SHEAR MODULI OF SOILS, IN-SITU AND FROM LABORATORY TESTS

by

K.H. Stokoe, II[I] and F.E. Richart, Jr.[II]

SYNOPSIS

In-situ and laboratory values of shear moduli at low-amplitude strain conditions were evaluated in three soils and a shale through measurement of shear wave velocities by the cross-hole seismic method in-situ and by the resonant-column method in the laboratory. Close agreement of shear moduli values were obtained for a sand by the two methods, whereas the laboratory values were about half the field values for two silts. Cohesive soils exhibited an appreciable time effect in laboratory tests. Resonant-column tests on shale samples included evaluation of shearing strain amplitude effects and the influence of fracture planes.

INTRODUCTION

Earthquakes develop extreme ranges of shearing strains in soils from low-amplitude strains during microtremors to high-amplitude strains under failure conditions. The behavior of soil masses and soil-supported structures under these conditions depends upon the shear modulus of the soil. The shear modulus, G, can be evaluated from the shear wave velocity, v_s, in the soil by

$$G = (\gamma/g)v_s^2 \qquad (1)$$

in which γ is the unit weight of the soil, and g is the acceleration of gravity. Thus determinations of v_s in soils under various conditions permit calculation of G for these same conditions.

Seismic methods are available for evaluating low-amplitude v_s in-situ. Laboratory methods permit studies of the influence of various parameters on v_s in samples of soils and thereby provide a means of extrapolating the low-amplitude field data to conditions representing the design situation. However, very few dynamic studies have been conducted which compare in-situ and laboratory results. This study presents such comparisons from investigations of four field sites.

FIELD AND LABORATORY MEASUREMENT OF SHEAR WAVE VELOCITY

The cross-hole seismic method (4) was employed in the field to determine in-situ shear wave velocities. By this method, the in-situ velocity of a horizontally-travelling shear wave was measured by monitoring the travel time of the shear wave between the bottoms of two boreholes a known distance apart. Measurements of shear waves travelling in both directions were made, and the average of these two values is reported herein as the value of v_s in the field.

Undisturbed samples recovered from the same boreholes were subsequently tested in the laboratory using the torsional resonant-column method (3). The tests were conducted by applying an initial confining

[I] Assist. Prof. of Civil Engineering, Univ. of Massachusetts, Amherst, Ma.

[II] Prof. of Civil Engineering, Univ. of Michigan, Ann Arbor, Michigan.

pressure, $\bar{\sigma}_0$, which was held constant over a certain time interval while the change in v_s was measured. The confining pressure was then increased, and the procedure was repeated. The shear wave velocity of all specimens was investigated in this manner at a maximum shearing strain amplitude of 1.0×10^{-5}cm/cm. At this order of amplitude, the influence of strain amplitude can be neglected when comparing field and laboratory values of v_s (2).

RESULTS OF LABORATORY TESTS

Before field and laboratory values of v_s can be compared, the effects of magnitude and duration of confining pressure on the laboratory results must be evaluated. This was done for both the soil and shale samples tested. In addition, the effects of shearing strain amplitude and fracture planes were also investigated for the shale samples.

Effect of Duration of Confining Pressure. Typical results of the change in v_s with time at a constant confining pressure for the three soils tested are shown in Fig. 1. These results show that v_s continued to increase with time over the duration of testing time employed. The increase in v_s which is represented by the v_s-log time relationship for the silty sand and by the second straight line of the v_s-log time relationship for the sandy silt and the clayey silt will be referred to as the *secondary time effect*. This secondary time effect cannot be accounted for merely by the change in void ratio. The intent in this study is not to explain the cause of the secondary time effect but to show the extent of its influence in laboratory testing.

The results of the secondary time effect are given in column 3 of Table I. These results were determined by dividing the change in v_s per log cycle of time by v_s at 1000 min. and multiplying by 100 percent. The values for the undisturbed soil samples compare well with those found by other investigators using artificial soils (1) and show that in general, the secondary time effect increased as soil particle size decreased. For the shale samples, the secondary time effect was negligible.

Effect of Magnitude of Confining Pressure. For all soil samples, v_s increased with confining pressure. In the normally-consolidated range, the values agreed well with those predicted by empirical expressions (2,3).

