PREDICTING IN SITU STRAIN-DEPENDENT SHEAR MODULI OF SOIL

by

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SYNOPSIS

Shear moduli evaluated from laboratory tests must be modified to approximate in situ moduli because of factors associated with laboratory testing procedures. The form of the moduli adjustment is primarily related to the time-dependent behavior of reloaded soils subjected to constant stress conditions. Because time effects occur at all shearing strain amplitudes up to 1.0 percent, it appears that in situ moduli can be best predicted by increasing laboratory moduli by a constant amount equal to the difference between moduli measured at low-strain amplitudes by laboratory and geophysical methods.

INTRODUCTION

Shear moduli of soils are strain dependent (Seed and Idriss, 1970; and Hardin and Drnevich, 1972) but are relatively constant for shearing strains below a threshold level of about 0.001 to 0.01 percent. Moduli values at or below this level are considered maximum values and are commonly denoted as G_{max}. Once the threshold strain level is exceeded, shear moduli decrease in a nonlinear manner until residual-like moduli are measured at strains of one percent or more. This nonlinear relationship between shear modulus, G, and shearing strain, γ, is important in analytical studies of earthquake response because strain levels in the free-field and near structures often exceed 0.01 percent. Therefore, to perform free-field stress evaluations or soil-structure interaction studies, shear moduli compatible with induced strain levels must be known.

Shear moduli are presently determined in the field by seismic methods and in the laboratory by tests on "undisturbed" samples. Field techniques such as crosshole, downhole, surface refraction and steady state vibration methods permit evaluation of shear moduli at shearing strains below the threshold level and hence determine G_{max}. Thus, field data are not directly usable for modeling earthquake response at higher strain levels (although Miller, et. al. (1975) have developed a method involving high shearing strains).

Laboratory evaluation of shear moduli by resonant column, cyclic simple shear, cyclic torsional shear, and cyclic triaxial shear tests permit evaluation of shear moduli over a range of shearing strains and permit easy control of other test variables. However, use of laboratory results to predict field behavior include problems of sample disturbance, possible changes in soil structure, boundary effects and difficulties in reproducing the in situ state of stress and stress history. As a result of these limitations, values of moduli determined in the laboratory may not be entirely representative of in situ soil behavior.

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In view of the limitations of laboratory and geophysical test data, a combination of field and laboratory test results are normally used to estimate in situ response. The generally accepted procedure involves determining the G versus γ relationship in the laboratory for the range of interest, and then normalizing all modulus values by the low-amplitude laboratory shear modulus. The modulus ratio, G/G_{max}, versus γ curve is used as the shape of the field curve. The magnitudes of field moduli are determined by multiplying the G/G_{max} curve by G_{max} measured in situ. This procedure is analogous to increasing the laboratory curve by a constant percentage equal to G_{max} lab/G_{max} field. It is assumed that factors causing the discrepancy between G_{max} lab and G_{max} field occur to the same proportion at high strain amplitudes as they do at low strain amplitudes.

No data presently exist to verify this approach for determining shear moduli in situ. In fact, evidence presented herein suggests that a percentage increase does not occur in the 0.01 to 1.0 percent range. Rather, an arithmetic increase in laboratory data may be more representative. The rationale for an arithmetic adjustment is based on observations of time-dependent behavior of soils recorded in the laboratory at low- and high-strain amplitudes.

LOW-AMPLITUDE BEHAVIOR

For cohesive soils the shear moduli measured in the laboratory at low shearing strain amplitudes, G_{max}, are generally less than shear moduli measured in situ by geophysical methods (Stokoe and Richart, 1973; Anderson and Woods, 1975; and Stokoe and Abdel-razzak, 1975). Typical results for this type of comparison are shown in Fig. 1. For this study laboratory measurements were made at low-strain amplitudes following one-day application of confining pressure on a drained sample. The differences shown in Fig. 1 can be attributed partly to errors in reproducing in situ confining pressure and to sample disturbance, but much of the difference is due to the significant effects of time on laboratory values of moduli. If laboratory determinations were made after one-week of confinement, closer agreement between laboratory and geophysical data would result.

