FIELD AND LABORATORY MEASUREMENTS OF MATERIAL DAMPING OF SOIL IN SHEAR

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SUMMARY

Field values of material damping were calculated by two methods from the decay of shear wave amplitudes determined by crosshole seismic tests. The first method consisted of manual determination of wave amplitudes, while the second method utilized Fourier analysis. Material damping of intact soil samples was also measured in the laboratory by the resonant column method. Manual determination of wave amplitudes yielded material damping values about twice those measured in the laboratory, while Fourier analysis gave about half the laboratory values. The Fourier analysis method accounts for dispersion during propagation and is therefore recommended for field measurements.

INTRODUCTION

Field measurements using seismic waves are employed in geotechnical engineering for a variety of purposes. Compression and shear waves are usually used, and wave velocities are normally determined. The crosshole method is often used for these measurements, especially when accurate shear wave velocity profiles are required as is the case for many earthquake analyses. Crosshole measurements of compression and shear waves are typically performed at strains below 0.001 percent, where wave behavior is assumed independent of strain amplitude and rate. The crosshole method is also well suited for determination of in situ material damping, although this type of measurement is still in the developmental stage.

The objectives of this paper are to outline two methods of determining in situ material damping from crosshole measurements and to compare in situ damping values obtained from these methods with laboratory damping values obtained by the resonant column method. The resonant column method is a common laboratory method used to measure material damping of soil samples in shear (Ref. 1). Material damping is obtained from the torsional-free-vibration-decay curve and is often expressed as a damping ratio, D. For soils in shear, damping ratio at small strains determined by the resonant column method is typically on the order of a few percent.

The following discussion concentrates on in situ determination of material damping in shear from crosshole measurements. However, a similar analysis and procedure also apply to determination of material damping in compression from crosshole measurements or to the use of other seismic field methods, such as the downhole method (Ref. 2), with body waves.

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CROSSHOLE METHOD

The basic concept of the crosshole method is quite simple: just pass the desired seismic wave over a horizontal travel path and measure wave particle motions 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 wave must be generated, and for proper tracking of wave particle motion, monitoring equipment must interact dynamically with both the soil and the recording equipment.

Requisite components of the crosshole method for accurate measurement of shear waves include: (1) mechanical sources which are strong, directional and repeatable shear wave generators; (2) receivers with proper coupling, orientation, and frequency response; (3) recording equipment with accurate timing, proper frequency response, and with more than one recording channel; (4) precise and consistent triggering systems; and, (5) well-trained, conscientious field personnel.

One crosshole field procedure which is successfully employed in the engineering profession today (Ref. 3) is shown schematically in Fig. 1. Two or more boreholes with spacings on the order of about ten feet are drilled and cased to the desired depth several days prior to testing. Either aluminum or plastic casing is used, and the casing is grouted in place. Either a split-spoon sampler from the standard penetration test or a thin-walled sampling tube can be employed as the mechanical source. To perform the test, another borehole (normally uncased and within about 7 ft of cased borehole one) 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. This impulse generates compression and shear waves in the soil and is used to trigger a recording device, usually a digital oscilloscope. Wave propagation is monitored by receivers securely coupled in the cased boreholes. 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.

A typical crosshole record is presented in Fig. 2. This record was obtained at a medium-stiff clay site at a depth of 15 ft. The record shows wave particle motion monitored by vertical receivers at three distances from the source borehole. Another vertical receiver was attached to the source, and the output of this receiver is shown as the top trace in the figure. Initial compression and shear wave arrivals are identified in the figure by "P" and "S", respectively. Compression and shear wave velocities determined from these initial wave arrivals averaged about 2,100 fps and 690 fps, respectively.

THEORETICAL BACKGROUND

When body waves propagate in soil, their amplitudes decay from the combined effects of geometrical and material dampings. (Wave amplitudes can also be affected by interference from reflected and refracted waves and from back-scattering). For body waves within a soil medium, the theoretical geometrical damping component predicts that body wave amplitudes decrease in

