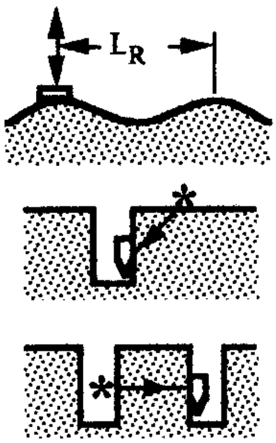
In Situ Measurement of Stiffness and Damping of Soil by Crosshole and Downhole Methods

Young Jin Mok, SsangYong Engineering Co., Ltd.

CONTENTS



INTRODUCTION

Seismic methods have been widely used to profile near-surface soils. In geotechnical earthquake engineering and soil dynamics, seismic methods are generally used to evaluate wave velocities and, hence, to characterize elastic moduli. The most common seismic methods include the crosshole, downhole, surface refraction, steady-state Rayleigh-wave and Spectral-Analysis-of-Surface-Waves (SASW) methods. These methods are illustrated schematically in Fig. 1. Of these techniques, the crosshole and downhole methods (body wave methods involving boreholes) are the most widely used methods and are the ones that provide the most reliable results for state-of-the-practice applications.

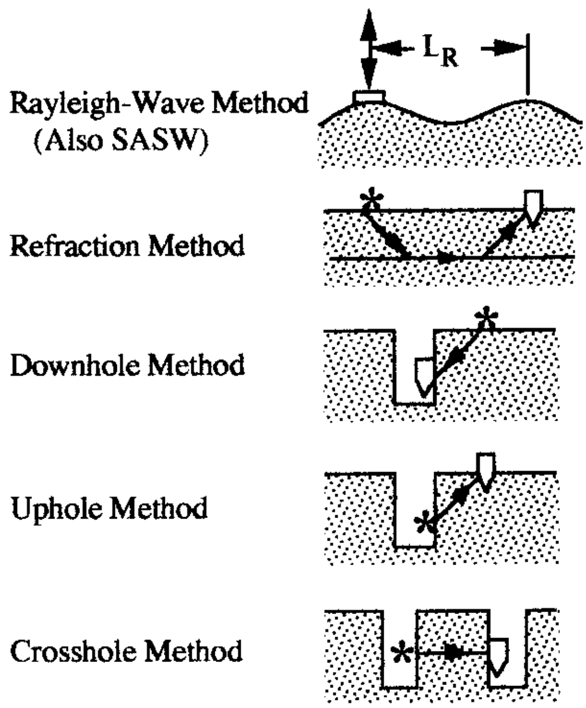


Fig. 1 Typical Methods Used in Geotechnical Engineering to Measure In-Situ Seismic Wave Velocities

When compared with all other in situ tests of soils, seismic methods have distinct advantages. These advantages include: 1) they can be tailored to sample small or large zones of soil; 2) they have a strong theoretical basis (the theory of elasticity); 3) the loading closely represents the analytical model used to evaluate the results; and 4) measured wave velocities are independent of equipment used. In comparison with laboratory tests on geotechnical materials, field seismic tests have the advantages that: 1) an undisturbed zone of material can be tested; 2) initial in-situ stress states, soil fabric, and inherent anisotropy are automatically incorporated; and 3) large zones of material which represent the macroscopic nature of the site can be sampled. As a result, in situ seismic methods, and borehole methods in particular, continue to have an important role to play in geotechnical engineering, with this role being especially strong when dealing with the deformational characteristics of soil.

DYNAMIC SOIL BEHAVIOR AT SMALL STRAINS

Seismic methods such as the crosshole and downhole methods have traditionally been employed in the field to determine initial tangent moduli (Woods and Stokoe, 1985; and Woods, 1987). One of the reasons these methods have been successfully used for this purpose is the magnitude of the strains generated in the soil during their use. The variation in shear modulus with shearing strain amplitude can be evaluated from the monotonic loading curve with secant moduli as shown in Fig. 2. The resulting modulus-strain relationship is shown in Fig. 3 and represents the G - log γ relationship for the first cycle of loading (N_c = 1). As seen in Fig. 3, there is an elastic threshold shearing strain, γ^e_t, of approximately 0.001 percent below which shear modulus can be considered constant and equal to the initial tangent modulus. Measurements made below γ^e_t are said to be small-strain or low-amplitude measurements. Because field seismic methods normally operate below this threshold strain and because frequencies generated in these tests are typically less than several hundred Hertz, measurement of G_{max} compatible with soil dynamics and geotechnical earthquake engineering problems is performed, and strain amplitude and strain rate can generally be ignored.

