Practical aspects of in situ measurements of material damping with the seismic cone penetration test

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The downhole seismic cone penetration test (SCPT) procedure has been extended to allow the measurement of material damping at small strains at minimum expense while one is measuring shear wave velocity. The nature of damping, the required equipment characteristics, and the recommended procedure and calculation methodology are presented in a practical way. SCPT results from four different sites give results that are in general agreement with laboratory measurements of damping for sands and clays and with values recommended by other authors. It appears, however, that previously reported measurements of damping by borehole methods are higher, by a factor of two or more, when compared with SCPT and laboratory results.

Key words: in situ, damping, seismic, shear wave, cone penetrometers, procedures.

La procédure d'essai de pénétration au cône sismique en bout de forage (SCPT) a été élargie pour permettre la mesure de l'amortissement de matériau à de faibles déformations à des frais minimum pendant la mesure de la vitesse de l'onde de cisaillement. La nature de l'amortissement, les caractéristiques de l'équipement requis, et la procédure et méthodologie de calcul recommandées sont présentées dans une forme pratique. Les résultats de SCPT de quatre différents sites donnent des résultats qui concordent généralement avec les mesures en laboratoire de l'amortissement des sables et des argiles, et avec les valeurs recommandées par des autres auteurs. Il semble cependant que les mesures d'amortissement par la méthode de forage dont on a fait état antérieurement sont plus élevées, par un facteur de deux ou plus, lorsqu'ils sont comparés aux résultats du SCPT et du laboratoire.

Mots clés : in situ, sismique, onde de cisaillement, pénétromètre au cône, procédures.

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Introduction

The evaluation of geotechnical engineering problems involving the transmission of waves through soil, such as seismic response under earthquake loading and foundation response under dynamic loading, requires a knowledge of the appropriate soil stiffness and material damping properties. Commonly the soil properties of greatest concern are the shear modulus G and the damping of shear waves D_s.

Determination of these properties, as with other soil properties, has traditionally been carried out in the laboratory, which offers some significant advantages. However, sampling of the soil causes disturbance, and in granular soils can cause a high level of disturbance. It is also difficult to measure and hence to reproduce the in situ stress conditions. Laboratory test programs can be complemented with in situ soil tests, which offer the advantage of sampling a larger volume of soil that has been minimally disturbed by the insertion of the testing tool.

Elastic theory shows that the maximum value of shear modulus at small strains, G_{max}, can be determined as follows:

$$[1] \quad G_{max} = \rho V_s^2 = \left(\frac{\gamma}{g}\right) V_s^2$$

where V_s is the shear wave velocity, ρ is the mass density, γ is the unit weight, and g is the acceleration of gravity. For depths to about 30 m, typical values of V_s at different sites vary from about 50 to greater than 300 m/s.

Studies at the University of British Columbia have concentrated on downhole measurements with a source at the ground surface and a receiver in the piezocone, i.e., the seismic cone penetration test (SCPT). These studies began in the early 1980s at the suggestion of Fugro Inc., Long Beach, California (now ERTEC), and were first reported by Robertson *et al.* (1986). The use of digital signal processing techniques for evaluating V_s was later described by Campanella and Stewart (1992). Generally speaking, a complete record of a signal is taken at each depth. However, determination of the shear wave velocity typically uses only one point or "pick" in the signal to estimate the time of shear wave arrival, or a crossover point, first peak, or cross correlation, etc., and the balance of the signal is not used.

The objective of our current study is to determine if signal records made for shear wave velocity measurements could provide, at minimal cost, further information on soil properties, with emphasis on the use of amplitude information in the signals to determine low-strain damping.

Because of the need to use the amplitude of signals, the development of the methodology required evaluation of the equipment (especially sources and receivers), field procedures, and calculation methods. Various analyses, assumptions, and calculation methods to evaluate damping have been discussed in detail by Stewart (1992) and Stewart and Campanella (1991). This paper will present a basic discussion of the nature of damping and then emphasize the practical aspects of the procedures used. Four different research sites with soil conditions ranging from clay to sand were tested at various times over a 2-year period. Standard equipment, procedures, and calculation methods were developed and test results successfully compared with laboratory and published results.

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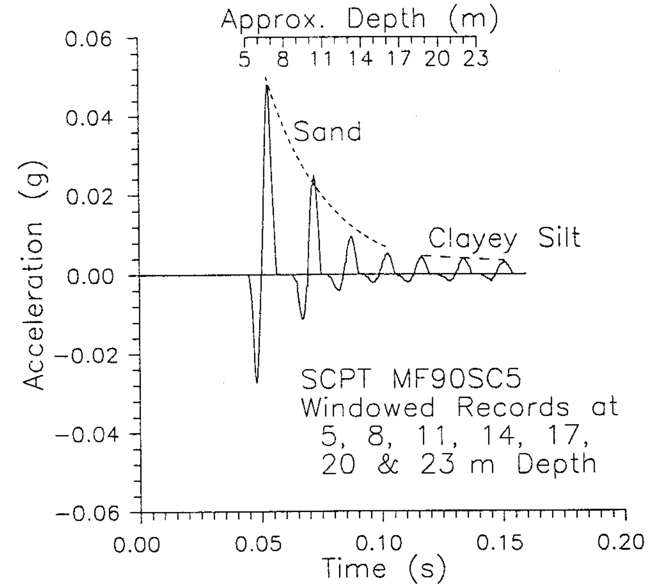

FIG. 1. Processed accelerometer records over seven depths.

