Crosshole Measurement and Analysis of Shear Waves

Etude des Ondes de Cisaillement entre Trous de Sondage

R.J. HOAR Graduate Research Assistant, The University of Texas, Austin, Texas
K.H. STOKOE Associate Professor, The University of Texas, Austin, Texas

SYNOPSIS In situ shear wave velocity measurements were performed by the crosshole seismic method at a clay site with both a source in natural soil and an in-hole source. For measurements over the same travel paths, similar velocities were determined with both sources, but the in-hole source generated smaller strains and slightly less distinct shear and compression wave arrivals. Methods of digital signal analysis such as cross correlation, impulse response and cross power spectrum were found to underestimate slightly shear wave velocities determined from initial arrivals. Measurements of in situ material damping in shear were performed with values ranging from six to eleven percent. These values compare favorably with laboratory determined values of material damping which range from three to six percent.

INTRODUCTION

In situ measurements with seismic waves are widely employed in the geotechnical engineering community. Compression and shear waves are normally used, and wave velocities are usually measured. One field method often used for such measurements is the crosshole seismic method, particularly when accurate shear wave velocity profiles are required as is the case in dynamic analyses. The crosshole method is also suited for in situ measurements of material damping, although this type of measurement is still in the developmental stages.

The basic concept in the crosshole method is quite simple: just pass the desired seismic wave over a horizontal travel path and measure wave particle motion at various points. This concept of passing seismic waves between points in an undisturbed medium and measuring particle motions is more easily visualized than implemented. In reality, holes have to be drilled in the soil, the desired waves must be generated, and monitoring equipment must interact dynamically with both the soil and recording equipment to track properly wave particle motion. Next, wave propagation records must be analyzed to determine travel times and amplitudes so that wave velocities and attenuations can be calculated.

The objectives of this paper are: 1) to compare the records obtained from two crosshole sources, namely a sampling tube embedded in natural soil and an in-hole source coupled directly to a cased borehole wall; 2) to present and compare different methods of determining shear wave travel times; and 3) to outline one method of determining in situ material damping and to compare preliminary results from this method with resonant column laboratory tests.

The discussion is confined to measurements of compression and shear waves at strains below 0.001 percent where wave behavior is essentially independent of strain amplitude and strain rate. Furthermore, the discussion concentrates on measurements with shear waves and stresses the measurement of velocity and attenuation.

TESTING PROCEDURES

Requisite components in the crosshole method for accurate field measurement of shear wave velocity and attenuation include: mechanical sources which are strong, directional and repeatable shear wave generators; receivers with proper coupling, orientation and frequency response; recording equipment with accurate timing and proper frequency response and with more than one recording channel; precise and consistent triggering systems; and well-trained conscientious field personnel.

Wave velocities are the quantities most often determined with the crosshole method. The time for compression or shear waves to travel between several points at the same depth within a soil or rock mass is measured. With travel times, wave velocities are calculated after travel distances have been determined at each measurement depth.

One field procedure which is successfully employed in the engineering profession today (Woods, 1978) is as follows. Two or more cased boreholes with spacings on the order of 2 to 5 m are drilled and cased to the desired depth several days before testing. Either aluminum or plastic casing is used, and the casing is grouted in place. Either a standard penetration test split-spoon sampler or a thin-walled sampling tube can be employed as the mechanical source. To perform the test, another borehole (normally uncased) is advanced to the first measurement depth, and the sampler is inserted and advanced into the soil at the bottom of the borehole. A vertical impulse is applied to the top of the drill rod at the surface. The impulse generates compression and shear waves in the soil and simultaneously triggers a recording device, usually an oscilloscope. Wave arrivals are monitored by receivers securely coupled in the cased boreholes at the same depth. After measurements have been performed for all travel paths at this depth, the source borehole is advanced to the next depth, and the test is repeated. In this manner testing is continued to the final depth.

Vertical impulses applied to the drill rod generate predominately vertically polarized shear waves (SV-waves) which are best monitored by vertically oriented receivers. Vertical impulses also generate compression wave motion (P-wave) in the horizontal direction which is best monitored by radial horizontal receivers. Horizontally polarized shear waves (SH-waves) can also be generated by torsional impulses applied to the drill rod. These SH-waves are best monitored by horizontal receivers oriented perpendicular to the wave path. Torsional impulses can be reversed so that the polarity of the initial SH-wave arrival is also reversed to enhance identification of the initial SH-wave arrival. This procedure is typically necessary because of the low amplitude signals generated by torsional impulses. It is also possible to reverse the polarity of the initial SV-wave arrival by applying both downward and upward impulses. However, if readily identifiable shear waves are monitored which is most often the case for SV-waves with this type of source, polarity reversal of the shear wave serves little purpose, especially if the compression wave polarity also reverses as can be the case much of the time.