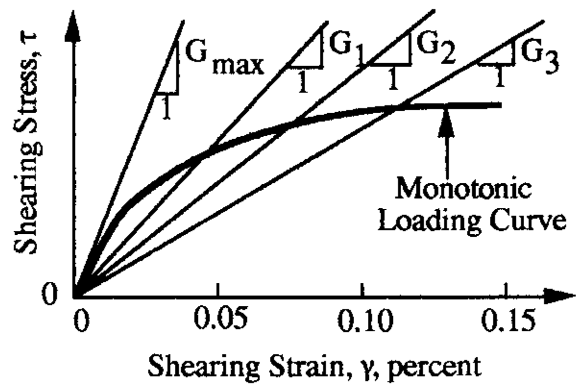


Fig. 2 Illustration of Variation in Secant Shear Moduli with Shearing Strain for Monotonic Loading of Soil

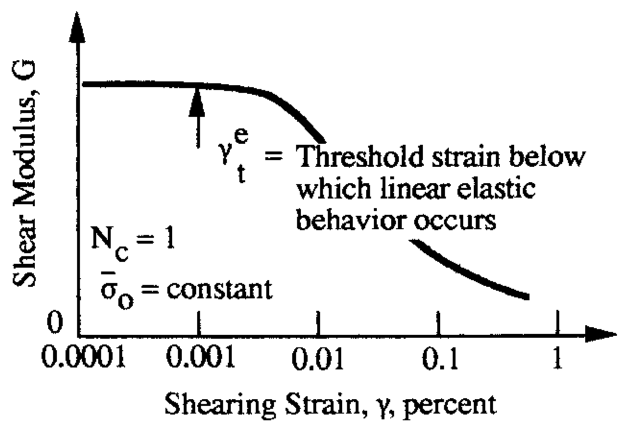


Fig. 3 Generalized Variation in Shear Modulus with Shearing Strain Obtained from Fig. 2

The state-of-practice in soil dynamics and geotechnical earthquake engineering in terms of field measurement of dynamic soil properties is generally limited to measurement of dynamic moduli (shear and constrained moduli) at small-amplitude strains. Although the in-situ impulse test (Wilson et al, 1978) and CIST (Air Force Weapons Laboratory, 1977) methods are useable at higher strains, economics and availability have severely limited their use. Efforts are underway to develop field methods for measurement of material damping using both the crosshole (Mok, 1987 and Mok et al, 1988) and downhole (Redpath and Lee, 1986) methods. Therefore, dynamic laboratory tests are generally used to determine material damping. These laboratory tests are also typically used to determine the variation in moduli with strain amplitude at and above the elastic threshold strain level. Field and laboratory results are then combined with engineering judgement to estimate the nonlinear dynamic properties of soil in-situ.

SEISMIC WAVES AND MEASUREMENTS

When a disturbance is initiated in any kind of a medium, a stress wave field is generated. For geotechnical engineering applications, the medium consists of soil or rock and is often represented as a layered elastic half-space. In such a solid system, the generated wave field can contain both stress waves (seismic waves) which propagate within the body of the medium, called body waves, and stress waves which propagate along the surface of the medium, called surface waves. Seismic waves which propagate through the body of the medium are either compression (P) or shear (S) waves. Seismic waves which are predominantly confined to the surface layers can be of either the Rayleigh (R) or Love type. When borehole methods like the crosshole and downhole methods are used, P- and S-waves are generated and measured. Of these waves, the shear wave is of most importance in geotechnical engineering.

Key variables in seismic testing are: 1. source, 2. receivers, 3. recording equipment, 4. triggering system, 5. borehole type and array, 6. soil disturbance, 7. data collection and analysis and 8. conscientious field personnel. These variables are briefly discussed in this presentation.

Borehole measurements typically entail monitoring wave particle motions (either particle velocity or acceleration) with some type of seismic receivers. Most seismic receivers are directional (i.e., have a single axis of maximum sensitivity), and therefore, for the optimum performance in any seismic test, receivers should be oriented in the direction of maximum particle motion for the wave type being monitored. Borehole testing with body waves simply consists of measuring the time required for these waves to travel given distances. Once travel times and distances have been measured, wave velocities are calculated by dividing distance of travel by travel time. The initial tangent modulus related to each wave velocity can be calculated by assuming an isotropic and homogeneous medium from:

Shear Modulus: $$G = \rho V_s^2 \quad (1)$$

Constrained Modulus: $$M = \rho V_p^2 \quad (2)$$

where V_s is shear wave velocity, V_p is compression wave velocity and ρ is the mass density of the soil ($\rho = \gamma/g$ where γ is total unit weight and g is gravitational acceleration). The constrained modulus, M, (which differs from Young's modulus) is determined from the compression wave velocity in the soil mass once measurements are made at distances greater than about two wavelengths from the source. In this region, plane wave motion can reasonably be considered to occur, and hence no lateral deformation results in a direction perpendicular to the propagation direction as illustrated in Fig. 4.