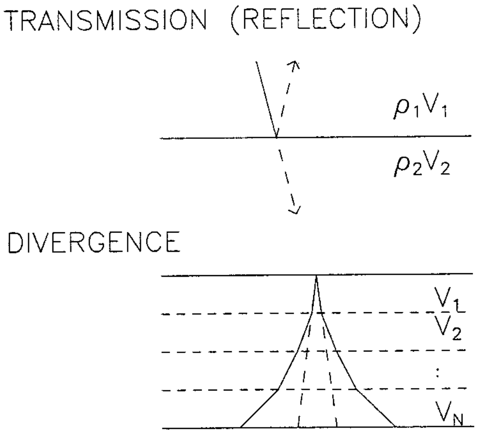

FIG. 2. Amplitude changes at soil layer interfaces. p, mass density; V, shear wave velocity of each layer.

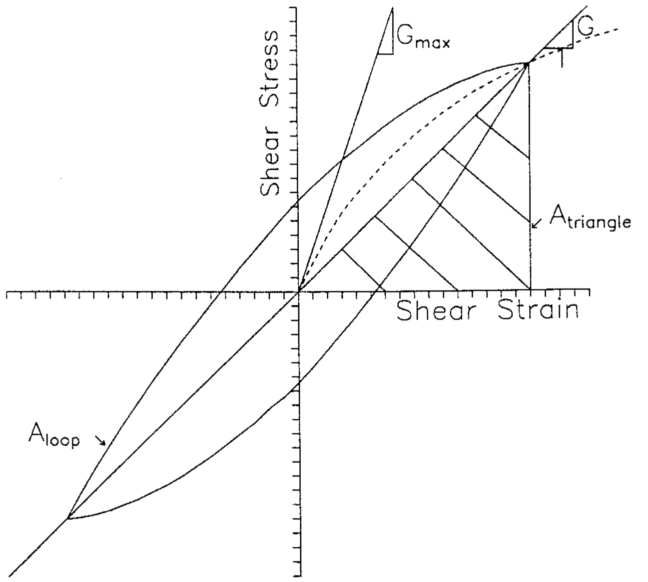

FIG. 3. Damping during cyclic loading. $D_s = A_{loop}/(4\pi A_{triangle})$.

TABLE 1. Laboratory measurements of damping

Soil type	Strain (%)	Damping (%)	Source
Cohesive	10^{-3}	3 (1–5)	Sun *et al.* 1988
Clay	10^{-3}	0.9–2.4	Zavoral 1990
Sand	10^{-3}	1.5	Ishihara 1982
Cohesionless	10^{-4}–10^{-3}	0.5–2	Seed *et al.* 1986
Sand	10^{-3}	1	Saxena and Reddy 1989

Nature of damping

The first cycle of the shear wave from processed accelerometer records from a SCPT is shown in Fig. 1. Repeatable hammer blows on a shear beam were the source for these records. The records have been windowed to isolate the first cycle of the shear wave (windowing is discussed in more detail below). For clarity only seven selected signals at different depths have been shown. At this site the upper portion (about 3–15 m depth) is primarily sand and the lower portion (below about 17 m) is primarily clayey silt. The signal peaks show a rapid attenuation in the shallow sands and less rapid attenuation in the deeper silts. This attenuation is caused by both geometric effects and material damping.

Waves in soil can be plane waves (for example, those generated by an earthquake movement of flat-lying bedrock), spherical waves (for example, those generated by a point-source explosive device), or in general, a mix of these two wave types. The effect of the surface (soil is a half-space) depends on the direction of propagation of the waves. Waves moving upwards will be changed by the surface. However, waves travelling downward as in the SCPT will not be affected by the surface during propagation (although there will be surface effects during generation of the wave, i.e., near-field effects). For spherical waves in a homogeneous medium, neglecting near-field terms, White (1965) showed that the amplitude decayed inversely with distance R (spherical spreading). However, soil is rarely homogeneous and commonly layered. At the interface between two layers, the amplitude of spherical body waves can be affected in at least two ways, namely, transmission–reflection and divergence. As shown in Fig. 2, the amplitude of the transmitted wave is reduced because (*i*) part of the wave energy is reflected (for both plane and spherical waves) and (*ii*) the wave front of spherical waves is refracted, decreasing the amplitude for increasing velocities. These effects (commonly termed the total geometric corrections) must be accounted for in analyzing seismic measurements if one is to evaluate material damping. Furthermore, the geometric corrections often vary with depth and are usually not decaying as $1/R$ (see Stewart 1992).

Material damping refers to the energy dissipation within a soil mass during dynamic (cyclic) loading. The stress–strain curve during unloading is not the same as that during loading, giving rise to a closed hysteresis loop (see Fig. 3). The area of the loop is a measure of the energy lost during a cycle of unloading–reloading. To relate the test results to a dashpot model with a viscosity c, Whitman (1970) expresses the damping ratio (D_s = ratio of actual viscous coefficient to critical value $= c/c_c$) as

TABLE 2. Previous field measurements of damping

Soil type	Damping (%)	Source
Sand	6	Kudo and Shima 1981
Silt	2.5	Kudo and Shima 1981
Alluvium (sand and clay)	12(<25 m); 3.5(>25 m)	B.B. Redpath (private communication) (laboratory: 1.5–3.5%)
Sandy	5	Tonouchi *et al.* 1983
Clayey	1.7	Tonouchi *et al.* 1983
Fine sand	1.7	Tonouchi *et al.* 1983
Sandy silt	2.5	Tonouchi *et al.* 1983
Bay mud	4	B.B. Redpath (private communication) (laboratory: 2.5%)
Clay	4–7	Mok *et al.* 1988
Sand (P-wave)	2–3	Mok *et al.* 1988 (laboratory: 0.7%)