Typical results for effects of time on G_{max} are shown in Fig. 2. In this figure, time effects refer to the increase in shear modulus with time after primary consolidation. This increase can usually be represented by a straight line on a semilogarithmic plot of shear modulus versus log time. The increase in shear modulus per log cycle of time after primary consolidation is denoted as ΔG. Values of ΔG vary from as little as 100 psi per log cycle of time (in minutes) for some clean sands to more than 4,500 psi per log cycle of time for some normally consolidated clays. In general, ΔG increases as particle size decreases (Afifi and Richart, 1973), and is less for overconsolidated soils than for the same soils in the normally consolidated state. Time effects have also been represented by the ratio, $\Delta G/G_{max(1000min)}$, where $G_{max(1000min)}$ is the low-amplitude modulus measured after 1000 minutes of confinement. This normalization procedure removes much of the effect of consolidation pressure on rate of modulus increase. Typical values of $\Delta G/G_{max(1000min)}$ are 1 to 3 percent in clean sands, 3 to 10 percent in overconsolidated clays, and 5 to 20 percent in normally consolidated clays. Procedures for estimating $\Delta G/G_{max(1000min)}$ are given in Afifi and Richart (1973) and Anderson and Woods (1976).

Similar trends occur for the variation in ΔG and for the variation between laboratory and geophysical values of G_{max}. Where time effects are small as in clean sands, agreement between field and laboratory values of G_{max} is usually close when high-quality samples are tested (Stokoe and Richart, 1973). When time effects are large as in normally consolidated clays, the discrepancy is large unless time effects are taken into account.

To account for time effects particular care must be used when adapting laboratory values of G_{max} to represent field conditions. An age factor for the site, F_A, must be estimated from

$$F_A = \log\ (\frac{t_c}{t_p}) \tag{1}$$

in which t_c equals the time in minutes since the last significant change in stress history of the site, and t_p equals the time to complete primary consolidation. (For most sand sites t_p can be taken to be equal to 100 minutes). Then, if only time effects cause the difference between field and laboratory shear moduli, the in situ G_{max} is

$$G_{max}\ \text{field} = G_{max}\ \text{lab (end of primary)} + F_A * \Delta G \tag{2}$$

Typical values of F_A range from 4 to 8 which correspond to site ages of 20 and 200,000 years, respectively, if primary consolidation occurs in a relatively short period of time (i.e., 100 to 1000 minutes as shown in Fig. 2).

HIGH-AMPLITUDE BEHAVIOR

Shear moduli determined at shearing strains above the threshold level are also time dependent. Figure 3 illustrates typical long-term resonant column results on a clay at various shearing strain amplitudes. Note that similar time effects occur over the range of shearing strain amplitudes used and, hence, the slopes of the increase in shear modulus with log time at different shearing strain amplitudes are nearly identical. By plotting modulus-strain values at equal values of time, a series of similar parallel, modulus-strain curves are defined as shown in Fig. 4. Because time effects at high-strain amplitudes occur in the same manner as found for low amplitudes, it can be postulated that the best field curve for G versus γ at the start of cyclic loading would result if the laboratory curve was shifted upward by a constant amount, as shown in Fig. 4, to incorporate time effects.

This same time effect is expected in sands before cyclic loading but to a lesser extent. Recent results presented by Seed (1976) on liquefaction characteristics of sand appear to substantiate this view. In these studies it was found that liquefaction strength of sand was also time dependent, and the strength after 100-days of confinement was approximately 30 percent higher than the strength after one-day.

The high-amplitude moduli, G, discussed previously represent G at the beginning of cyclic loading. Values of G at a given γ may, however, continually change during cyclic loading. For clays G decreases with repetitions of high-amplitude loading but regains to its initial value with sufficient time of rest after loading (Anderson and Richart, 1976). For sands G may increase or decrease with cyclic loading depending on pore pressure generation and volume changes but following cyclic loading and dissipatio of pore pressure, G at all strain levels will usually be permanently changed (Drnevich and Richart, 1970). These behaviors indicate the significant permanent effect of seismic history on sands which does not occur for clays.

