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Dynamic Behavior of Soils From Field and Laboratory Tests

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SYNOPSIS: Both geophysical and laboratory tests were used to determine the dynamic shear moduli of medium stiff to hard clays and silts at six sites. The geophysical measurements included conventional downhole tests conducted at low strain levels and modified cross hole impulse tests conducted over a wide range of strains. Laboratory resonant column and cyclic triaxial tests were performed on soi samples retrieved from borings made at the sites. The results from both the field and laboratory tests of the medium stiff to stiff soils showed fairly good agreement. The laboratory test results of the hard clays and silts, however, were typically half the values of the field tests at corresponding strain levels. This would suggest the need for adjusting the laboratory results performed on hard cohesive soils Also, the field test results suggest that as soil stiffness increases, the modulus attenuation rate with strain decreases.

INTRODUCTION

One of the most important parameters required in a dynamic site response analysis is an evaluation of the dynamic properties of the subsurface soils. Typically, this includes determining the nonlinear behavior of the shear modulus of the soil as a function of shear strain. In most instances, this is determined by combining the results from different laboratory tests performed at both low (10^{-4}%) and at intermediate to high strains (10^{-2} to 1%). Unfortunately, there is no single laboratory test suitable for evaluating shear modulus over this entire strain range.

To provide a method of determining the nonlinear behavior of soil over a wide strain range, the joint venture of Shannon & Wilson and Agbabian Associates (SW-AA) developed field equipment and testing procedures for a modified cross hole geophysical test in which shear wave velocities may be evaluated in situ over the strain range of 10^{-4} to 10^{-1} percent (SW-AA, 1977b). This equipment and the testing procedures were developed for the U.S. Nuclear Regulatory Commission (NRC) as part of an overall research program to evaluate soil behavior under earthquake loading conditions.

This new impulse test was used in conjunction with a research study to investigate the subsurface conditions at sites of strong motion accelerograph stations in the United States. In this program, borings were drilled at selected accelerograph stations and conventional downhole and the modified cross hole impulse procedures were used to evaluate shear wave velocities and moduli. Additionally, laboratory resonant column and cyclic trixial tests were performed to evaluate equivalent shear and elastic moduli. This full testing program was performed at eight sites, and the results are presented in three reports to the NRC (SW-AA, 1975, 1976a, 1977a).

This paper summarizes the test results obtained at six of the eight sites. Five of these sites are located in California: Ferndale (SW-AA, 1975), Cholame (SW-AA, 1975), El Centro (SW-AA, 1975), Hollister (SW-AA, 1976a) and Gilroy (SW-AA, 1977a). The sixth site is located at Bozeman, Montana (SW-AA, 1977a). Only test results that were obtained for medium stiff to hard clays and silts are presented.

FIELD TEST PROCEDURES

The downhole geophysical method used at all sites involved the generation of low strain seismic waves rich in shear energy by striking a partially embedded post at the ground surface adjacent to a borehole. The time of first arrival of the downward-propagating shear wave was identified at multi-axis geophones clamped in a single borehole at three elevations spaced 10 feet apart. The arrival times were obtained at other elevations and compiled as a cumulative plot of travel time versus depth. The slope of the curve was then defined as a series of straight lines, each segment representing the low strain average shear wave velocity over the depth interval. Detailed procedures for this test are presented in Schwarz and Musser (1972).

The impulse geophysical test (SW-AA, 1977b) employs a cross-hole wave propagation technique with vertically oriented velocity sensors, one attached to the source and three others located in closely spaced borings (Figure 1). The signal source (Figure 2) is a specially designed in-hole anchor and hammer assembly which expands outward, pressing tightly against the walls of the borehole. The sensors are velocity transducers fixed directly to the anchor or pressed to the borehole walls with rubber packers (Figure 2).