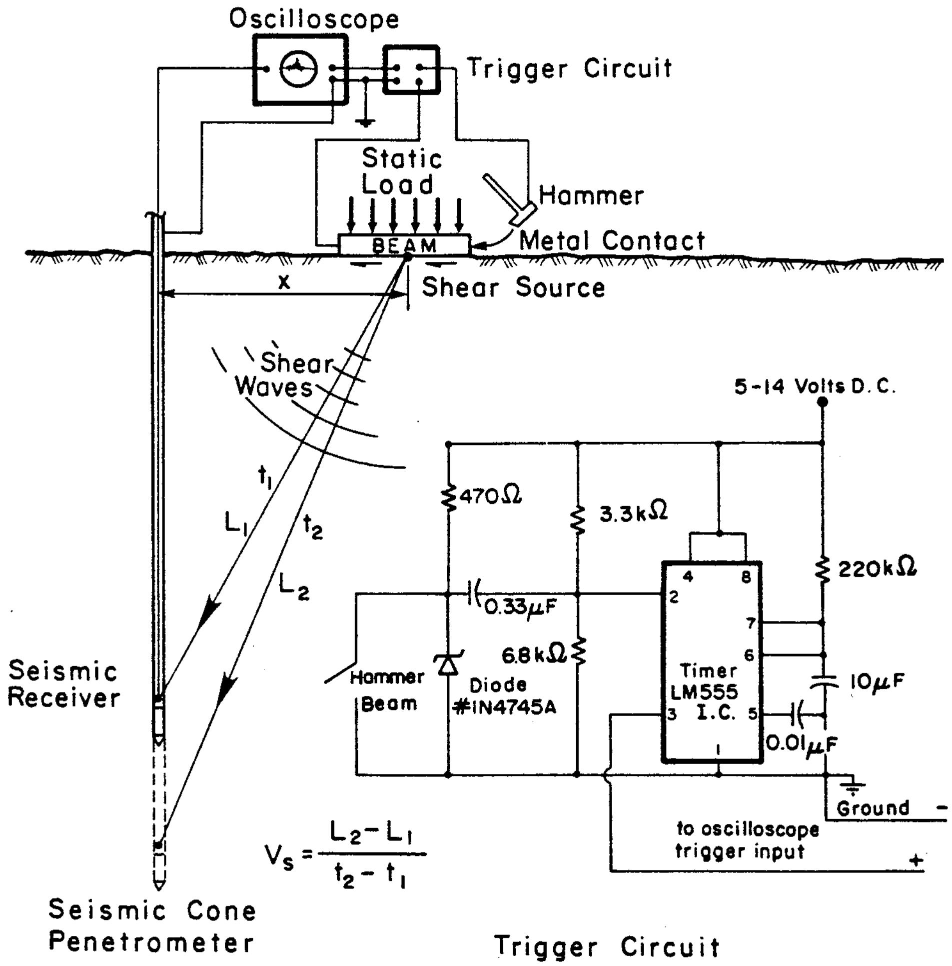

FIG. 4. Schematic diagram of downhole SCPT arrangement with trigger (from Campanella and Stewart 1992). *L*, distance of each signal path; *t*, time of each signal.

[2] $$D_s = \frac{A_{loop}}{4\pi A_{triangle}}$$

where A_{loop} is the area of the loop and $A_{triangle}$ is the area of the right triangle between the strain axis and the line from the origin to the point of the loop. The geophysics literature most commonly refers to the measurement of attenuation as the quality factor Q and its inverse Q^{-1}. Johnston and Toksoz (1981) define Q as the ratio of stored energy to dissipated energy ($2\pi W/\Delta W$). Thus Q can be related to D_s as

[3] $$Q = \frac{1}{2D_s}$$

Typical laboratory values of damping at small strains are given in Table 1. Thus, the laboratory values of damping at small strains have been found to be about 0.5–2% for sand and typically 1–3% (but up to 5%) for clay.

Some previously reported field values of damping by others using a variety of techniques are given in Table 2. Small-strain damping values from field tests in the literature

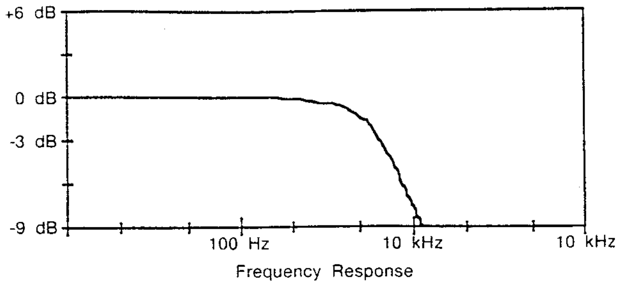

FIG. 5. Accelerometer frequency response provided by IC Sensors Inc., Milpitas, Calif.

give damping values of 1.7–6% for sands, 1.7–7% for clays, about 2.5% for silts, and 3.5–12% for alluvium. Compared with laboratory values, these values are higher by about a factor of three for sands and two for clays. Also, laboratory results given by B.B. Redpath, Murphys, Calif. (private communication), suggest that previous field values were also higher by a factor of two to three for the alluvium. The previous field results also show a large scatter in measurements. The poor agreement may be attributable to instrumentation difficulties, inappropriate data processing using smoothing and filtering, and inadequate consideration of geometric damping effects for the field tests.