$$V_p \longrightarrow M_{max} = \frac{\gamma}{g} V_p^2$$

$$V_s \longrightarrow G_{max} = \frac{\gamma}{g} V_s^2$$

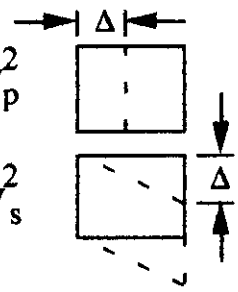


Fig. 4 Low-Amplitude Dynamic Moduli Determined from Body Wave Velocities in an Isotropic Medium

WAVE VELOCITY MEASUREMENTS

It is common practice in the crosshole or downhole methods to use a linear source-receiver array with one or two receivers located at distances d_1 and d_2 from the source. Propagation of body waves generated by the source is monitored with receivers at the same depth as the source. The traditional approach used today to determine shear (S) or compression (P) wave velocity is based on identifying visually the time of arrival of the compression or shear wave at the first receiver or by similarly identifying the time interval between first arrivals of the wave at the first and second receivers. Once these times are determined, velocities are calculated by dividing distances by the appropriate times. Wave velocities determined by source-to-receiver measurements are termed direct velocities while velocities determined by receiver-to-receiver measurements are termed interval velocities (Stokoe and Hoar, 1978).

Interval velocities can also be evaluated using the visual approach but by using time differences determined from other reference points on the waveforms. Reference points such as first troughs, first peaks or zero crossings have been used. All of these approaches give similar velocities, although the results may differ slightly due to the dispersive nature of the waves. This traditional time-domain procedure, although easy to understand, requires some expertise in reducing the data and lacks the potential for full automation.

Other techniques based on correlation and spectral analysis theories can be employed to determine body wave velocities in the crosshole and downhole tests. All time-determination techniques require the use of at least three test locations; one for the source and two (or more) for the receivers. Wave velocities are then calculated as interval velocities. Such techniques offer benefits in two areas. First, interval velocities have fewer potential errors than direct velocities. Second, the techniques can be fully automated. Furthermore, the retrieval of additional information such as strain rate effects and material damping is possible with spectral analysis.

Case Study - Records obtained from shear wave velocity measurements in a crosshole test at a clay site are analyzed as an application of the travel-time determinations outlined above. Details of the field setup and equipment used can be found in Stokoe et al, 1985.

The time records of shear motion obtained with two vertical velocity transducers located 2.92 m and 5.65 m from the source are presented in Figs. 5a and 5b. The time interval obtained from first arrivals of the shear wave is 11.55 msec. This corresponds to a shear wave velocity of 236 m/s. The time measured from first troughs is 11.87 msec, which gives a shear wave velocity of 230 m/s. If the velocities are calculated using times between first peaks or between zero crossings, the velocities are 231 and 226 m/s, respectively.