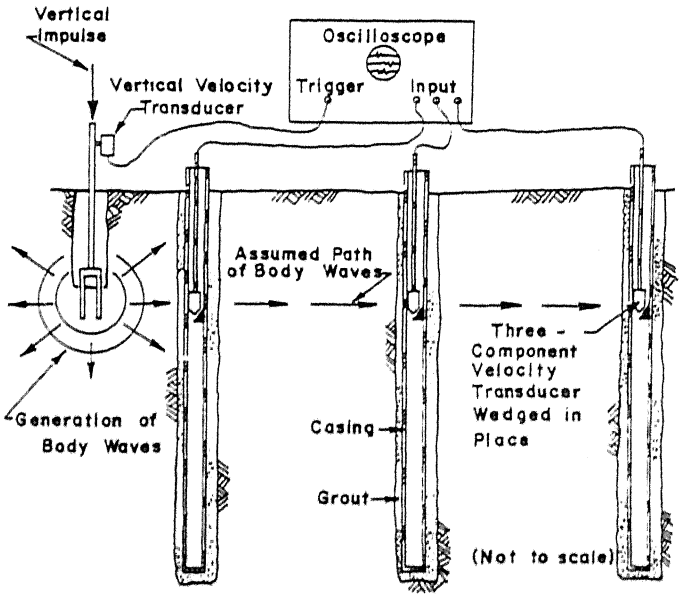

Fig. 1 - Cross-Sectional View of Crosshole Seismic Method

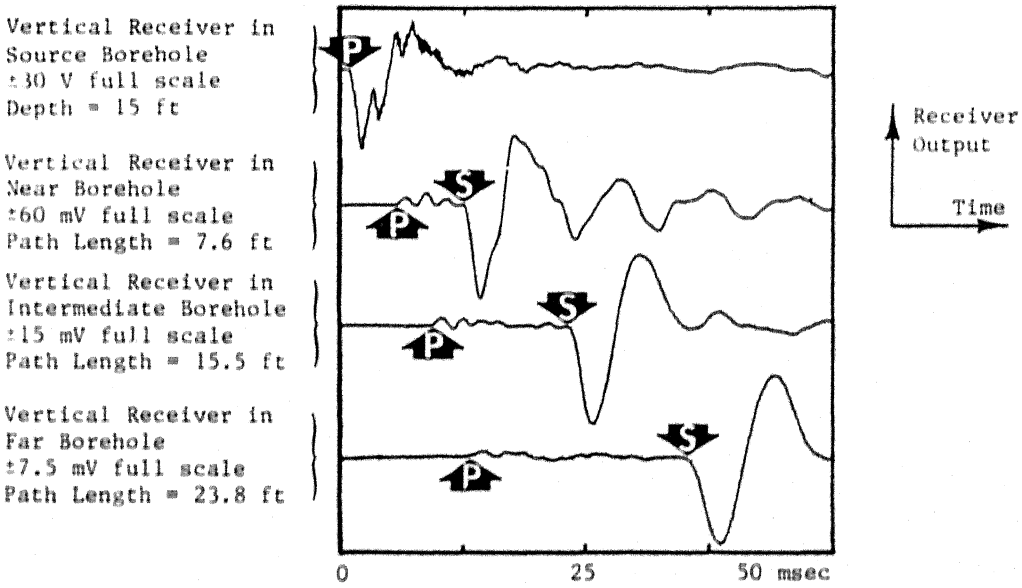

Fig. 2 - Typical Waveforms for Shear Waves

proportion to the inverse of distance from the source (i.e., 1/R, where R is the distance from the source). The viscous material damping component for body waves expressed as a damping ratio, D, is (Ref. 4):

$$D = \frac{\ln(A_1R_1/A_2R_2)}{\sqrt{(2\pi t_I/T)^2 + [\ln(A_1R_1/A_2R_2)]^2}} \qquad (1)$$

where A_1 and A_2 are amplitudes of similar characteristic points on the waveform at distances R_1 and R_2, respectively; T is the period of the wave; and t_I is the interval travel time for the wave to propagate from distances R_1 to R_2. An "idealized" crosshole shear wave record in which these variables are defined is presented in Fig. 3. Use of Eq. 1 to calculate material damping from measured waveforms assumes that: (1) material damping is independent of strain amplitude within the generated strain range; (2) actual free-field particle motions can be determined from receiver output with no casing or receiver-coupling effect, and (3) measured wave amplitudes are not affected by reflected or refracted waves or by back-scattering.

In situ determination of material damping using Eq. 1 requires determination of wave amplitudes at a minimum of two different distances from the source. To assure that the amplitude of the source impulse is the same for both amplitude measurements, simultaneous monitoring of receivers for the same source impulse is essential, which is consistent with properly performed crosshole measurements.