Equipment and field procedure to measure damping

The basic equipment for the SCPT as used at the University of British Columbia is illustrated in Fig. 4. The only modifications required for damping measurements were those to the receiver and hammer. The very small geophone needed to fit in the cone was only available in a partially damped (18% of critical damping) model that resonates to give a strong arrival signal for P and S waves, which is used for velocity measurements. Thus the amplitude response of the geophone was nonlinear in the frequency range of the measured signals, and the damping characteristics of the geophone could not be eliminated from the measurement. The geophone was therefore replaced with a fully damped (70% of critical damping) piezo-resistive accelerometer produced by IC Sensors Inc., Milpitas, Calif., which has an essentially flat or constant-amplitude response from 0 up to about 300 Hz as shown in Fig. 5. This response is necessary to make calculations using the amplitudes of the measured signals and means the instrument records only the actual wave amplitudes in the soil.

Several soundings were conducted with two receivers in two different configurations. In the "true-interval" arrangement the two receivers were separated by 1 m in a single cone assembly. In the "fixed-moving" arrangement, two cones were used with one at a fixed shallow depth and one pushed to increasing depths. In both cases the results showed that there was no need or advantage to using two receivers, provided a reliable trigger (such as the one shown in Fig. 4) is incorporated in the measurement system.

To compare signal amplitudes at different depths the hammer blows must represent a repeatable source, so a mechanical swing hammer was constructed as shown in Fig. 6. The hammer is attached to a rail on the side of the truck and can be adjusted to suit the site conditions. Once the hammer weight and height are selected, they are kept constant for the duration of a sounding. In general, the

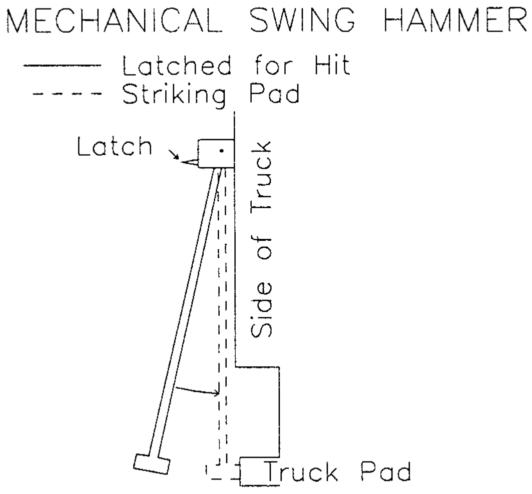

FIG. 6. Schematic diagram of repeatable shear source.

measured signals are highly repeatable. However, occasionally an erratic signal is received which is often due to traffic or other spurious vibrations. It has been found useful to repeat blows four times at each depth to ensure that any erratic results can be detected and removed. In addition, the repeated signals can be averaged to improve the signal to noise ratio.

The cone rods used are 1 m in length, so testing is normally done in 1 m depth increments. The pushing head is moved to the bottom of its travel before each test. To reduce the possibility of waves travelling down the rods, the head is lifted clear of the rods before doing the test and the truck engine stopped, if necessary. If heavy traffic is nearby, it may be necessary to carry out the tests in off-hours, very early in the morning or on weekends.

To provide a constant frequency step (increment between points of the fast Fourier transform, FFT) in the calculations, it is necessary to use the same time step (recording time interval) for all of the depths. The time step to be used must be selected so that the shear wave can be recorded at the greatest depth expected. Typically time steps of 100 or 200 μs have been used. It has also been found useful to "AC-couple" the incoming signals to eliminate any zero offset. The AC-couple acts as a high-pass filter set around 2–5 Hz.

Signal processing

After testing is completed, the signals were processed using a wave-analysis software program called VU-POINT 2. A plot of the cone data is also required to indicate the stratigraphy of the site. Initially, the four signals at each depth are reviewed to ensure that they are essentially the same. If one of the signals does not match the others, it is removed. The signals are then averaged. This gives a more representative signal and improves the signal to noise ratio. For plotting purposes the averaged signals are usually reduced in size by removing every second point. It has been found useful to plot, on one sheet, up to eight of these signals at increasing depths, in both the time and frequency domains. These plots can show any problems with the data set, and changes in the shape of the FFTs can indicate depth zones (soil layers) to be used in the damping calculations.

It is necessary to review the nature of the measured signals before further processing is done. In general, the measured

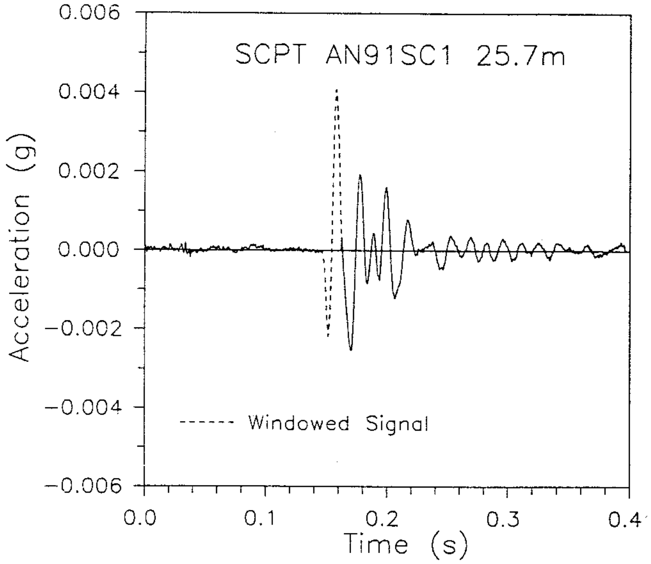

FIG. 7. Typical shear wave signal showing the main shear value.