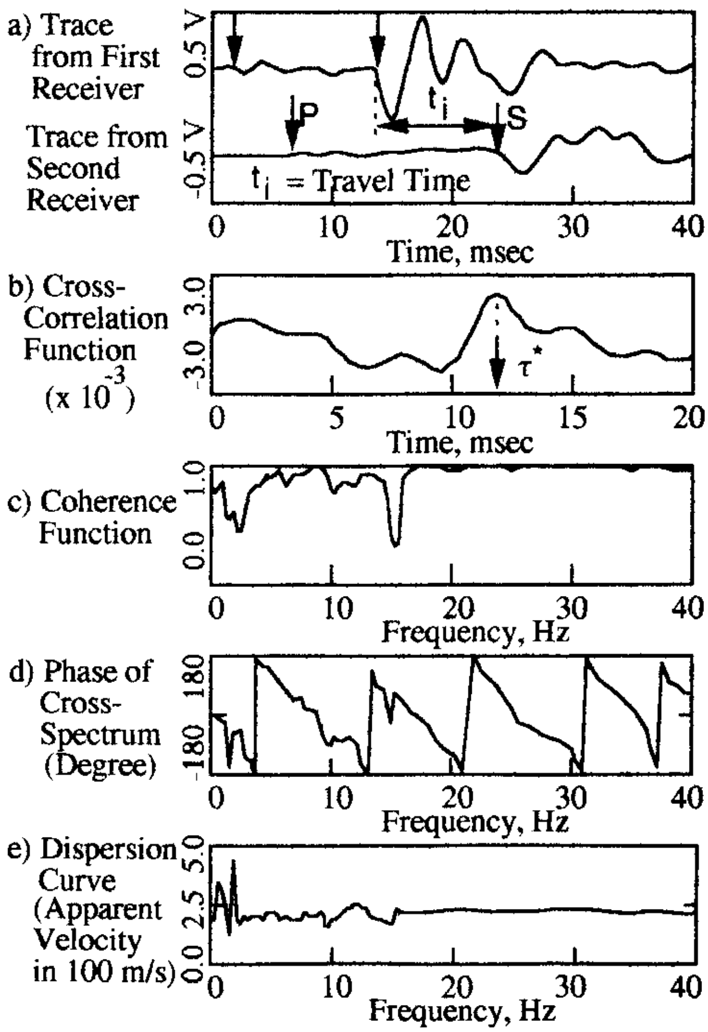


Fig. 5 Determination of Shear Wave Velocity of Saturated Clay at a Depth of 7.6 m (from Sanchez-Salinero et al, 1986)

The cross-correlation function of the two time records is presented in Fig. 5b. The maximum value of this function occurs at a time of 11.64 msec. The shear wave velocity calculated with this time is 235 m/s. The phase of the cross-spectrum is shown in Fig. 5d along with the coherence function in Fig. 5c. The coherence function function can be used as an indication of the signal-to-noise ratio. For a signal with no background noise, the coherence function should have a value of one at any frequency if the system is considered linear. Extraneous noises of a certain frequency will be reflected by a low value of coherence at that frequency. Based on the phase of the cross-spectrum, an apparent velocity versus frequency graph can be constructed using the equations described previously. This graph is presented in Fig. 5e. It can be observed that the apparent velocity fluctuates significantly at low frequencies. These fluctuations decrease as frequency increases, and at high frequencies the value of the velocity stabilizes to a value of about 230 m/s. The fluctuations decrease at a frequency of approximately 160 Hz which corresponds to a wavelength of about one-half the distance form the source to the first receiver. The fluctuations are caused primarily by the additional near-field effect (Sanchez-Salinero, 1987).

USE OF INVERSE THEORY FOR DOWNHOLE ANALYSIS

In the downhole method, wave velocities are determined by evaluating travel times either between the source and receivers (direct measurements) or between receivers (interval measurements). These conventional methods of determining wave velocities are very simple and generally result in rather smooth velocity profiles, especially when compared with the more detailed profiles determined by the crosshole seismic method (Patel, 1981 and Lopez, 1989). This lack of detail in profiles can tend to negate some of the advantages of the downhole seismic method such as low cost, ease of operation and use of simple seismic sources.

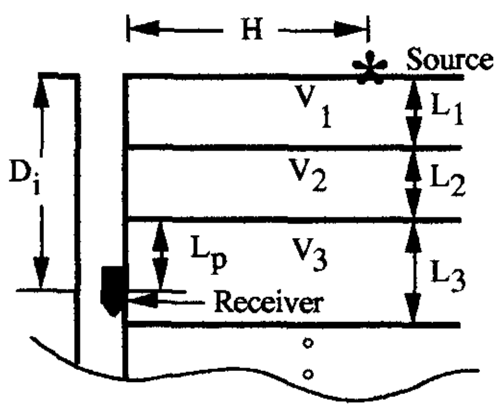


Fig. 6 Layered Model Used in Developing the Inversion Method

The superiority of the inversion method relative to conventional methods (direct and interval downhole measurements) has been verified in several case studies (Mok, 1987; Mok, et al, 1988). To apply inverse theory to the analysis of downhole velocity measurements, the subsurface of a downhole site is modelled as a stack of homogeneous horizontal layers as shown in Fig. 6. In the first stage, a ray path from the source to any receiver depth is assumed to be straight. Ray bending based upon Snell's law is then considered in the second stage. In terms of field testing, it is also assumed that the source-receiver combination permits one to identify clearly the initial arrival of the wave of concern, either the compressional or the shear wave.

Case Study - The downhole and crosshole seismic methods were used at a site near Red Oak, Oklahoma. To invert the downhole measurements, the site was simulated as a stack of three homogeneous layers on top of a homogeneous half-space. The geotechnical profile shown in Fig. 7 was used as a priori information for adopting the four-layer model. Seismic data were the direct (source-to-receiver) travel times of the shear wave measured at 18 different depths over the depth range of 1.0 to 25 ft (0.3 to 15.5 m). Unfortunately, this number of data was not enough to resolve a more detailed velocity profile than the four-layer system.