MANUAL WAVEFORM ANALYSIS

Because of the idealized nature of the waveforms presented in Fig. 3, the period of the main S-wave pulse appears to be the same for both receivers. These idealized S-wave pulses are also symmetrical (in terms of amplitude) about the initial arrival, and therefore the same value of damping ratio would result if either double amplitudes (i.e., trough-to-peak) or single amplitudes (i.e., either initial arrival-to-trough or initial arrival-to-peak) are used. A similar analysis of real measured seismic waveforms, such as the waveforms presented in Fig. 2, is not as simple because the period and shape of the waves change as they propagate and also because the waveforms are not usually sinusoidal or even symmetrical.

Wave amplitudes and periods can be defined in a number of different ways. As shown in Fig. 4, wave amplitudes and periods can be measured from: (1) the initial arrival to the first trough, A_{it} and T_{it}; (2) the first trough to the first peak, A_{tp} and T_{tp}; and (3) the cross-over point to the first peak, A_{cp} and T_{cp}, respectively. Because seismic waves are nonsymmetrical and change shape as they propagate, different methods of defining wave amplitude and period can produce different calculated values of damping ratio. Therefore, use of Eq. 1 requires selection of one of these definitions.

The three definitions of wave amplitude and corresponding wave period were used to determine damping from the shear waves presented in Fig. 2 (receivers in cased boreholes). Damping ratios from this analysis, which are presented in Table 1, ranged from 2.2 to 8.0 percent and averaged 5.2 percent. A similar analysis was also performed on two other sets of

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Table 1 - Material Damping Ratios of Shear Waves
From Manual Analysis of Waveforms

Reference Points on Waveform (see Fig. 4)	Damping Ratio, D, percent				
	Receiver Locations (see Fig. 1)				
	Cased			Uncased	
	R1 - R2	R2 - R3	R1 - R3	R2 - R3	R2 - R3
initial arrival and first trough	8.0	5.6	6.9	8.2	7.6
first trough and first peak	7.0	3.6	5.1	8.0	8.8
cross-over point and first peak	5.0	2.2	3.6	8.9	10.4
Measurement Depth (ft)	15			9	12

crosshole measurements performed earlier at this site. Receivers for these two measurements were at depths of about 9 and 12 feet in the same boreholes which were uncased at the time. Damping ratios from these measruements are also included in Table 1 and averaged 8.4 and 8.9 percent for the shallower and deeper measurements, respectively.

FOURIER WAVEFORM ANALYSIS

An inherent problem with the manual analysis procedure is that since seismic waveforms are not sinusoidal or even symmetrical, the frequency

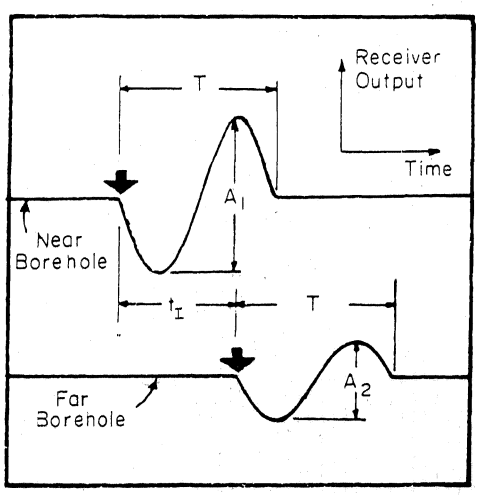

Fig. 3 - Idealized Waveform Defining Qualities for Damping Calculation

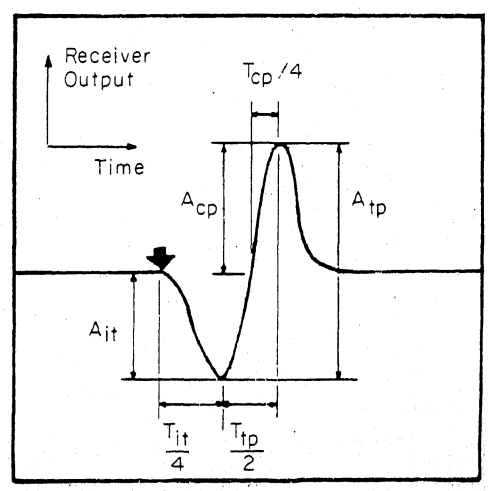

Fig. 4 - Nonsymmetrical Waveform with Associated Amplitudes and Periods

(or period) and amplitudes which should be used in Eq. 1 are not clear. Fourier analysis can be used to overcome these problems by determining wave amplitudes and travel times at specific frequencies.