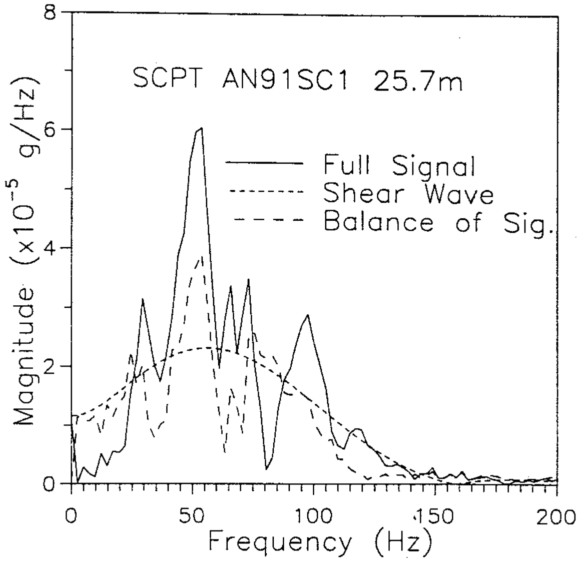

FIG. 8. Fast Fourier transforms (FFTs) of portions of signal shown in Fig. 7.

accelerometer signals can be seen (Fig. 7) as consisting of three components: (*i*) the underlying noise, which can be observed at the beginning and end of the signals; (*ii*) the main shear wave pulse; and (*iii*) a series of smaller pulses following the main pulse. The noise and the main pulse are expected in the signal, and the sources of each are easily explained. However, the nature of the source or cause(s) of the smaller pulses is not clear, and the boundary between the main pulse and the smaller pulses is somewhat arbitrary. A detailed evaluation of the signals using the complex cepstrum method (Ulrych 1971), which evaluates reflections in signals, did not clarify the cause of the smaller pulses. Figure 8 shows the FFTs of portions of the signal shown in Fig. 7. When considering the FFTs in Fig. 8, it can be seen that the full signal is quite irregular. By contrast the main shear wave windowed to retain one cycle is smoothly varying with frequency, as would be expected for the main single cycle pulse. The balance of the signal shown in Fig. 8 seems to contain the source of the irregularities in the full signal.

This example of separating an accelerometer signal into the three component parts (main pulse, small pulses, and noise) does show that the main shear pulse should be isolated from the balance of the signal if "clean" FFTs are to be derived and used in further calculations.

The process of separating out the main shear pulse is termed windowing. A window 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. For a sample signal, many different window types (rectangle, triangle, cosine, etc.) were considered to isolate the shear wave. It was concluded that the rectangle window was the best window to isolate the shear waves in the data in this study. This is fortunate, as the signals before and after the shear wave can simply be zeroed out and the amplitudes within the shear wave remain unchanged.

The averaged signals calculated above are therefore windowed to isolate the main shear wave, and these windowed signals are used for the calculation of both shear wave velocities and damping values.

Damping calculations

Six methods of analysis have been evaluated to measure material damping (rise time, random decrement, attenuation coefficient, modified SHAKE, damping spiral, and spectral ratio slope), and complete details are presented elsewhere (Stewart 1992). The spectral ratio slope (SRS) method, which is applied over a soil layer (uses several measurements in one calculation), eliminates or cancels out all geometric corrections and was found to be the most reliable and consistent approach. The basic SRS approach was also used by B.B. Redpath (private communication) and others.

The SRS method is based on the following two equations:

$$[4] \quad k = \frac{\partial^2\left(-\ln \dfrac{A_R}{A_0}\right)}{\partial f\, \partial R}$$

$$[5] \quad D_s = \frac{kV_s}{2\pi}$$

where f is frequency (Hz), R is distance (depth) (m), A_0 is the amplitude of FFT of the reference signal, A_R is the amplitude of FFT of the signal at depth R, k is the slope of SRS with depth (s/m), V_s is the average shear wave velocity of layer (m/s), and D_s is the damping (decimal in this equation, but often given as a percent). A theoretical derivation of the SRS method and others mentioned above can be found in Stewart and Campanella 1993.

The first step in the method is to select a reference signal, by viewing the FFTs of the signals. The shallowest signal (typically about 3–5 m) for which the FFT does not appear to be affected by the surface, or a shallow surficial layer, is selected as the reference signal.

At each successive depth, the FFT of the windowed signal is divided by the reference FFT, the natural logarithm (ln) of the magnitude of the ratio is computed, and the negative of the ln(spectral ratio) is plotted as a function of frequency. An example is given here in which the signal at a depth of

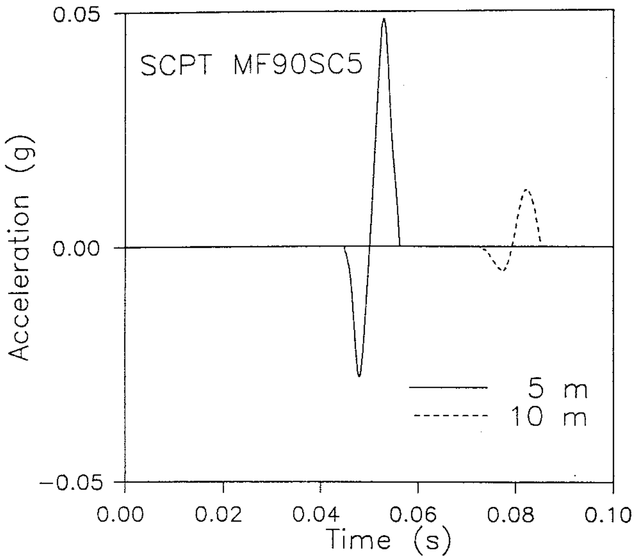

FIG. 9. Example of main shear wave, windowed, in time domain at 5- and 10-m depths in sand layer.