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Results shown in Figs. 3 and 4 suggest that the G versus γ curve would continue shifting upwards until the low-amplitude modulus value coincided with the geophysical result. At this point the expected field curve is represented mathematically by

$$G_{field} = G_{lab} + A_r \tag{3}$$

where A_r is the <u>difference</u> between G_{max} field and G_{max} lab. If, however, the shear modulus increases on a percentage basis, as is often assumed, then

$$G_{field} = G_{lab} * P_r \tag{4}$$

where P_r is the <u>ratio</u> of G_{max} field to G_{max} lab.

The two approaches are shown schematically in Fig. 5. Note that at lower strains (less than 0.01 percent) the two procedures give similar values of shear modulus, but as the strain increases the difference in the two values increases. In the 0.01 to 0.1 percent range the two values may differ by as much as 40 percent with the value predicted by the arithmetic method being higher than that predicted by the percentage method.

The concept of an arithmetic increase also implies that the shape of the G/G_{max} versus γ curve is not unique but changes with time. In fact G/G_{max} will vary with the magnitude of the low-amplitude modulus as well as rate, ΔG, and amount of time effects, F_A. Figure 6 indicates that the most significant differences occur for soft soils (low G_{max}) exhibiting large time effects and the least difference for stiff soils (large G_{max}) with small time effects. In Fig. 6 the upper bound of the time effects band represents a site age of about 200,000 years and the lower bound about 20 years (assuming a short period of primary consolidation).

Because laboratory test results are time dependent, the G/G_{max} versus γ curve cannot be unique. Therefore, the percentage increase procedure will be at best a lower bound. Due to the impracticality of conducting extremely long-term tests, a question exists regarding the best location for the field curve. Whether the actual curve will be equal to the arithmetically corrected curve or will fall between the two can only be verified by conducting high-amplitude in situ tests and comparing results to results predicted on either basis. Laboratory data suggest that results will more closely resemble the arithmetic correction (Eq. (3)).

Importance of the variation between accepted procedures and procedures described herein for predicting G at the start of cyclic loading arises when modeling response during free-field or soil-structure interaction studies. Depending on site characteristics and level of induced shaking, the calculated response may differ considerably from field behavior at critical earthquake strains because the field is governed by a stiffer modulus. In view of the uncertainty in the correct location of the field G versus γ curve at the start of cyclic loading, it is essential that parametric studies be conducted incorporating the percentage increase value as a likely lower bound (Eq. (4)) and the arithmetic increase value as a likely upper bound (Eq. (3)).

CONCLUSIONS

1. Shear moduli evaluated in the laboratory depend on the time elapsed after the confining pressure is applied to a sample. After primary consolidation, a linear increase with the logarithm of time has been found for clays and sands with larger increases developed for clays.

2. Time effects measured in the laboratory can be used to estimate in situ shear moduli which exist just before earthquake loading. The numerical difference between G_{max} field and G_{max} lab is added to the shear modulus associated with each level of shearing strain, thus elevating the one-day laboratory shear modulus versus shearing strain curve by a constant amount, as shown in Fig. 5.

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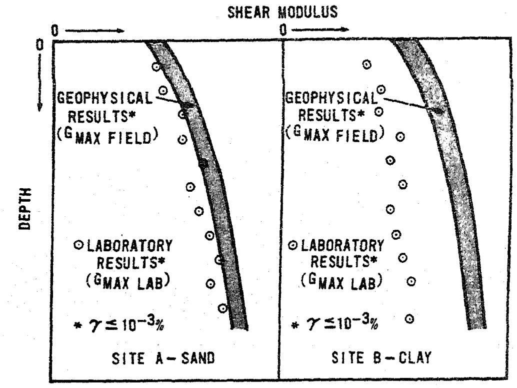