A digital signal analyzer was used to determine amplitudes and phase differences of the waveforms in Fig. 2 as a function of frequency at 6.25-Hz intervals up to a maximum frequency of 1600 Hz. The linear spectra obtained from this analysis are presented in Fig. 5. The major frequency components, which represent the shear wave, lie within a bandwidth from about 25 to 300 Hz. It is difficult to distinguish any higher frequency components which might represent the compression wave.

The magnitude and phase difference of the crosspower spectrum for waveforms measured at the near- and intermediate-receiver boreholes (R1 and R2, respectively) are shown in Fig. 6. The magnitude is a measure of the power common to both signals. The phase difference is the relative phase between the different frequency components of the two waveforms. Interval travel times at frequency are calculated from the phase difference by

$$t_I(f_n) = T_n[\phi(f_n)/360] \quad . \; . \; . \; . \; n = 1, 2, 3, \; . \; . \; . \; \text{etc.} \tag{2}$$

where $t_I(f_n)$ is the interval travel time at the given frequency f_n; T_n is the period of the frequency under consideration ($= 1/f_n$); and $\phi(f_n)$ is the phase difference in degrees between the components of the two waveforms at frequency f_n.

Interval shear wave travel times determined by Eq. 2 were used with wave amplitudes contained in Fig. 5 to determine damping ratio as a function of frequency using Eq. 1. The results of these calculations are presented in Fig. 7. Either very low positive (less than two percent) or negative damping ratios were determined. Negative damping ratios mean that

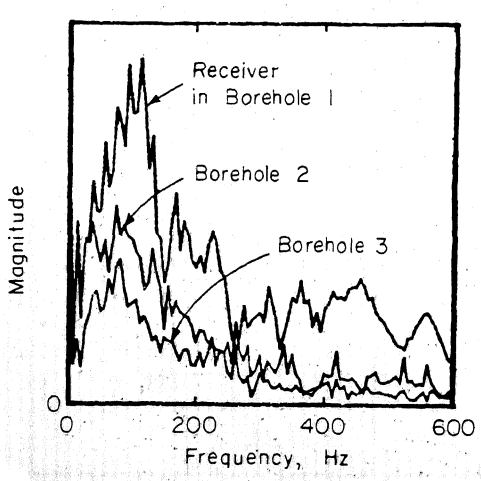

Fig. 5 - Linear Spectra of Waveforms in Fig. 2

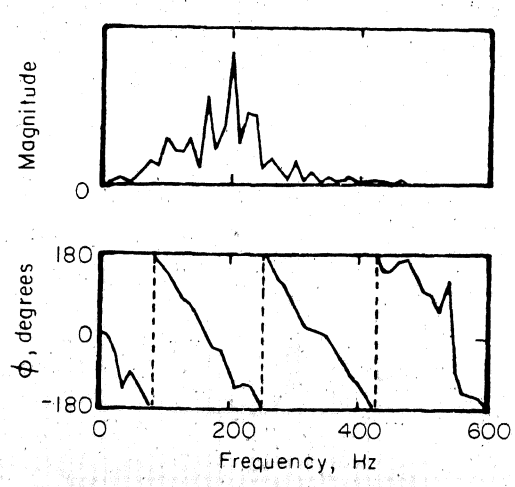

Fig. 6 - Crosspower Spectrum from Receivers in Boreholes 1 and 2 in Fig. 2

the measured combination of both geometrical and material damping is less than the theoretically assumed value for body waves with only geometrical damping. Obviously, negative material damping values are incorrect. However, these negative values are generally associated with wavelengths greater than the spacing between boreholes, and in this case a near-field term should probably be included in Eq. 1. The low positive damping ratios seem reasonable, especially considering the small shearing strains associated with the waves which ranged from 0.00006 to 0.0004 percent.

LABORATORY MEASUREMENTS

Laboratory measurements of material damping were performed on two "undisturbed" soil samples from nearly the same depths where the crosshole measurements were performed. The two soil samples were obtained from depths of 9.3 and 11.0 ft. Laboratory measurements were performed by the resonant column method. Values of the damping ratio in shear only for material damping were determined from torsional-free-vibration-decay curves assuming viscous damping (Ref. 5).

Results of the resonant column measurements are presented in Fig. 8. The in situ total overburden pressures were estimated at 8 and 10 psi for the shallower and deeper samples, respectively. Laboratory measured values of damping ratio at these in situ pressures ranged from 4.6 to 5.1 percent for the shallower sample and from about 4.6 to 5.4 percent for the deeper sample. There is considerable scatter in these data which is typical of such measurements (Ref. 5), and no clearly discernible variation in damping ratio with time after initial confinement is evident.