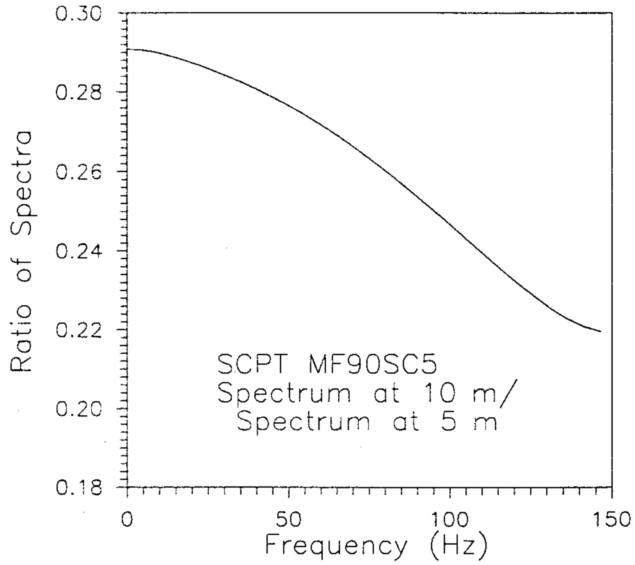

FIG. 11. Ratio of spectra (FFT at 10 m/FFT at 5 m) from Fig. 10 data.

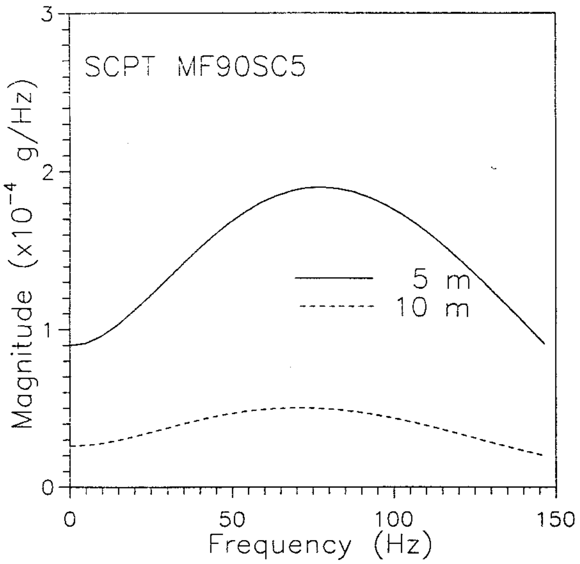

FIG. 10. Signals in Fig. 9 shown in the frequency domain as FFTs.

5 m is selected as the reference, and the signal at a depth of 10 m is analyzed. The windowed shear wave signals are presented in the time domain in Fig. 9 and in the frequency domain in Fig. 10. The ratio of the spectra is shown in Fig. 11.

Applying the method does require some iteration as the data are processed. The plot of the negative of the ln(spectral ratio) is presented in Fig. 12. The best frequency range for analysis is not immediately obvious. It has been found necessary to plot a series of such curves to select an appropriate frequency range for the full depth of the layer to be analyzed. Other calculations such as the phase velocity variation with frequency can assist in selecting the frequency range. For this example a frequency range of 40–100 Hz was selected, and the slope was found to be 0.00211 s, as shown in Fig. 12. This gives the first derivative with respect to f or frequency in [4], and the value of 0.0021 s at 10-m depth is plotted in Fig. 13.

This process was repeated for the same frequency range for all of the signals from 6 to 25 m (although different frequency ranges might have been selected for different soil layers). The slopes measured as a function of frequency at each depth are then plotted against depth as shown in Fig. 13. The slopes in each layer on the depth plot then give the second derivative (with respect to depth) and therefore give the k-value for each layer.

The average shear wave velocity in each layer can be calculated separately (Campanella and Stewart 1992), and then the damping can be calculated using [5]. For this example the damping in the sand was also calculated to be 2.2% and in the clayey silt to be 0.5%. The damping in the clayey silt was also recalculated using the signal from 17 m depth at the top of the clayey silt layer as the reference signal. It was interesting to find that the damping was unchanged and equal to 0.5%.

Results

The results presented here are based on the SRS method applied to averaged windowed signals.

Figure 14 shows all *in situ* damping measurements in sand deposits plotted against the measured range of single amplitude strain in each series of measurements. The single amplitude strain is taken as the peak amplitude strain for *in situ* tests and is calculated by dividing the peak particle velocity by the average shear wave velocity (White 1965). The peak particle velocity is the maximum velocity as determined from the integration of the acceleration versus time measurements at each depth. The average shear velocity at each depth is calculated separately (Campanella and Stewart 1992). Thus, within one layer the shallowest measurements are at higher strain than the deepest. Also shown in Fig. 14 are available resonant column laboratory results provided by Klohn Leonoff Ltd., Vancouver, B.C. (private communication), for a sample identified as a gray, clean, fine- to medium-grained sand (SP) from another site in the Fraser delta. Also shown in Fig. 14 are recommended global values for design from Seed and Idriss (1970) and Idriss (1990).