The effect of $\bar{\sigma}_0$ on v_s for one of the shale samples is shown in Fig. 2. For the intact sample, increasing the confining pressure produced only a small increase in v_s for pressures greater than the in-situ confining pressure, about 280 kN/m^2. For confining pressures below the in-situ pressure, the effect of $\bar{\sigma}_0$-changes on v_s was greater because cracks which opened as a consequence of stress relief during sampling were again closed as pressure was reapplied.

Effects of Shearing Strain Amplitude and Fracture Planes. For one shale sample, the effects of shearing strain amplitude and fracture planes on v_s and material damping (expressed in terms of the logarithmic decrement) were investigated. These results are also shown in Fig. 2. The effect of increasing the strain amplitude was to reduce v_s and to increase material damping in an amount and a manner similar to that found for dry sand (2). The presence of fracture planes within the sample significantly reduced v_s and increased damping, with the effect increasing as strain amplitude increased.

COMPARISON OF FIELD, LABORATORY AND EMPIRICAL SHEAR WAVE VELOCITIES

Columns 4 to 6 of Table I include comparisons of v_s determined in the field, in the laboratory after 1000 min., and from empirical expressions (2,3). The values obtained by the three procedures were nearly identical for the silty sand, and good agreement was found for the shale. However, for the clayey silt and the over-consolidated sandy silt, the laboratory values of v_s were about 70 percent of the field values.

CONCLUSIONS

Dynamic shear moduli were evaluated in three soils and a shale from measurements of shear wave velocities in the field by the cross-hole seismic method and in the laboratory by the resonant-column method. General conclusions based on these measurements are:

1. For all soils tested in the laboratory, G increased with increasing magnitude of confining pressure and with increasing time at each confining pressure. This increase in G with time, called a secondary time effect, increased in magnitude as soil particle size decreased and agreed well with values predicted by other investigators (1). For the shale samples, magnitude and time of confining pressure had a much smaller effect on G.

2. Good agreement between laboratory and field values was found for the sand. For the two silts, the laboratory values of G were about half of the field values. These comparisons emphasize the importance of selecting the appropriate confining pressure and evaluating secondary time effects in laboratory testing.

3. For the shale samples tested in the laboratory, G decreased and material damping increased with increasing shearing strain amplitude. The presence of fracture planes within the sample significantly reduced G and increased material damping, with the effect increasing as strain amplitude increased.

REFERENCES

1. Afifi, S.A., and Woods, R.D., 1971, "Long-Term Pressure Effects on Shear Modulus of Soils," *J. Soil Mech. Found. Div., Proc. Am. Soc. Civil Engrs.,* Vol. 97, No. SM10, Oct., pp. 1445-1460.

2. Hardin, B.O., and Drnevich, V.P., 1972, "Shear Modulus and Damping in Soils: Design Equations and Curves," *J. Soil Mech. Found. Div., Proc. Am. Soc. Civil Engrs.,* Vol. 98, No. SM7, July, pp. 667-692.

3. Richart, F.E., Jr., Hall, J.R., Jr., and Woods, R.D., 1970, *Vibrations of Soils and Foundations,* Prentice-Hall, New Jersey, 414 pp.

4. Stokoe, K.H., II, and Woods, R.D., 1972, "In-Situ Shear Wave Velocity by Cross-Hole Method," *J. Soil Mech. Found. Div., Proc. Am. Soc. Civil Engrs.,* Vol. 98, No. SM5, May, pp. 443-460.

Table I Field and Laboratory Test Results

Material	Sample Depth, m	Avg Secondary v_s Increase[III]	Shear Wave Velocity, m/sec		
			Field	Lab	Empirical
(1)	(2)	(3)	(4)	(5)	(6)
Silty Sand (SP-SM)	2.4 3.3 4.3 5.3	1.5 1.0 1.9 1.8	170 186 207 226	175 186 217 206	173 180 207 210
Sandy Silt (ML)	2.0	2.0	293	207 (K_o=2)	214 (K_o=2)
Clayey Silt (CL-ML)	2.4	5.3	263	186 229[IV]	244
Shale	11.3 11.6 11.9	0.2 0.2 0.3	1010 1050 1160	940 980 830	- - -

