IN SITU IMPULSE MEASUREMENTS OF SHEAR MODULUS
OF SOILS AS A FUNCTION OF STRAIN

by

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SYNOPSIS

In situ determinations of shear moduli at different strain levels have been accomplished by impulse-generated shear wave velocity measurements. The results show that soil deposits of different geologic origin respond with somewhat different rates of reduction in modulus at increasing levels of strain. These differences indicate the need for in situ measurements for obtaining this important soil parameter for many earthquake engineering projects. Preliminary tests using the standard penetration test as an alternate source of energy show results consistent with other data.

INTRODUCTION

Strong earthquake motions generate shear strains in the order of 10^{-3} to 10^{-1} percent in the foundation soils which support man-made structures. In this range of strain, the shear modulus of soil varies as a function of the strain level. The in situ structure of a soil and the natural state of stress are important variables which control these modulus-strain curves. Because the soil structure is difficult to preserve during field sampling and specimen preparation procedures for testing in the laboratory, and because natural stresses are usually unknown, in situ measurements of soil shear moduli by this means is a significant improvement in the obtaining of realistic parameters for seismic site response analyses.

Normally, geophysical tests are utilized for obtaining moduli at very low strain levels, in the order of 10^{-4} percent or less. Laboratory tests permit determination of the shear modulus of small specimens at various strain levels. To correlate the results of these tests and evaluate laboratory test effects, there is also a need for in situ tests which could provide, in one single test, determinations of moduli at different strain levels.

This paper summarizes the results of in situ measurements of shear modulus versus shear strain performed in different soil deposits by means of a modified crosshole impulse test. Descriptions of the equipment and testing procedures have been presented elsewhere (Ref. 1). The test set up is shown schematically in Fig. 1.

SOIL SHEAR MODULUS TESTS

The dynamic shear modulus of soil has been defined as the secant modulus of the hysteretic shear stress-shear strain relationship determined

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under symmetrical cyclic loading conditions (Ref. 2). The dashed curve in Fig. 2 shows the relationship of the shear modulus variation with shear strain for compacted specimens of a dense silty sand tested using cyclic triaxial test procedures (Ref. 3).

To determine an "in situ" curve of shear modulus versus shear strain of a large compacted soil mass for comparison with the laboratory results, the impulse test (shown schematically in Fig. 1) was carried out. In this test, vertically polarized shear waves are generated from a source and the velocities of these waves are measured as they travel through the soil mass. Since the modulus or velocity is strain dependent, the wave velocities usually increase as the wave travels outward where strains are becoming increasingly smaller. Shear wave velocity, V_s and shear modulus, G, are related by the equation:

$$G = \rho V_s^2 \qquad (1)$$

where ρ is the mass density of the soil. The shear strain, γ, is estimated as the ratio of the velocity of a soil particle, $\dot{w}$ (moving perpendicular to the direction of wave propagation), to the wave velocity, or:

$$\gamma = \frac{\dot{w}}{V_s} \qquad (2)$$

Therefore, shear strains and shear moduli are determined by measurements of particle velocities and shear wave velocities between receiving stations positioned at different distances in the soil mass. The results from these in situ tests, performed in a compacted dense silty sand fill, are shown in Fig. 2. This curve compares well with the dashed curve obtained from cyclic triaxial tests on compacted specimens of the same soil.

A variation of the in situ impulse test was introduced using the split spoon sampler, in the standard penetration test, as a source for generating waves at small strain levels. Limited testing with this alternative wave generating source was also performed in the compacted dense silty sand fill. The results, plotted in Fig. 2, indicate that there is good agreement between the in situ measurements using different wave input sources. This indicates that it may be possible with future development and testing to use the well known split spoon sampler from the standard penetration test, or similar dynamic cone penetrometers, to make measurements of wave velocities and at the same time obtain the penetration resistance of the soil deposit.

SHEAR MODULUS OF NATURAL SOIL DEPOSITS

In situ impulse tests have been performed in several natural deposits of different geologic history. The results obtained in five of these deposits are summarized in Fig. 3. Three of the sites are located near U.S. Accelerograph Stations which have recorded major earthquakes: El Centro, Ferndale and Cholame No. 2, in California (Ref. 4). The other two sites are located in Seattle, Washington (Ref. 5). The soils tested in California are normally loaded and moderately overconsolidated silty clays of stiff to very stiff consistency. The subsurface soils at the two Washington sites (Queen Anne and Ft. Lawton) consist of heavily overconsolidated hard silty clays and very dense silty sands, respectively.