Recently, in-hole sources which couple energy to a borehole wall at any desired depth within the borehole have become popular, cost-effective alternatives to sources which couple energy directly to the soil at the bottom of a borehole. These sources are normally employed in cased boreholes. The most publicized in-hole source consists of a pneumatically activated wireline device (Woods, 1978). The authors have recently developed and field tested a simple in-hole source which can be used to generate both vertical and torsional impulses at depth in cased boreholes. This in-hole source which is shown in Fig. 1, consists of a simple mechanical wedging system which works well and can be constructed for less than a thousand dollars. Vertical or torsional impulses are delivered through a rod to the upper wedge while the vertical position of the lower wedge is fixed by wedging action and a wire rope.

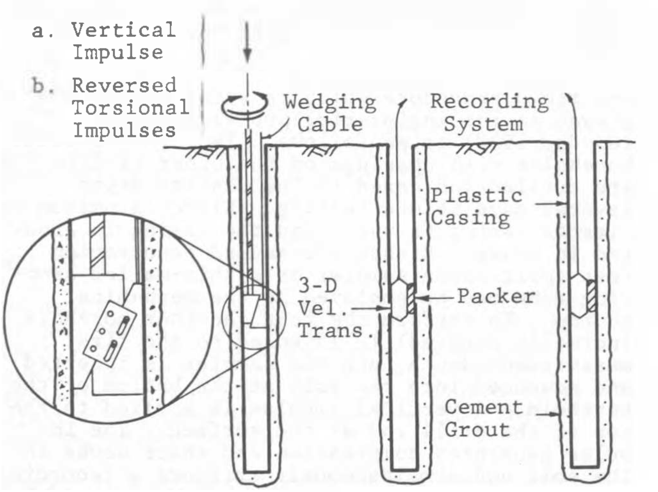

Fig. 1 - Schematic of Crosshole Testing With In-Hole Source

The field procedure used to employ the in-hole source is shown schematically in Fig. 1. This procedure is similar to that just described for the source in natural soil, except that all boreholes are cased to the final depth before testing. The in-hole source used in this study was designed so that its configuration would allow direct comparison to the tube source in natural soil. Thus rods were connected to the in-hole source so that impulses could be applied to the source through a pipe which extends to the ground surface. This configuration limits the depth to which this source can be easily operated to about 10 m. However, this in-hole source has been converted to a wireline device for operation to essentially unlimited depths.

COMPARISON OF CROSSHOLE SOURCES

Travel time records for vertical impulses of similar amplitudes monitored by vertical receivers approximately 4.9 m and 7.3 m from both a source in natural soil and an in-hole source in a cased borehole are presented in Fig. 2 for wave propagation over the same travel paths. Both source types generate readily identifiable SV-waves, although the source in natural soil generates slightly larger amplitudes (30 to 50 percent greater) with more distinct initial arrivals for similar impulses. The source in natural soil also generates larger and more distinct compression waves arrivals which is helpful in compression wave measurements.

A comparison of travel time records for reversed torsional impulses applied to both types of crosshole sources is presented in Fig. 3. These measurements were performed over the same travel path using tangential horizontal receivers approximately 2.4 m from the sources. Both source types generate identifiable SH-waves with reversed polarity of the initial SH-wave arrival for reversed impulses. However, the source in