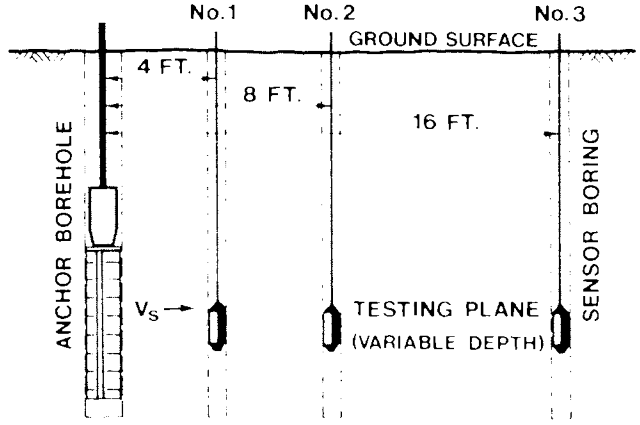

Fig. 1 SCHEMATIC OF IN SITU TEST

Fig. 2 IN SITU TEST EQUIPMENT

Once in-place, the hammer is dropped onto a stiff belleville spring on the anchor, imparting a large impulsive shearing load and a single clear shear wave to the surrounding soil. The velocity record (Figure 3) has a consistent shape which allows determination of the change in shear wave velocity with strain as the wave propagates outward. The points shown in Figure 3 correspond to a characteristic arrival time marking the passage of the wave through each sensor at a time after peak straining has occurred.

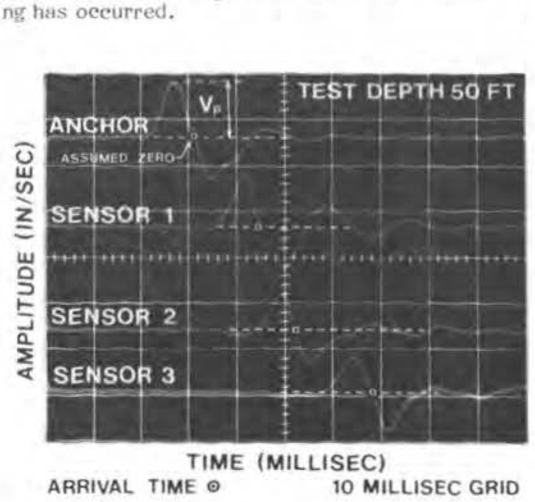

Fig. 3 PHOTO OF VELOCITY RECORDS

The arrival time at each sensor is plotted versus the measured distance (Figure 4) of each sensor from the anchor. Borehole surveying is required for determining these distances, since boreholes are seldom drilled truly vertical. The slope of the time distance curve (Figure 4) at each sensor is the shear wave velocity (V_s) at that location. The corresponding shear strain (γ) is then computed at each location as the ratio of the particle velocity amplitude, V_p, from Figure 3, to the shear wave velocity, V_s, from Figure 4. The test is then repeated at different elevations, providing additional moduli values, both as a function of strain and depth.

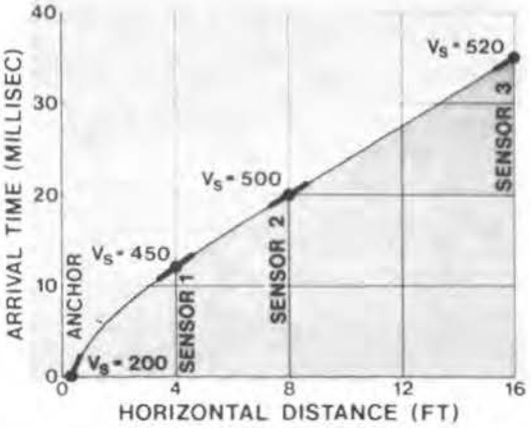

Fig. 4 SHEAR WAVE VELOCITY VALUES

LABORATORY TEST PROCEDURES

Resonant column tests and cyclic triaxial tests were performed on 2.8-inch diameter by approximately six-inch tall, relatively undisturbed cylindrical samples from borings at each site. Shear moduli values are obtained from the results of the resonant column tests and elastic moduli are obtained from the cyclic triaxial tests.

In the resonant column test, the specimen is subjected to a steady-state forced torsional vibration until its resonance is obtained (SW-AJA, 1972). For this testing, the specimen is placed in a chamber between two end caps, with the cap at the base being fixed, and the top cap serving to excite the specimen with a system of magnets and coils. Prior to testing, the sample is consolidated under an all-around confining pressure, generally taken as the effective overburden pressure. When consolidation is completed, the specimen is vibrated using a frequency generator to control the amplitude and frequency of the forced vibration. The response of the specimen is measured using accelerometers attached to the top cap. Resonance is obtained by varying the frequency of the input motion until the specimen response (acceleration) reaches a maximum.