[III]percent per log cycle of time [IV]extrapolated to a time of 20 yrs

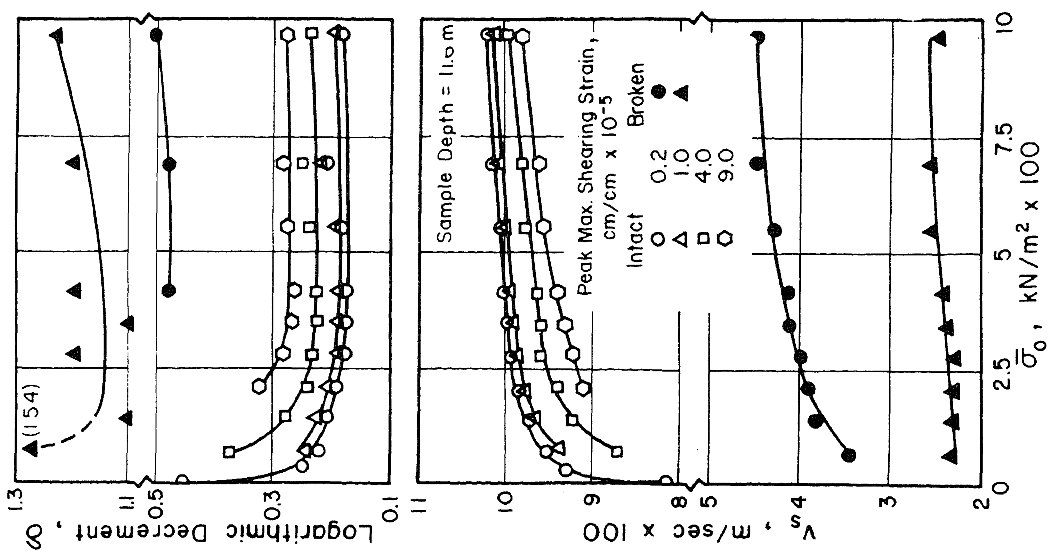

Fig. 2 - Results of Torsional Resonant-Column Test of Shale Sample

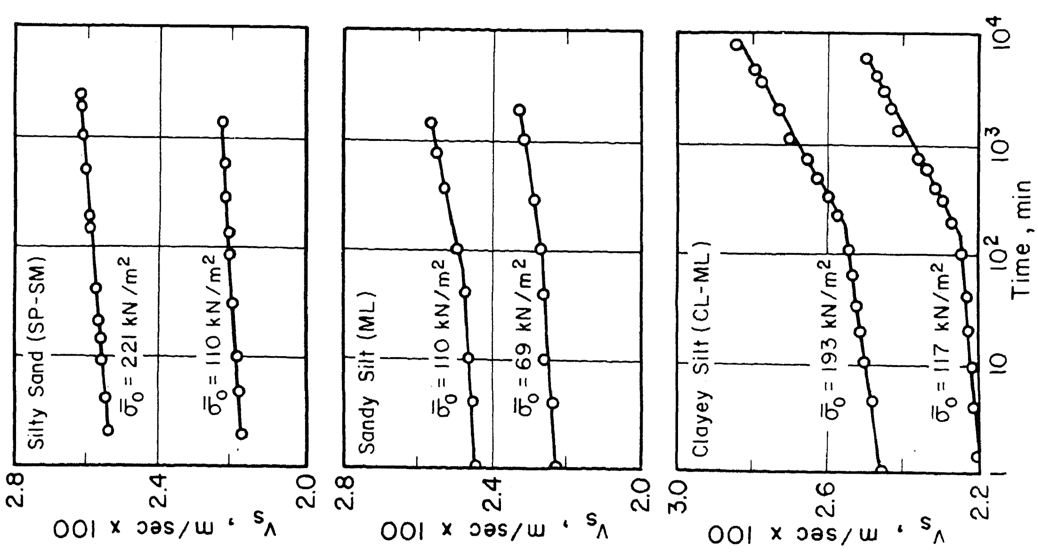

Fig. 1 - Typical Results of Change in V_s with Time under Constant Confining Pressure