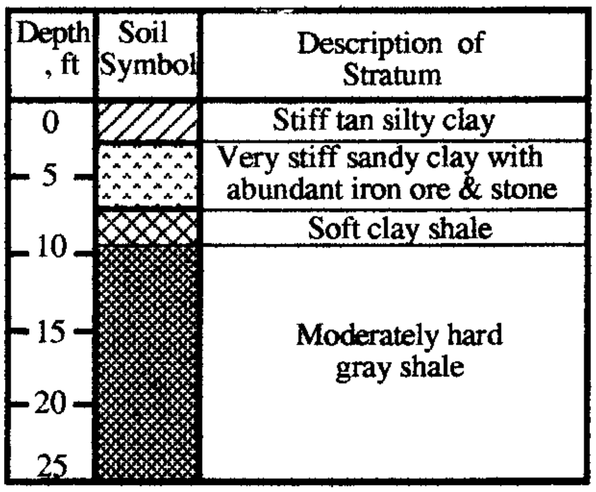


Fig. 7 Geotechnical Profile at Red Oak, Oklahoma

The shear wave velocity profile determined by inverting the downhole data is shown in Fig. 8 by the solid line. Also shown in Fig. 8 are the crosshole profile determined at the same location and the velocity profile obtained from the direct downholemeasurements. The velocity profiles from crosshole and downhole inversion are reasonably close (indicating the reasonableness of these profiles). However, the profile from the direct downhole measurements is erroneous because the implicit assumption of straight ray paths in data analysis is no longer valid at this site with a high velocity contrast between adjacent layers. Usually, for sites at which the properties are quite uniform or only vary gradually with depth, direct measurements work reasonably well even though they do not give detailed profiles (Patel,1981). For such sites, straight ray paths are not a bad assumption, and direct measurements can be used.

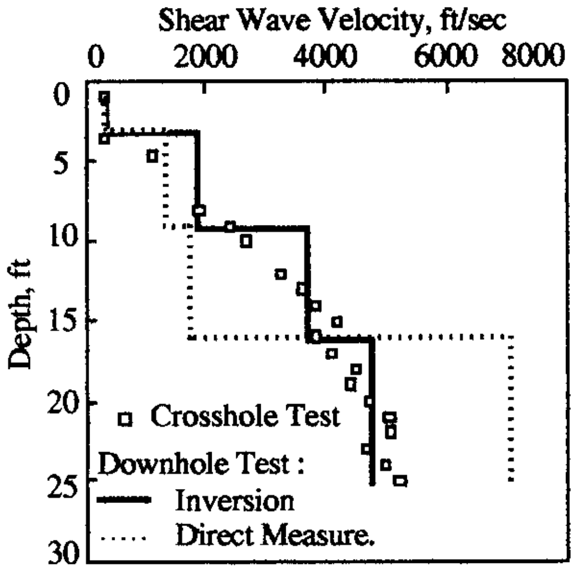


Fig. 8 Comparison of Velocity Profiles from Crosshole and Downhole Tests

IN SITU DAMPING MEASUREMENT

If soils were perfectly elastic materials, the static and dynamic parameters could be characterized by seismic wave velocities (or elastic moduli) alone. However, soils are not perfectly elastic materials. Even at small strains on the order of 10^{-3} percent or less, soils exhibit some energy absorbing capacity upon cyclic loading. This capacity, commonly called damping, is generally quite small at small strains and, hence, has been ignored in the application of most in situ seismic tests. The primary use of these tests has been to characterize the elastic components of moduli. However, a more complete characterization of soil requires the measurement of damping characteristics in addition to seismic wave velocities.

The amplitudes of seismic waves decrease as the waves propagate through soil. This attenuation of wave amplitude is caused by two mechanisms: 1) spreading of wave energy from a source, generally called geometrical or radiational damping, and 2) dissipation of energy due to mainly frictional losses (particle sliding) in the soil itself,commonly known as attenuation, material or internal damping. The phenomenon of attenuation is much more complex than the elastic aspects of seismic wave propagation. Both laboratory and field measurements of material damping have proven to be difficult to make. One reason is that the exact nature of material damping is poorly understood and may occur from several phenomena whose magnitudes vary with strain amplitude.

The basic approach to the field measurement is the generation of seismic energy in the form of compression or shear waves at one point and the monitoring of the amplitude of the energy at other points. For the crosshole seismic method presented herein, this process consists of installing three or more boreholes at a site and then conducting measurements with a source and receivers placed at similar depths in the boreholes. Care is necessary in performing amplitude measurements under these conditions, and consideration must be given to the following points and/or possible problems: 1) precise calibration of the receivers is necessary; 2) interference from reflected and refracted waves adversely affects the measurements; 3) electrical or mechanical noise decreases signal quality; 4) intimate coupling between the boreholes and receivers is necessary; 5) the boreholes should not alter the free-field motions; 6) the three-dimensional orientation of the receivers must be accurately controlled; 7) the radiation pattern of the source must be understood; and 8) coupling between additional near- and far-field components has to be considered. If these points are properly taken into account, field measurement could be an accurate means of representing the damping characteristics of the site, at least at small strains.