Curves of shear modulus versus shear strain, for three different depths, are shown in Fig. 3, for each site. Several trends are observed from these curves. First, the shear modulus increases with depth (or confining stress); second, the shear modulus decreases with an increase in the shear strain level; third, overconsolidated soils have much larger moduli than normally loaded soils; fourth, the curves of reduction of shear modulus with shear strain are steeper for the stiffer soils than for the softer soils, and finally, the specific strain intervals covered by this test correspond to a range in which the change in modulus is generally very large. It also corresponds to a range in which laboratory and conventional field geophysical test data are not commonly obtained.

To further study and compare changes in moduli over given strain intervals, the following ratios are introduced:

$$r_1 = \frac{G_1}{G_3} \quad \text{and} \quad r_2 = \frac{G_2}{G_3}$$

where G_1, G_2 and G_3 are the soil shear moduli for shear strains of 0.5×10^{-1}, 0.7×10^{-2} and 1×10^{-3} percent, respectively. These strains cover a wide range of values, and are generally spaced at approximately equal intervals apart (i.e., in terms of strain magnitude these three strain values are approximately a factor of 7 apart, respectively). When these ratios are computed for the curves in Fig. 3 it is observed that:

1) Shear moduli at 0.5×10^{-1} percent strain are only one-fourth to one-third of the moduli values at 1×10^{-3} percent strain in the heavily overconsolidated soils. For the same strain range, the reduction is about one-half in the normally loaded and moderately overconsolidated soils.

2) Shear moduli at 0.7×10^{-2} percent strain are in the order of one-half the moduli values at 1×10^{-3} percent strain in the heavily overconsolidated soils. For the same strain range, the reduction in modulus is much smaller, about one-fifth, for the normally loaded and moderately overconsolidated soils.

3) Rapid and thus important changes in moduli are observed to occur in the small strain interval, between 1×10^{-3} to 0.7×10^{-2} percent.

CONCLUSIONS

The differences observed in the curves of shear modulus reduction with increasing shear strain, for soil deposits of different geologic history, indicate the importance during testing of preserving as much as possible the undisturbed structure and the natural state of stress of the soil mass. These conditions may be maintained by in situ testing as described herein.

The experiments performed in an artificially compacted fill indicate a potential of using dynamic penetration tests to obtain simultaneous information about penetration resistance and wave propagation properties of soil deposits.

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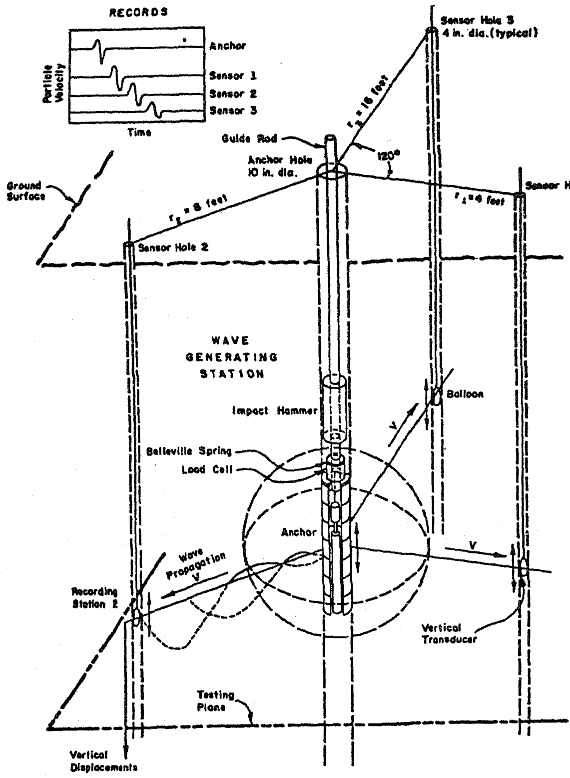
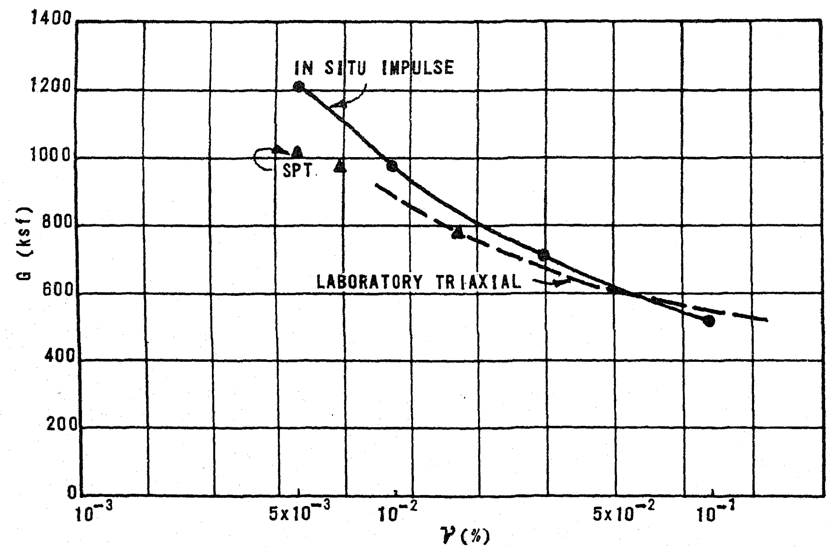