Cyclic triaxial tests are performed at higher strain levels than the resonant column tests. In the cyclic triaxial test, the specimen is placed in a chamber and consolidated using the same procedures described for the resonant column test. After consolidation is completed, the specimen is tested using a pair of pneumatically actuated belloframs to apply the cyclic axial load. The axial load is applied as a sine wave at a frequency of 1 Hz. Eight to ten cycles of loading are applied with the fourth loading cycle being used to compute the stress strain behavior of the specimen. Three sets of tests were performed on each specimen starting at low strains and progressing to two higher strain levels. Moduli values from this test data were then determined from the hysteresis loops using the procedures given in SW-AJA, (1972).

TEST RESULTS

In order to provide a common basis for comparing the results from both the field and laboratory tests, all test data initially have been expressed in terms of shear wave velocity. Values of shear moduli (G) and elastic moduli (E) obtained from the laboratory tests were converted to shear wave velocities (V_s)

using equations (1) and (2) below. In these equations, which are based on the theory of elasticity, ρ is the mass density of the soil and Poissons' Ratio (μ) was estimated to be 0.4.

$$V_s = \sqrt{G/\rho} \tag{1}$$

$$V_s = \sqrt{E/(2\,(1 + \mu)\,\rho)} \tag{2}$$

The results from the field and laboratory tests have been separated into two categories depending upon soil stiffness. Data corresponding to medium stiff to stiff clays and silts with a low strain shear wave velocity of less than 1000 feet per second (fps) are presented in Figure 5. Data corresponding to hard clays and silts with a low strain shear wave velocity greater than 1000 fps are presented in Figure 6. In both plots, the solid symbols represent the results from field tests and the open symbols represent the results from laboratory tests. The lines in Figures 5 and 6 illustrate the general trend of the data obtained from the field impulse test.

Several interesting trends are apparent in Figures 5 and 6. First, shear wave velocities obtained from the downhole geophysical test are generally within about 10 percent of the values from the in situ impulse test extrapolated to a strain of 10^{-4} percent. Secondly, the cyclic triaxial test data are in good agreement (±30%) with the field test results for the medium stiff to stiff soils (Figure 5), but are typically less than half the field values for the harder soils (Figure 6). Also, the cyclic triaxial test data for the medium stiff to stiff soils show a modulus attenuation rate that is similar to the field test results. Laboratory test results for the hard clays and silts, however, show a much more rapid attenuation rate when compared to the field tests. Finally, the resonant column tests indicate fair agreement (±40%) with the field test data for the medium stiff to stiff soils, and values which are typically less than half the field values for the hard soils.

In analyzing the similarities and differences in the data shown in Figures 5 and 6, attention is directed to the absolute values of shear wave velocity obtained from the laboratory tests. Irrespective of the consistency of the soil, the equivalent shear wave velocities determined from the laboratory tests were not significantly different. The shear wave velocities determined from the field tests, however, do reflect an increase for the harder soils as compared to the medium stiff to stiff soils. There may be a number of reasons for the laboratory results being significantly lower than the field values, including confining pressures, sample disturbance, non-uniformity of test conditions, and limitations of test apparatus or reduction procedures. These general results, though, would suggest the need for adjusting laboratory test results on very stiff to hard soils to provide better agreement with field conditions.

COMPARISON WITH COMMONLY USED RELATIONS

Typically, the nonlinear behavior of shear modulus (G) is expressed as the ratio G/G_{max} for different levels of shear strain, where G_{max} represents the shear modulus of the soil at low strains. Seed and Idriss (1970) have compiled laboratory data for different soil types, and based on the results have published an average G/G_{max} attentuation curve for clay. This average curve is commonly used in site response analyses. The results obtained from the current field and laboratory tests were normalized for direct comparison with the published relationship of Seed and Idriss.