In geotechnical engineering, the frictional energy loss associated with a system of equations for a dynamic problem is often used as a measure of attenuation. This energy loss can be defined by the following relationship:

$$D = \frac{\Delta E}{4\pi E} \qquad (3)$$

where ΔE = the amount of energy dissipated per cycle of harmonic excitation in a certain volume, E = the peak elastic energy stored in the same volume, and π = 3.14159... D is called the damping ratio and is commonly expressed as a percent. D is generally assumed to be independent of the frequency and amplitude of particle motion at small strains (less than 10^{-3} percent) and is often called hysteretic damping.

Most data suggest that, for dry rocks and dry soils, D is indeed independent of frequency (Pandit and Salvage, 1973; Toksoz el al, 1979; Tittmann et al, 1981; and Stoll, 1985), and intergrain friction (grain sliding) is the dominant cause of energy loss. On the other hand, water-saturated rocks, sands and silts show a definite dependency of D on frequency (Stoll, 1985). Saturated clays are the least understood, but the dependency of D on frequency seems to be relatively small. Therefore, in the work which deals with geotechnical materials, the approximate frequency independence of D is assumed.

For a harmonic wave propagating in an infinite homogeneous medium, material damping ratio can be expressed as:

$$D = \frac{\ln[A_1R_1/A_2R_2]}{2\pi t_l f} \qquad (4)$$

in which A_1 = body wave amplitude at distance R_1 from the source, A_2 = body wave amplitude at distance R_2 from the source t_l = the interval travel time of the wave between R_1 and R_2, and f = the frequency of the wave. To use Eq. 4 to calculate material damping, the following assumptions are made: 1. material damping is independent of frequency and strain amplitude for small strains (less than 10^{-3} percent), 2. measured wave ampitudes are not affected by reflected or refracted waves, 3. any additional near-field effects on amplitude are negligible (thus, geometrical damping is inversely proportional to the distance from the source), and 4. particle motions (A_1 and A_2) are accurately tracked at both measurement points.

Equation 4 is based on measurement of a harmonic wave. To utilize these equations for waves generated from a point source, frequency domain analysis should be adopted. Two time records at distance R_1 and R_2 from the pont source need to be converted to amplitude spectra using Fourier transforms. At each frequency, the spectral ratio is calculated by dividing the Fourier amplitude of the signal at R_1 by that of the signal at R_2. Damping ratio for each frequency is then calculated using Eq. 4.

Case Study - Crosshole records from shear wave velocity measurements in a clay layer at a depth of 7.6 m at O'Neill Forebay Dam are shown in Fig. 9. An in–hole source was used to generate these shear waves, and the predominant frequency range was found to be about 10 Hz to 300 Hz. The distances of the first and second receivers form the source were 9.0 ft and 18.0 ft (2.7 m and 5.5 m), respectively. Measured shear wave velocity, based on initial arrivals in time-domain records, was about 770 fps (236 m/sec).

The windowed time-domain signals are also presented in Fig. 9. Elimination of energy not transmitted by the direct shear wave is clearly shown by comparing the windowed and non-windowed signals.

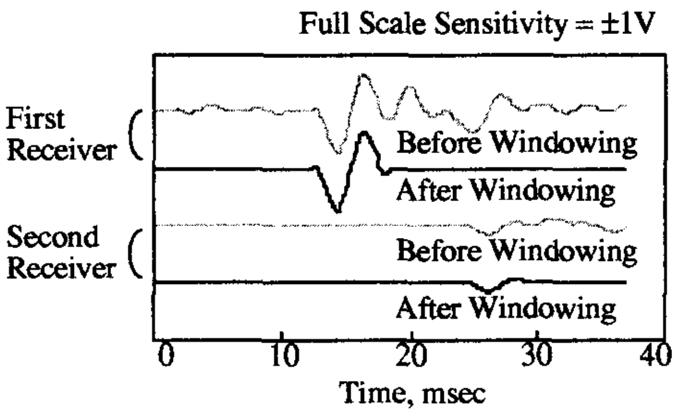


Fig. 9 Shear Wave Records from a Depth of 7.6 m in a Clay Layer at O'Neill Forebay Dam, California