FIG. 1 SCHEMATIC REPRESENTATION OF IN SITU IMPULSE TEST



▲ FROM STANDARD PENETRATION TESTS

FIG. 2 SHEAR MODULUS VERSUS SHEAR STRAIN FOR COMPACTED SILTY SANDS

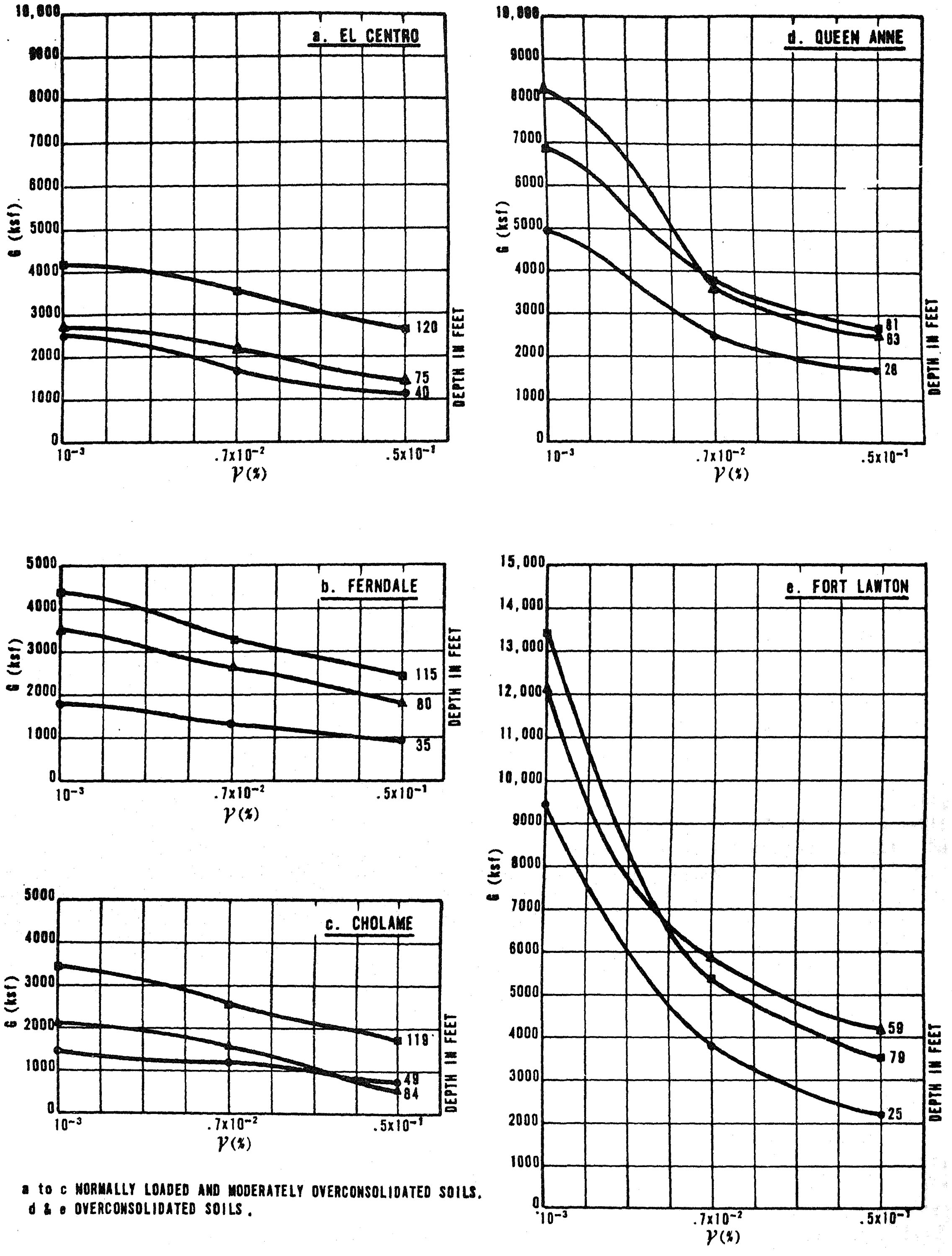


FIG. 3 SHEAR MODULUS VERSUS SHEAR STRAIN FOR SOILS OF DIFFERENT GEOLOGIC HISTORY