FIG. 1 LABORATORY AND GEOPHYSICAL TEST RESULTS COMPARED

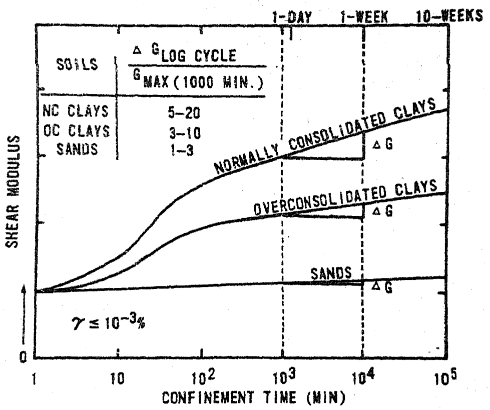

FIG. 2 EFFECT OF CONFINEMENT TIME ON SHEAR MODULUS

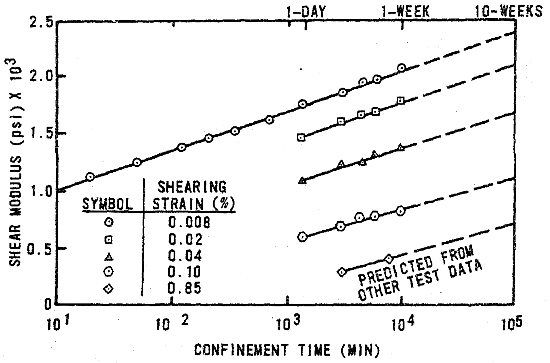

FIG. 3 TYPICAL HOLLOW-SAMPLE RESONANT COLUMN TEST RESULTS FOR CLAY

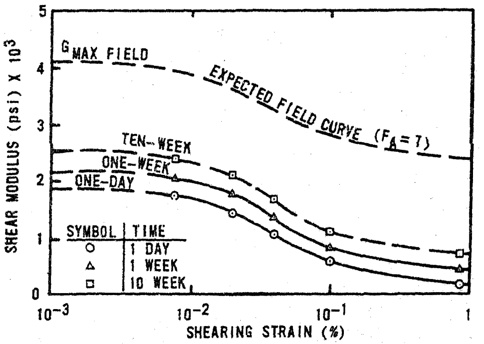

FIG. 4 EFFECT OF TIME ON SHEAR MODULUS - SHEARING STRAIN RELATIONSHIP

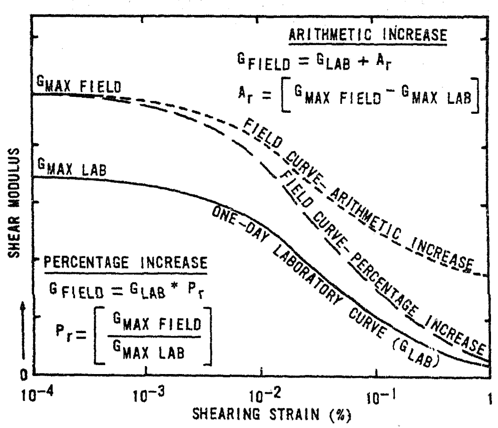

FIG. 5 FIELD CURVE PREDICTED BY ARITHMETIC AND PERCENTAGE INCREASE IN MODULI

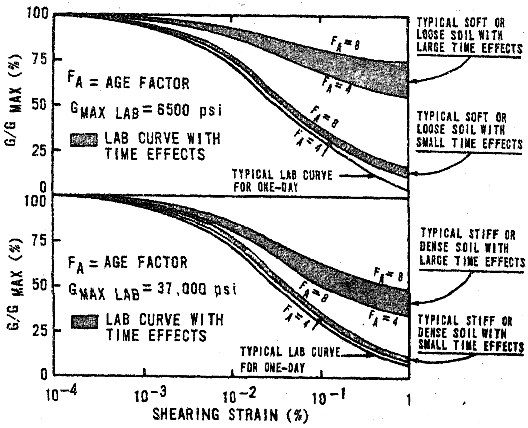

FIG. 6 EFFECT OF TIME ON MODULUS RATIO CURVES