Apparent phase velocities before and after windowing are shown in Fig. 10. The term "apparent" in apparent phase velocity is used to denote a velocity calculated simply by dividing distance (d) by travel time (t). The term "phase" in apparent phase velocity is used to denote that the velocity of a particular frequency (f) is being calculated. Therefore, apparent phase velocity is d/t(f), where t(f) is the travel time of the frequency of interest (Sanchez-Salinero, 1987). Apparent phase velocities from the windowed signals are more stable than those from the non-windowed signals and are around 770 fps (236 m/sec) over a frequency range of about 100 Hz to 360 Hz. The 100-Hz frequency corresponds to a wavelength of 7.7 ft (2.3 m) which is about equal to R_1. Without filtering, a value of λ_S equal to 0.5 R_1 is necessary before a stable value of velocity is reached. This behavior shows one of the beneficial effects of the window. The variation in apparent phase velocities at low frequencies (long wavelengths) is caused by coupling between the additional near-field and far-field terms. Also the slight increase in apparent phase velocity with increasing frequency above 100 Hz is possibly due to dispersion created by material damping, but more research is necessary to understand this behavior.

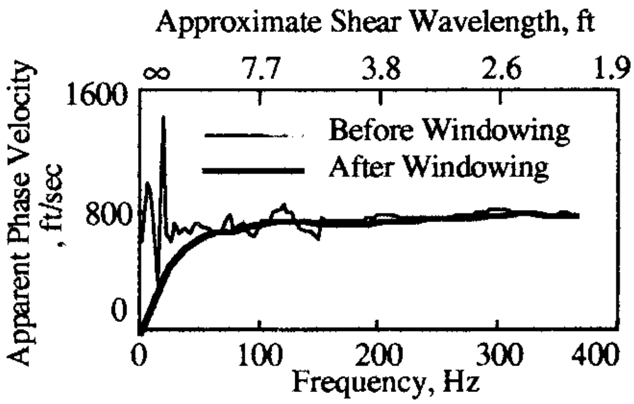


Fig. 10 Dispersion Curves of Shear Wave Velocities of Clay at O'Neill Forebay Dam, California

Calculated damping ratios are shown in Fig. 11. Apparent damping ratios determined without windowing fluctuate significantly with frequency. On the other hand, the window reduces the fluctuations. The frequency bandwidth over which the average damping ratio should be selected is from 170 Hz to 300 Hz. The average damping ratio over this bandwidth is about 5 percent, with a variation from about 4 to 7 percent.

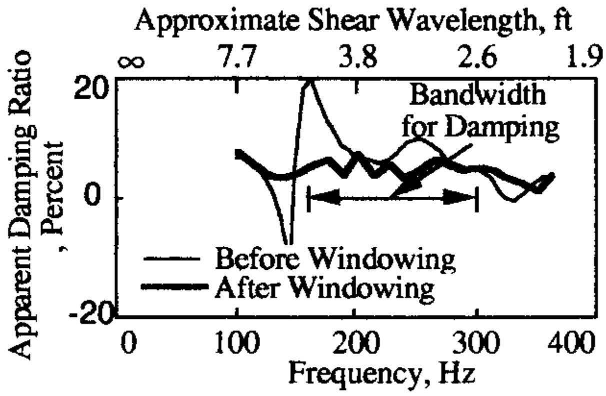


Fig. 11 Apparent Damping Ratios from Shear Wave Measurements Shown in Fig. 10

SUMMARY AND CONCLUSIONS

Borehole seismic measurements of the type presented herein are made at strains below 0.001 percent where properties of the soils are essentially independent of strain amplitude. However, when seismic methods like the crosshole and downhole methods are used in the field, near-field components of the shear and compression waves can have a significant effect on the time domain records and dispersion curves used to evaluate propagation velocities (and hence moduli). If one ignores the existence of near-field components, erroneous elastic properties or attenuation parameters may be evaluated with these seismic methods. Because of coupling between the near- and far-field components, body waves are dispersive even in an elastic medium with no damping. For a crosshole setup, near-field effects can be very important and generally should be taken into account when the distances from the source are less than two wavelengths.

An improved method of analyzing downhole seismic data is presented. The method is based upon inverse theory and can be used to resolve wave velocity profiles to a much greater accuracy than possible with conventional anaysis methods such as direct or interval measurements. In addition, use of inverse theory permits a rational basis for judging the quality of the velocity profile. One case study is briefly presented to illustate application of the inversion method to a site whose velocity profile exhibits a high contrast between adjacent layers.