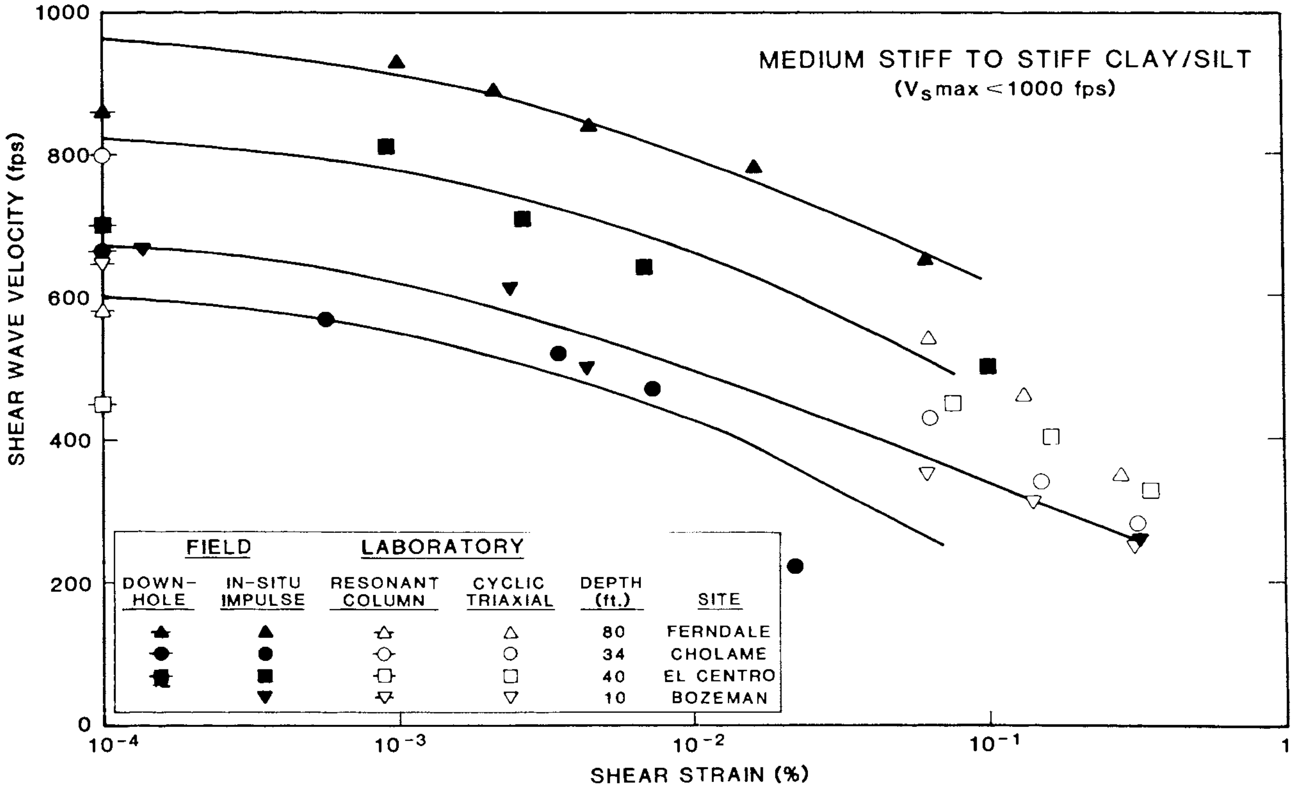

Fig. 5 SHEAR WAVE VELOCITY ATTENUATION - MEDIUM STIFF TO STIFF CLAY/SILT

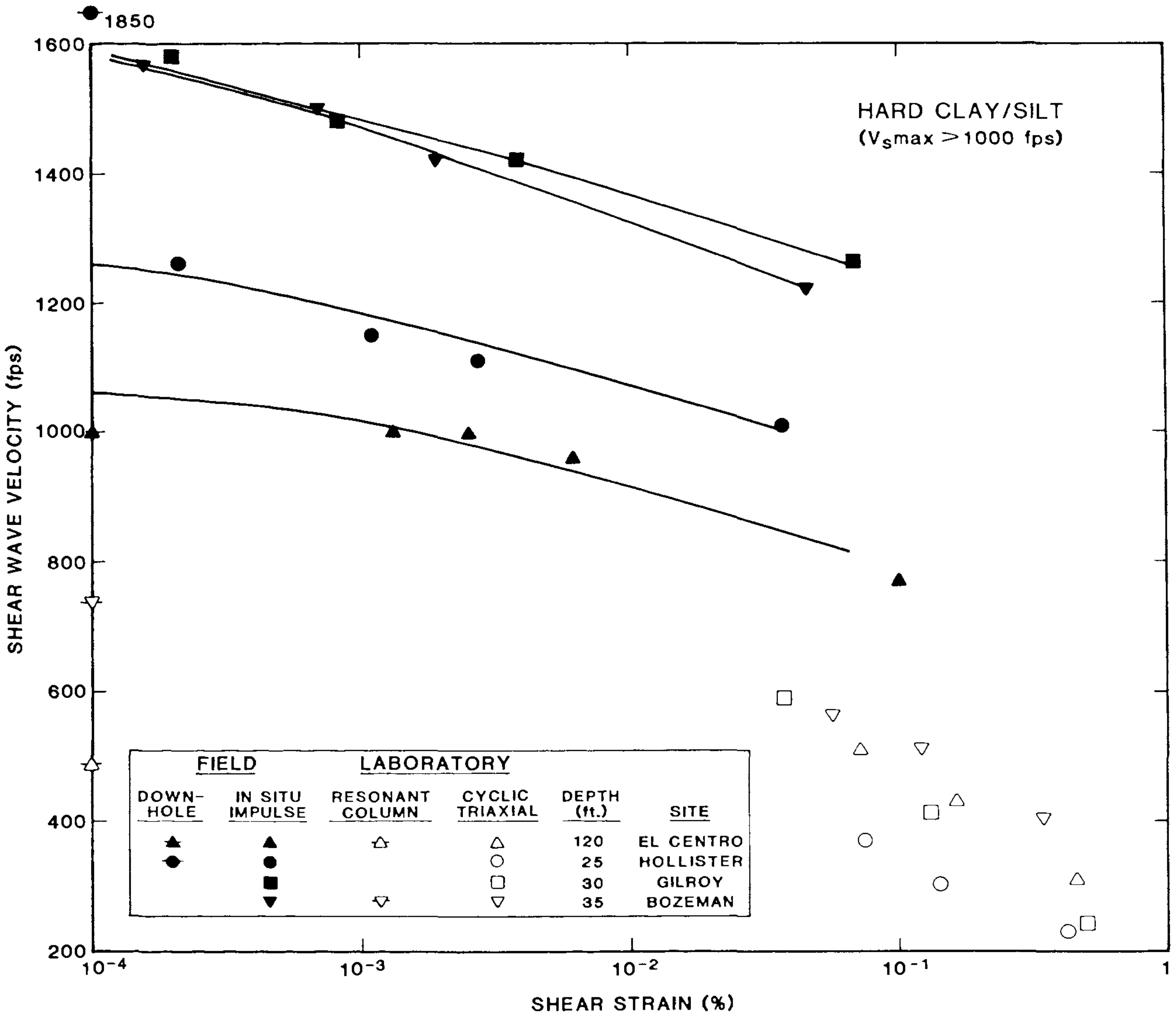

Fig. 6 SHEAR WAVE VELOCITY ATTENUATION - HARD CLAY/SILT

Normalized test data illustrating the attenuation of shear moduli with increasing shear strain are presented in Figure 7 for medium stiff to stiff soils and in Figure 8 for hard soils. As the shear modulus is proportional to the square of shear wave velocity, equation (1), the test data were normalized as follows:

$$G/G_{max} = V_s^2/V_{s\,max}^2 \qquad (3)$$

Where V_s is the shear wave velocity at a given strain level and $V_{s\,max}$ is the low strain shear wave velocity. Values of $V_{s\,max}$ were obtained by extrapolating the field impulse test data to a strain of 10^{-4} percent from Figures 5 and 6. The curves for clay and rock are average relationships for shear modulus attenuation reported by Seed and Idriss (1970) and Schnabel and others (1971).

The data plotted in Figures 7 and 8 show several interesting trends. First, as previously mentioned for the medium stiff to stiff soils, there is good agreement between the field and cyclic triaxial test data, both in terms of absolute values as well as attenuation rates. Also, both the normalized field and laboratory data exhibit a higher stiffness than the "clay" curve reported by Seed and Idriss (1970). This difference is reasonable considering that the medium stiff to stiff soils tested in this study are significantly stiffer than the soft to medium stiff clays that were used to develop the "clay" curve, but not as stiff as the "rock" curve (Schnabel and others, 1971).

Similar to Figure 6, the normalized data for the hard clays and silts that are shown in Figure 8 indicate a sharp discontinuity between the field impulse test results and the results from the cyclic triaxial tests. The normalized field data, however, show a much flatter modulus attenuation rate approaching the "rock" curve rather than the "clay" curve. Again, this may be attributed to the much stiffer nature of the soils that were tested for this study.

