.

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

It is the authors' recommendation that the optimum determination of shear wave velocity can be obtained by using, whenever possible, (1) a heavily loaded, shear-beam source to generate clear S-waves with little P-wave energy; (2) a high-sensitivity, critically damped, piezoresistive accelerometer receiver with a flat frequency response from 0 to 350 Hz or higher; (3) a single accelerometer with its active axis oriented in the horizontal direction parallel to the swing of the hammer and fixed firmly into a cone penetrometer; (4) a rectangular window to isolate a full cycle of the main shear wave by multiplying the signals by a rectangular window; (5) a cross-correlation method in the frequency domain to find the time shift, and if filtering is required, the use of only a zero phase shift digital filter over a band-pass width indicated by the FFT (or coherence or phase velocity); and (6) a versatile signal-processing software like VU-POINT, which has proven invaluable and is recommended to anyone carrying out the analysis of seismic waves.

The cross-correlation method assumes no dispersion and (or) distortion of the two signals over adjacent depths to obtain a correlation coefficient value close to 1.000. This assumption has been found to be very reasonable over the usual 1-m-depth intervals, provided a soil layer boundary is not intercepted, but caution and judgment must be used for larger spacings.

It is also interesting that a careful examination of recent experience with digital signal processing of many cone-accelerometer records at different sites, but all with water table near the surface, now suggests that the predominant frequency content of shear waves is relatively constant at about 75-Hz when full signals are analyzed. This value seems to be independent of soil type and depth to 30 m. These results, however, are only valid for sources and receivers used to date, namely, shear-beam and Buffalo-gun sources with 70% damped accelerometers. Furthermore, these results are different from those previously reported which were based on limited data (Campanella *et al.* 1989).

The Buffalo gun generates a strong P-wave as well as S-wave, whereas the shear-beam source generates a strong S-wave and almost no P-wave. Although the Buffalo gun is rarely used for on-land downhole seismic cone shear wave velocity logging, it is used in the offshore where a shear source is not feasible. Some of the characteristics of Buffalo-gun seismic data have been presented to aid in its analysis.

Acknowledgements

The authors wish to acknowledge the financial assistance of a Natural Sciences and Engineering Research Council of Canada strategic grant to study soil dynamics and of the British Columbia Science Council in the form of a GREAT grant in combination with industry participant Conetec Investigations, the use of British Columbia Ministry of Highways equipment, and the assistance of Graduate students in course Civil 577, Soil exploration for engineering design. Civil engineering technician support was indispensable, especially in the field.

Campanella, R.G., Robertson, P.K., Gillespie, D., *et al.* 1987. Seismic CPT in the near offshore of the MacKenzie Delta, N.W.T. Canadian Geotechnical Journal, **24**: 154–160.

Campanella, R.G., Baziw, E.J., and Sully, J.P. 1989. Interpretation of seismic cone data using digital filtering techniques. Proceedings, 12th International Conference on Soil Mechanics and Foundation Engineering, Rio de Janeiro, Brazil, vol. 1, pp. 195–199.

Davis, A.M. 1989. Determination of dynamic elastic parameters from crosshole testing. Scientific Drilling, **1**: 54–62.

Hoar, R.J., and Stokoe, K.H.II. 1978. Generation and measurement of shear waves in-situ. *In* Dynamic geotechnical testing. American Society for Testing and Materials, Special Technical Publication 654, pp. 3–29.

Laing, N.L. 1985. Sources and receivers with the seismic cone test. M.A.Sc. thesis, Civil Engineering Department, The University of British Columbia, Vancouver, B.C.

Pullan, S.E., and MacAulay, H.A. 1987. An inhole shotgun source for engineering seismic surveys. Geophysics, **52**: 985–996.

Rice, A.H. 1984. The seismic cone penetrometer. M.A.Sc. thesis, Civil Engineering Department, The University of British Columbia, Vancouver, B.C.

Robertson, M.D. 1986. Principles and parameters for the design of a portable shear wave source. B.A.Sc. thesis, Geological Engineering Program, The University of British Columbia, Vancouver, B.C.

Robertson, P.K., and Campanella, R.G. 1983*a*. Interpretation of cone penetrometer tests. parts I: Sand. Canadian Geotechnical Journal, **20**: 718–733.

Robertson, P.K., and Campanella, R.G. 1983*b*. Interpretation of cone penetration tests. Part II: Clay. Canadian Geotechnical Journal, **20**: 734–745.

Robertson, P.K., Campanella, R.G., Gillespie, D., and Rice, A. 1986. Seismic CPT to measure in-situ shear wave velocity. Journal of Geotechnical Engineering, **112**: 791–804.

Stewart, W.P. 1992. Insitu measurement of dynamic soil properties with emphasis on damping. Ph.D. thesis, Civil Engineering Department, The University of British Columbia, Vancouver, B.C.

Stewart, W.P., and Campanella, R.G. 1991. Insitu measurement of damping of soils. Proceedings, 2nd International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, St. Louis, Miss., vol. 1, pp. 83–92.

Tonouchi, K., Sakayama, T., and Imai, T. 1983. S wave velocity in the ground and the damping factor. Bulletin of the International Association of Engineering Geologists **26-27**: 327–333.

Woods, R.D., and Stokoe, K.H.,II. 1985. Shallow seismic exploration in soil dynamics. Richart Commemorative Lectures, American Society of Civil Engineers, New York, pp. 120–156.