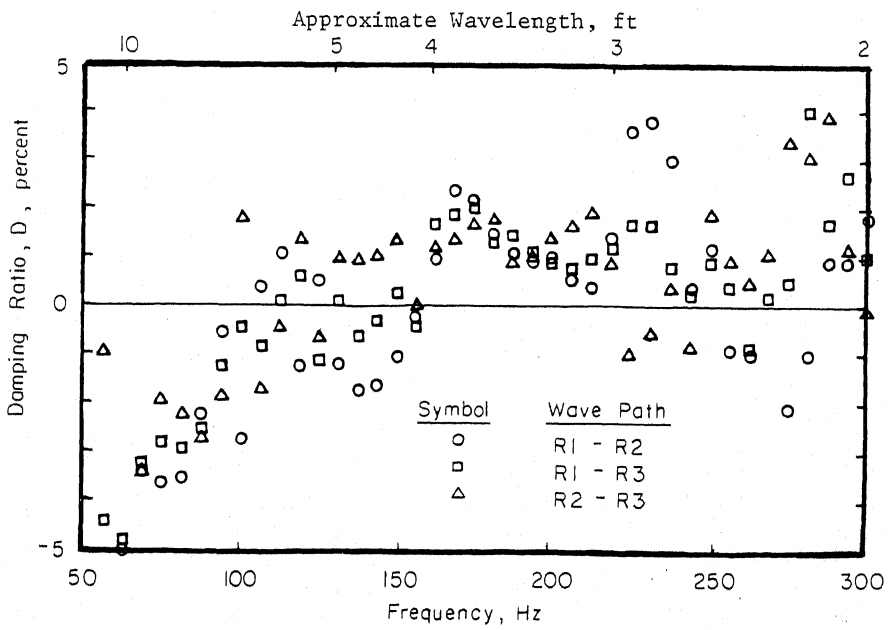

Fig. 7 - Material Damping Ratios from Waveforms in Fig. 2 Using Fourier Analysis Method

DISCUSSION AND CONCLUSIONS

In general, differences between field and laboratory values of damping ratio can be attributed to: (1) sample disturbance, (2) inability to reproduce in situ stress conditions in the laboratory, (3) confinement time in the laboratory, (4) inherent problems with laboratory testing and analysis methods, (5) samples unrepresentative of in situ material, and (6) inherent problems with field testing and analysis methods. Items (2) and (3) are not suspected to be a problem with these measurements because of the relatively small effects of confining pressure and time on damping ratio as evidenced in Fig. 8. However, any of the other items could be contributors to the observed differences. For this clayey soil, it seems likely that damping values determined in the laboratory should be higher than those determined in the field. In situ material damping calculated by manual analysis of measured waveforms exceeded laboratory damping values by a factor of about two, while damping values calculated by the Fourier-analysis method were about one-half of the laboratory values. Therefore, calculation of in situ damping by the Fourier-analysis method seems more appropriate and is recommended for field use.

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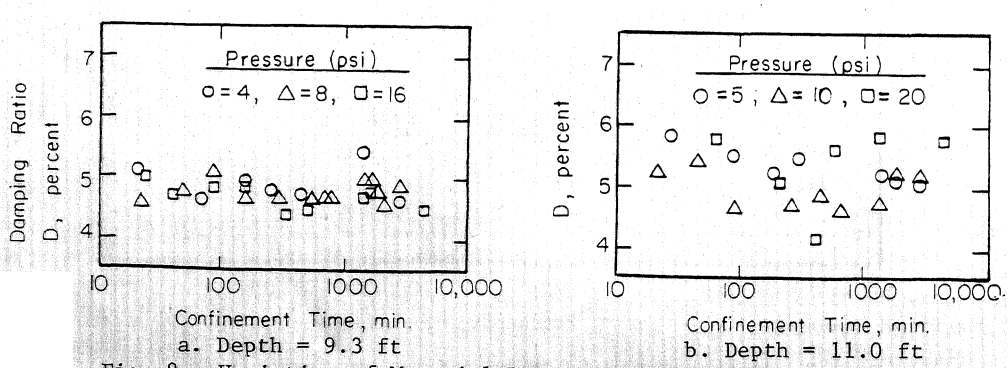

Fig. 8 - Variation of Material Damping Ratio with Pressure and Time for Clay Samples