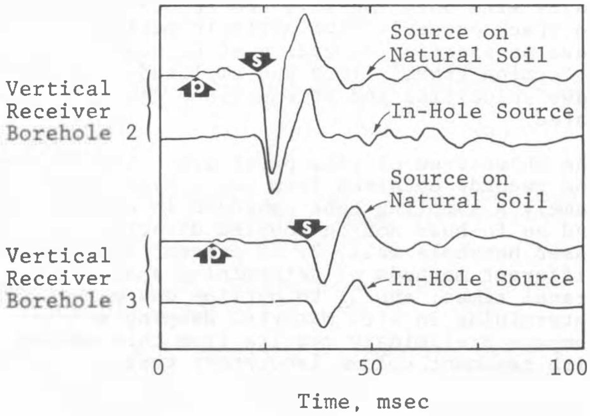

Fig. 2 - Crosshole Travel Time Records Generated With Vertical Sources

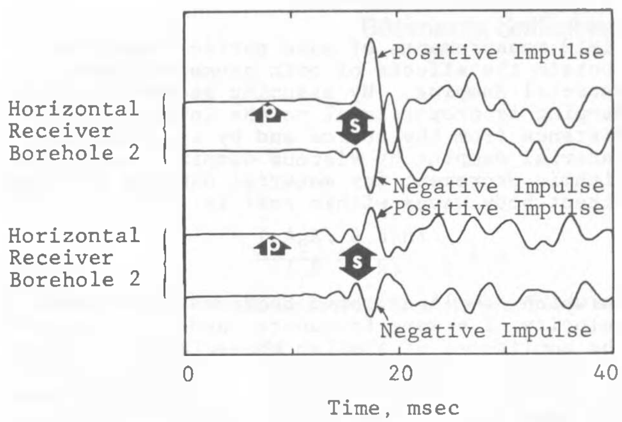

Fig. 3 - Crosshole Travel Time Records Generated with Torsional Sources

natural soil generates larger amplitude shear waves for similar impulses and produces a less complicated waveform. Initial compression wave amplitudes generated by both sources are small and neither source generates completely coincident compression wave energy for reversed impulses. Identification of initial shear wave arrivals for both sources is aided by knowledge of the receiver polarity with respect to source polarity, and monitored SH-wave motion is enhanced by correctly orienting the horizontal receiver (perpendicular to the direction between the source and receiver).

By using a plane wave approximation, shearing strain amplitudes can be estimated by dividing particle velocity by propagation velocity of the shear wave. Shearing strains generated by SV-waves at distances of 2.4, 4.9 and 7.3 m from the source in natural soil with receivers secured in cased boreholes averaged 0.00029, 0.00008, and 0.00003 percent, respectively. SH-wave shearing strains under the same conditions averaged 0.000021, 0.000005, and 0.000002 percent, respectively. Shearing strain values obtained from the in-hole source at the same depth and over the same travel paths were approximately one-half of those obtained with the source in natural soil.

The spatial distribution of P-, SV- and SH-wave energy from both types of crosshole sources was investigated. The spatial distribution of shear wave energy shows that large vertical components of the SV-wave are present over large angles (greater than 45 degrees) measured from the horizontal elevation of the source. The angle over which the amplitudes are significant is greater for the in-hole source inside a cased borehole than for the source in direct contact with natural soil.

IN SITU VELOCITIES

Seismic wave travel time records are typically analyzed by identifying initial wave arrivals and then determining either direct travel times from the source to a receiver or interval travel times between two receivers for the same impulse (as shown in Figs. 2 and 3). Interval travel times may also be determined by using points on the waveform other than the initial wave arrival, such as the first trough, first cross-over point or first peak after the initial arrival. Using points on the waveform other than the initial arrival tends to produce longer interval travel times and therefore slower velocities because of wave spreading. It is generally recognized that interval travel times produce more consistent and reliable velocity profiles because the effects of variables such as triggering, soil disturbance and casing are minimized.

Method of Travel Time Determination	Shear Wave Velocity, m/s					
	Direct			Interval		
	S-1	S-2	S-3	1-2	2-3	1-3
Initial Arrival*	199	207	206	217	206	209
First Trough*	-**	-	-	202	192	197
First Cross-Over*	-	-	-	202	189	196
First Peak*	-	-	-	175	182	188
Cross Correlation	169	-	191	185	182	191
Impulse Response	185	196	200	-	-	-
Cross Spectrum+	193	195	200	194	206	218

*from time history (see Fig. 2) + at 80 Hz
**not applicable or indeterminable

Table I - Wave Velocities Based on Various Travel Time Determination Methods

Crosshole measurements were performed at a clay site to a depth of about 10 m using a tube source in natural soil with receivers secured in three cased boreholes at about 2.3, 4.7 and 7.3 m from the source. Direct velocities from the source to the first receiver (S-1), second receiver (S-2) and third receiver (S-3) were determined from initial arrivals. Interval velocities between the first and second receivers (1-2), second and third receivers (2-3) and first and third receivers (1-3) were determined using both initial arrivals and the other points on the waveform described above. Direct and interval P-, SV- and SH-wave velocities were determined over all combinations of travel paths