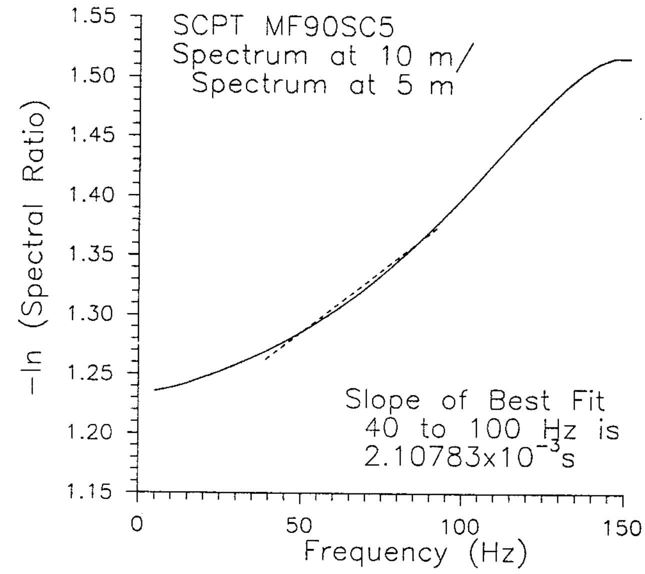

FIG. 12. Plot of negative of natural logarithm of data in Fig. 11 with slope over 40–100 Hz range.

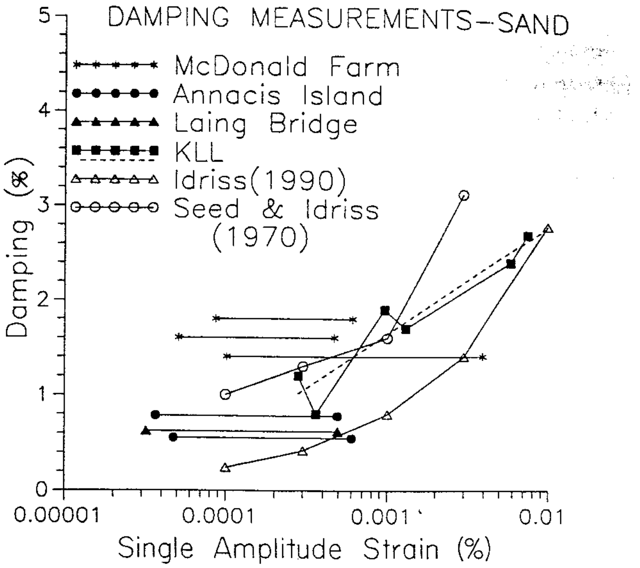

FIG. 14. Damping measurements in sand. KLL, Klohn Leonoff, Ltd.

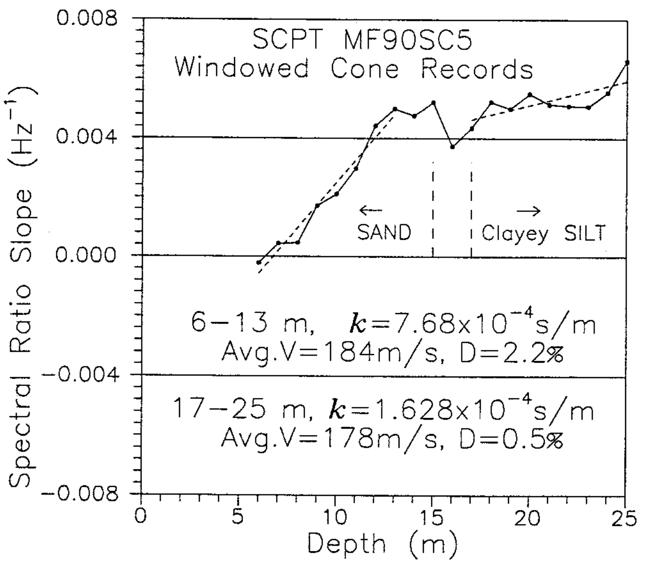

FIG. 13. Spectral ratio slope versus depth with reference signal at 5 m for McDonald Farm site, Vancouver International Airport, Vancouver, B.C.

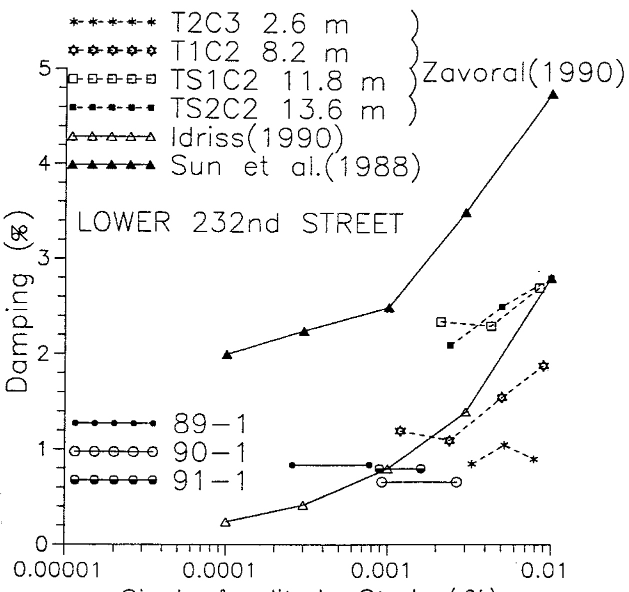

FIG. 15. Damping measurements in clay.