Attenuation or material damping as measured in crosshole tests is discussed herein. It is shown that such measurements are possible if carefully performed.The major conclusions of this initial study are as follows: 1. Spectral analysis is necessary in attenuation measurements so that spectral ratios can be used to calculate apparent phase velocities and associated damping ratios, 2. The frequency bandwidth for computing damping ratios must be based upon the frequency range generated by the source. Wavelengths appropriate with the source-receiver spacing must be generated. The source should be at least two wavelengths from the first receiver for S-wave measurements (and more for P-wave measurements), 3. Windowing of the time-domain records seems to be a promising method for reducing the adverse effect of reflected and/or refracted waves on the amplitude spectra of direct shear or compression waves. The window type and possible associated undesirable effects, if any, on amplitude spectra needs more study.

REFERENCES

Air Force Weapons Laboratory, (1977), "Cylindrical In Situ Test at Selected Nuclear and High-Explosive Test Sites," AFWL-TR-76-709, Kirtland Air Force Base, N.M., February.

Lopez, R.A., (1989), "Borehole Seismic Investigations of a Proposed Low-Level Radioactive Waste Disposal Site in Hudspeth County, Texas," M.S. Thesis, The University of Texas at Austin.

Mok, Y.J., (1987), "Analytical and Experimental Studies of Borehole Seismic Methods," Ph.D. Dissertation, The University of Texas at Austin, 266 pp.

Mok, Y.J., Sanchez-Salinero, I., Stokoe, K.H., II, and Roesset, J.M., (1988), "In Situ Damping Measurements by Crosshole Seismic Method," *Proceedings*, ASCE, Specialty Conference on Earthquake Engineering and Soil Dynamics II - Recent Advances in Ground Motion Evaluation, Park City, Utah, June.

Pandit, B. I., and Savage, J. C., (1973), "An Experimental Test of Lomnitz's Theory of Internal Friction in Rocks," *J. Geophysical Research*, Vol. 78, pp. 6097-6099.

Patel, N.S., (1981), "Generation and Attenuation of Seismic Waves in Downhole Testing," M.S. Thesis, The University of Texas at Austin, 411 pp.

Redpath, B.B., and Lee, R.C., (1986), "In-Situ Measurements of Shear-Wave Attenuation at a Strong-Motion Recording Site," URS/John A. Blume and Associates, San Francisco, California.

Sanchez-Salinero, I., Roesset, J.M., Stokoe, K.H., II, Lee, S.H.H., and Mok, Y.J., (1986), "Body Wave Velocities from Crosshole Tests Using Time and Spectral analyses," *Proceedings*, Eighth European Conference on Earthquake Engineering, Lisbon, Portugal, September.

Sanchez-Salinero, I., (1987), "Analytical Investigation of Seismic Methods Used for Engineering Applications," Ph.D. Dissertation, The University of Texas at Austin.

Stokoe, K.H., II, and Hoar, R.J., (1978), "Variables Affecting In Situ Seismic Measurements," *Proceedings*, Conference on Earthquake Engineering and Soil Dynamics, ASCE, Geotechnical Engineering Division, Vol. II, pp. 919-939.

Stokoe, K.H., II, Sanchez-Salinero, I. and Mok, Y.J., (1985), "Evaluation of Shear Wave Velocity Profiles at O'Neill Forebay, San Luis and Contra Loma Dams, California," Geotechnical Engineering Report GR85-2, The University of Texas at Austin, 339 pp.

Stoll, R.D., (1985), "Marine Sediment Acoustics," *J. Acoustical Society of America*, Vol. 77, No. 5, pp. 1789-1799.

Tittmann, B. R., Nadler, H., Clark, V. A., Ahlberg, L. A., and Spencer, T. W., (1981), "Frequency Dependence of Seismic Dissipation in Saturated Rocks," *Geophysical Research Letters*, Vol. 8, pp. 36-38.

Toksoz, M. N., Johnston, D. H., and Timur, A., (1979), "Attenuation of Seismic Waves in Dry and Saturated Rocks: I. Laboratory Measurements," *Geophysics*, Vol. 44, pp. 681-690.

Wilson, S.D., Brown, F.F., Jr., and Schwarz, S.D., (1978), "In Situ Determination of Dynamic Soil Properties," *Dynamic Geotechnical Testing*, American Society for Testing and Materials, ASTM STP 654, pp. 295-317.

Woods, R.D., (1987), "In Situ Tests for Foundation Vibrations," *Proceedings*, Conference on Use of In Situ Tests in Geotechnical Engineering, ASCE, Geotechnical Special Publication 6, pp. 336-375.

Woods, R.D., and Stokoe, K.H., II, (1985), "Shallow Seismic Exploration in Soil Dynamics," *Proceedings*, Richart Commemorative Lectures, ASCE, Geotechnical Engineering Division, pp. 120-156.