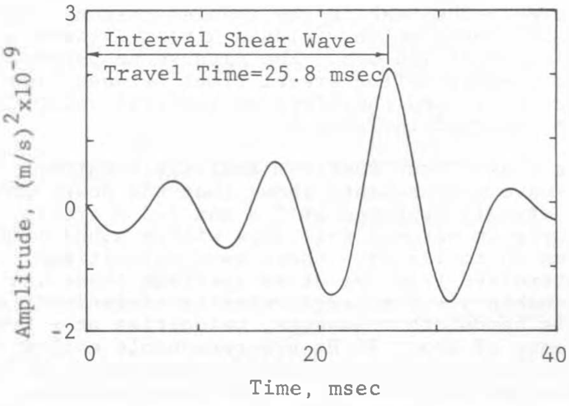

Fig. 4 - Interval Travel Time From Cross Correlation Function

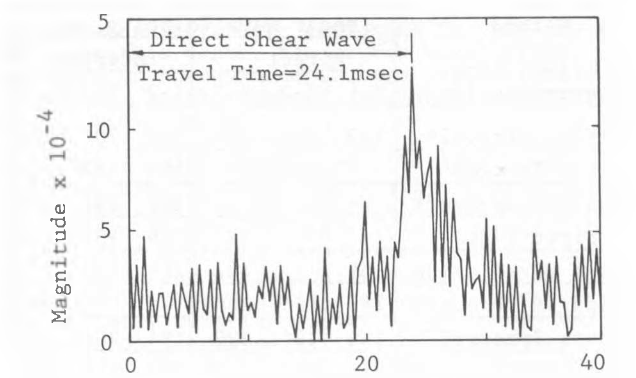

Fig. 5 - Direct Travel Time From Impulse Response Function

versus depth. At this site, SV-waves generally propagated at higher velocities than SH-waves. Direct and interval SV-wave velocities measured at a depth of about 4.6 m at this site are reported in Table I. Direct and interval velocities determined from points on the waveform other than the initial arrival are less than those determined from the iniital arrival with velocity decreasing as the time between the initial arrival and reference point increases.

Cross correlation, impulse response and cross power spectrum digital signal analysis methods were also used at this clay site to determine direct and interval SV-wave velocities over the same travel paths as those shown in Table I for direct analysis of the time histories. The results of these digital signal analysis methods are also reported in Table I for comparison.

A typical cross correlation function for the SV-wave measurements with receivers about 2.3 and 7.3 m from the source is shown in Fig. 4. The peak of the cross correlation function occurs at a time shift between signals of 25.7 msec which yields an interval SV-wave velocity of 191 m/s. A typical impulse response for SV-wave measurements is shown in Fig. 5. This measurement was performed with one receiver secured to the source and the other receiver 4.7 m away from the source. The peak in the impulse response occurs at 24.1 msec which yields a direct SV-wave velocity of 196 m/s. The impulse response did not clearly define travel times between receiver boreholes, and therefore no interval velocities are reported in Table I.

The cross power spectrum analysis obtained for SV-wave measurements shows that the power common to signals measured at 2.3 and 7.3 m from a source in natural soil lies within a bandwidth from 25 to 125 Hz. Shear wave velocities determined from the cross spectrum phase relationship yield a large velocity variation over this bandwidth. However, velocities at a frequency of about 80 Hz are reasonable estimates of both direct and interval velocities obtained from initial arrivals on the time histories. This frequency was chosen because it is in the center of the bandwidth with significant power common to both signals.

IN SITU MATERIAL DAMPING

Field measurements of wave particle motions contain the effects of both geometric and material damping. By assuming geometrical damping is proportional to the inverse of the distance from the source and by representing material damping by viscous damping, the logarithmic decrement for material damping only for direct body waves within soil is:

$$\delta = \frac{v}{f} \frac{\mathrm{In}(R_1A_1/R_2A_2)}{(R_2 - R_1)} \qquad (1)$$

in which δ = logarithmic decrement; v = wave velocity; f = wave frequency; and A_1 and A_2 are the amplitudes of similar characteristic points on the waveform at distances R_1 and R_2, respectively from the same impulse. The logarithmic decrement equals $2\pi D/\sqrt{1 - D^2}$ in which D is damping ratio. Use of these equations to calculate in situ material damping from field measurements assumes that: 1) material damping is independent of strain within the strain range being generated; 2) actual free-field particle motions can be measured with no receiver-coupling or casing effects; and 3) measured amplitudes are not affected by reflected or refracted waves.

The previous equations were used to calculate in situ material damping versus depth at a clay site. In situ material damping ranged from 7 to 11 percent and from 7 to 8 percent at depths of 2.7 and 3.7 m. Material damping was also determined on samples obtained from similar depths at this site and confined at comparable stresses in laboratory resonant column tests. Laboratory values of material damping of from 4 to 6 percent and from 3 to 6 percent were measured for the shallow and deep specimens, respectively.

CONCLUSIONS

1. In-hole sources can be used to produce identifiable P-, SV- and SH-waves, but sources in natural soil generate larger amplitude waves and less complicated waveforms. Wave velocities measured using both types of sources compare favorably.
2. Methods of wave travel time determination other than direct analysis of time histories tend to underestimate shear wave velocities based on initial arrivals by about ten percent or less. However, these methods require time histories with identifiable shear waves in order to work well.
3. Measured values of in situ material damping tend to overestimate laboratory values determined by resonant column tests by about a factor of two.

REFERENCE

Woods, R. D., (1978), "Measurement of Dynamic Soil Properties," Proceedings, Earthquake Engineering and Soil Dynamics, ASCE, Vol. I, Pasadena, California, pp. 91-178.