The Annacis Island and Laing Bridge results fall between the recommendations of Seed and Idriss (1970) and those of Idriss (1990) and are in good agreement with the laboratory results. The results from the McDonald Farm site are two to three times higher and fall just above the recommendations of Seed and Idriss. It was noted that the cone bearing was higher at the McDonald Farm site and the damping appears to increase with cone bearing. The good agreement between the Annacis North Pier and Laing Bridge results and the available laboratory data indicates that the *in situ* damping results are comparable to those obtained in the laboratory at low strain levels.

Damping measurements in clay are reported in Fig. 15 for the upper portion (above 12 m) of the Lower 232nd Street site which is reasonably uniform. Figure 15 shows the *in situ* measurements along with laboratory measurements by Zavoral (1990) and recommendations by Idriss (1990) and Sun *et al.* (1988) (following Seed and Idriss 1970).

The laboratory data generally fall close to the recommendations of Idriss (1990). A review of the soil profile showed that sand layers exist below about 11 or 12 m, and field values were only used to about 11–12 m. If the lowest-strain laboratory results from only above 11 m (at 2.6 and 8.2 m) are compared with the field data there is close agreement (averaging about 1.0% for the laboratory and 0.8% for the field). This close agreement generally confirms the validity of the field measurements.

It appears that the recommendations of Sun *et al.* (1988) give very high damping values that are not verified in this clay. The current recommendations by Idriss (1990) are verified by both field and laboratory results.

Summary

Shear wave velocity measurements only require a sensitive pickup to determine arrival time, whereas the measurement of material damping requires the analysis of the amplitude of the signals. Some of the reasons why low-strain material damping is difficult to evaluate in the field are as follows. (1) Low-strain material damping requires a repeatable energy source and trigger timing. (2) The receiver must reflect the soil movements or measure the amplitude of the stress wave through soil, and the damping characteristics of the instrument must be eliminated or nonexistent. Thus, a critically damped pickup is required. (3) Windowing of the shear wave is used in the analysis to reduce the effects of reflections and spurious signals. (4) Only the spectral ratio slope (SRS) method developed by B.B. Redpath (private communication) cancels out the very large influence of radiation or geometric damping with depth. The SRS method requires a double differentiation, first with respect to frequency and then with respect to depth. This calculation of the rate of change puts a requirement of higher than normal signal to noise resolution of the sensor. With currently available sensors, it is therefore not possible to work with incremental measurements, say, at 1-m intervals, as is done in wave velocity measurements, but the differential with respect to depth must be averaged over a minimum of a 3- to 5-m interval to measure an average material damping value.

Velocity transducers or geophones are inherently much more stable with much higher signal to noise than accelerometers. When a small, critically damped geophone is available to fit in a cone penetrometer, it should be possible to considerably improve the accuracy of measuring material damping by the SRS method over the current use of accelerometers. Although the current miniature piezoresistance accelerometers have exceptional frequency characteristics, they lack sensitivity, which limits their use to depths of about 30–40 m, even with signal averaging.

Conclusions

A listing of reported values of damping at low strain from laboratory testing was provided earlier in Table 1. The values can be summarized as ranging from about 0.5 to 2% for sands and 1 to 5% for clays. The results from the present field measurements generally fall within the range of values reported for sand but were at the low end of the range of values reported for clay.

Damping values from field measurements reported by others were provided earlier in Table 2 and are summarized as follows: 1.7–6% for sands; 1.7–7% for clays; about 2.5% for silts; and 3.5 and 12% for alluvium. Damping values from this study are lower than those reported earlier by others. It appears that differing instrumentation, test procedures, and signal-processing procedures may have affected earlier results.

Except for the results in the sand at the McDonald Farm site, which were somewhat higher, the field measurements of damping reported herein are in general agreement with the values of available laboratory data and with the recommendations of Idriss (1990). For the Lower 232nd Street site, site-specific laboratory test results agreed closely with the in situ measurements of damping.

Applications

From a practical standpoint the SRS method appears to be the only technique to allow the measurement of material damping in situ. The material damping and shear wave velocity of sedimentary layers of soil are required to model the propagation of earthquake waves to the surface to predict ground motions. Although the material damping measurements using the seismic cone are only for small strain amplitudes, they provide a reference for any laboratory testing (resonant column, etc.) where larger strains are achieved. This reference at low strains is essential, since any disturbance of laboratory samples can shift the laboratory results, which can then be adjusted to agree with the low-strain in situ measurements.

Observed amplification of ground surface acceleration levels during earthquakes as large as two times and more compared with base motion is an important consideration in foundation design and soil liquefaction susceptibility. Low material damping is the major cause of high amplification. The material damping characteristics at low strain, where damping values are lowest, is the most important characteristic to consider when predicting amplification. Thus, an accurate approximation of low-strain damping is essential for many earthquake design problems, especially in sandy ground where the seismic cone assesses stratigraphy and gives a more reliable measure of damping than laboratory testing.

Finally, the lower in situ damping measurements reported herein in comparison to earlier measurements help explain the recent observations of high surface accelerations during earthquakes on soft ground where amplification factors of two and more are observed. Analyses have shown that to predict these high amplifications at the ground surface, it is necessary to have material damping values more in keeping with those reported herein rather than the high values reported earlier.

Current research is addressing the need to determine damping and shear modulus at larger strains by the use of other in situ tests. These results would be combined with the seismic cone low-strain values to completely characterize both the damping and modulus characteristics in situ as a function of strain.

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