In general, the results from the normalized field data in Figures 7 and 8 suggest that the "clay" curve reported by Seed and Idriss (1970) is applicable for soft to medium stiff materials. However, as the soil stiffness increases, the general trend of the field test results indicates a flatter attenuation rate of shear modulus, approaching the "rock" curve, as represented by the dashed lines in Figures 7 and 8.

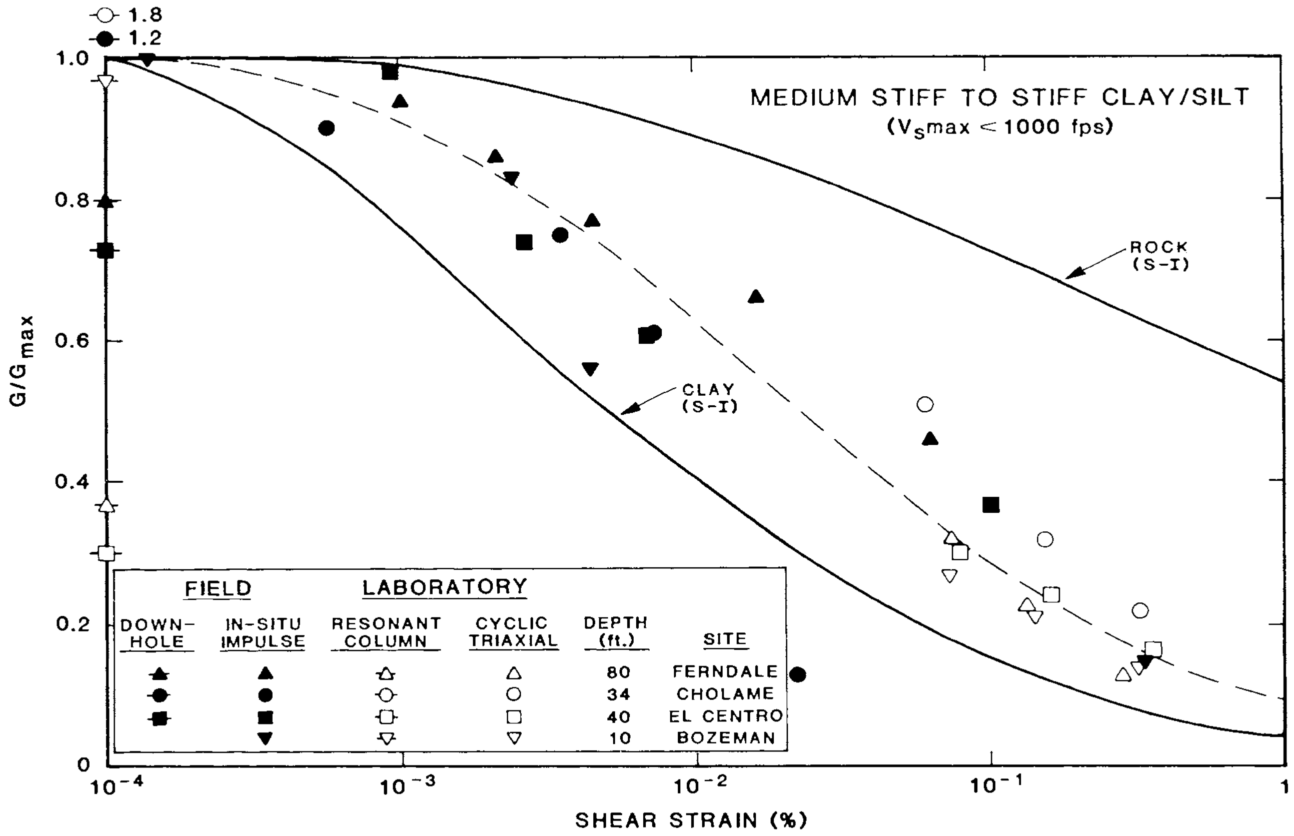

Fig. 7 NORMALIZED SHEAR MODULI - MEDIUM STIFF TO STIFF CLAY/SILT

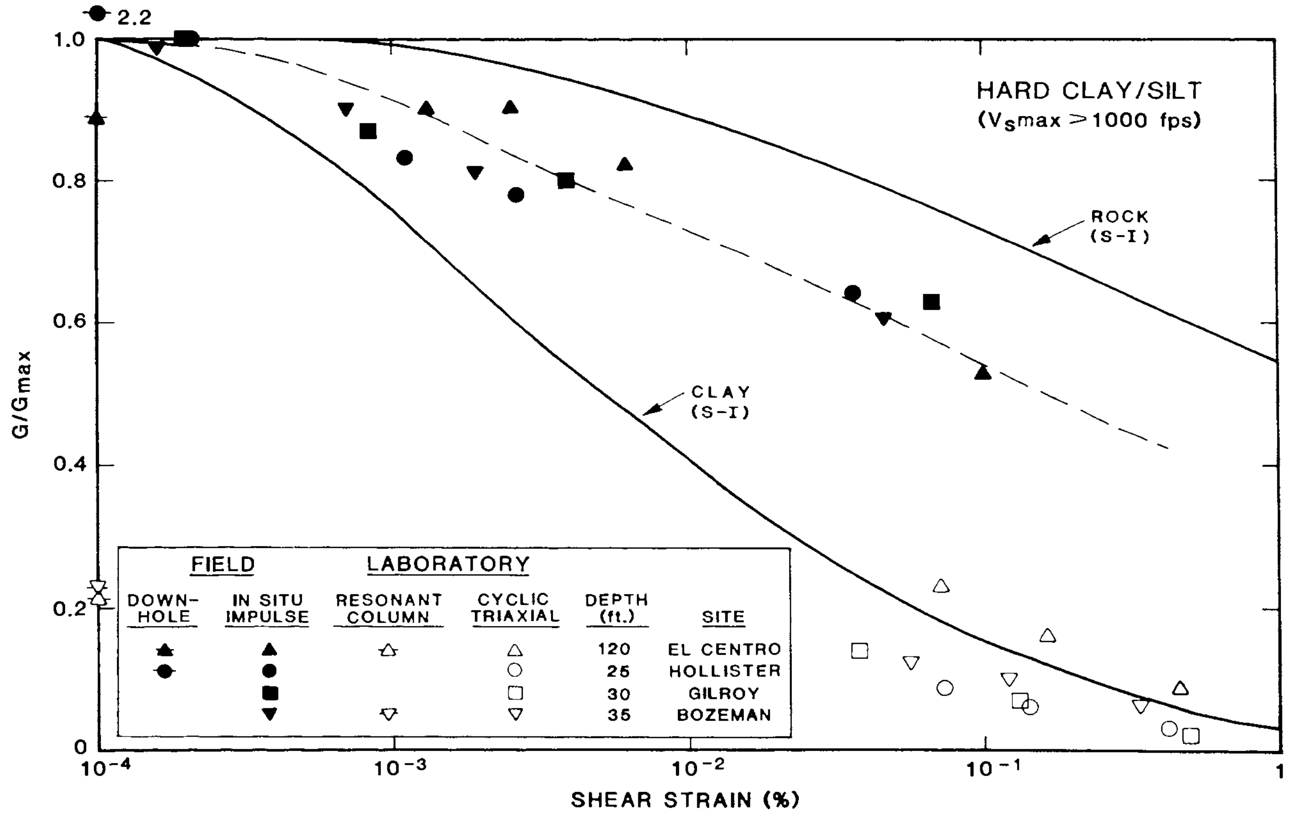

Fig. 8 NORMALIZED SHEAR MODULI - HARD CLAY/SILT

SUMMARY AND CONCLUSIONS

Field and laboratory tests were used to evaluate dynamic soil properties of cohesive soils at six sites. The data were differentiated into medium stiff to stiff clays and silts with $V_{s\,max} < 1000$ fps and hard clays and silts with $V_{s\,max} > 1000$ fps. The results of the study indicate that:

1. Laboratory test results for the medium stiff to stiff soils are generally within 30% of the field values at corresponding strain levels.
2. Laboratory test results for the hard soils are typically less than half the field values at corresponding strains.
3. The difference in the field and laboratory test results for the hard soils indicates that laboratory data for very stiff to hard soils may need to be adjusted.
4. The field test results suggest that the modulus attenuation rate of a soil decreases as the soil stiffness increases.
5. The field test data also suggest that the Seed-Idriss curves are applicable for soft to medium stiff clays, but that other relations (dashed lines Figures 7 and 8) are applicable for stiffer soils.

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