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ABSTRACT The effects of shearing strain amplitude and shearing strain rate on the shear modulus of normally consolidated specimens of San Francisco Bay Mud were studied with a specially constructed torsional shear/resonant column device. Torsional shear measurements were performed at excitation frequencies of 0.03, 0.1, 0.3, and 1.0 Hz and were followed by a resonant column measurement at the same strain amplitude. This testing sequence was conducted at constant values of shearing strain amplitude over the range from 0.001 to 0.1 percent. From these measurements the dependency of shear modulus on shearing strain rate and amplitude was studied. Shear modulus was found to increase with the logarithm of shearing strain rate at a constant shearing strain amplitude. The influence of shearing strain rate was found to be independent of shearing strain amplitude, mean effective normal stress, and duration of confinement at constant mean effective normal stress. Typical variation in shear modulus with shearing strain rate at a constant shearing strain amplitude was about four percent per log cycle of shearing strain rate. Shear modulus was found to decrease with the logarithm of shearing strain amplitude at a constant shearing strain rate. No ultimate value of shear modulus at low-amplitude shearing strains (below 0.001 percent) at a constant shearing strain rate was found. Thus, the ultimate value of low-amplitude shear modulus measured in the resonant column test is seen to be a special case in which the decrease in shear modulus due to lower shearing strain rate is counterbalanced by an increase in shear modulus due to lower shearing strain amplitude.

INTRODUCTION

Recently, a new version of an older form of testing device to evaluate dynamic soil properties has been developed at The University of Texas at Austin. This device is a torsional shear/resonant column (TSRC) device. This device is unique in the aspect that it is capable of both torsional shear and resonant column measurements on the same soil specimen over a range in shearing strains from below 0.001 percent to in excess of 0.1 percent (Isenhower, 1979). With this device, it is possible to study the effects of variables such as shearing strain amplitude, shearing strain rate (the frequency of loading), number of cycles of loading, mean effective normal stress, and duration of confinement at a constant mean effective normal stress upon the shear modulus and material damping of the soil.

The subject of this paper is the effect of shearing strain rate upon the shear modulus of a cohesive soil, San Francisco Bay Mud. The test procedure used with the TSRC device is first briefly explained. Then the dynamic behavior of Bay Mud as determined with this equipment is presented. Finally, the resonant column test results are examined and discussed from the viewpoint of shearing strain rate.

TESTING PROCEDURES

All samples of Bay Mud tested in this study were taken from Hamilton Air Force Base with thin-walled sampling tubes. The sample depth was approximately 30 ft, and each sample was tested as an undisturbed, normally consolidated sample.

Low-Amplitude Testing - In dynamic soils testing, the testing procedure varies with the purpose of the test. The variation usually consists of different combinations of measurements, i.e. different excitation frequencies, shearing strain amplitudes, times of confinement, etc. For resonant column testing presented herein, the purpose was to determine the influence of confining pressure and time of confinement at a constant pressure on the shear modulus at shearing strains less than 0.001 percent. The shear modulus in this strain range is commonly denoted as G_{max}, the low-amplitude shear modulus (Hardin and Drnevich, 1972), and the change in G_{max} with time at a constant pressure is referred to as the long-term time effect (Anderson and Stokoe, 1978).

The procedure for this testing was then to apply a hydrostatic confining stress to the specimen with drainage allowed for consolidation, and measurements were made in a sequence similar to that used in a consolidation test, i.e. 1, 2, 4, 8, 15, 30, 60 ... minutes after application of the confining stress. Each measurement consisted of taking readings of the resonant period, accelerometer output, and specimen length from which the shear modulus, shearing strain amplitude, and void ratio were calculated. The duration of vibration for each measurement was typically about 30 seconds, and the sample was vibrated only during the measurement period. For most tests, the duration of confinement under one confining pressure was on the order of 6,000 to 10,000 minutes (4 to 7 days).

High-Amplitude Testing - After primary consolidation had ceased and the low-amplitude long-term time effect had been defined, the specimen drains were closed and a high-amplitude testing series was performed. It should be noted that the specimen drains were closed only during high-amplitude testing and were opened again at the conclusion of this testing. High-amplitude testing is defined as dynamic testing where shearing strains in excess of 0.001 percent are generated. For this study, high-amplitude testing consisted of both torsional shear and resonant column measurements. The essential difference between these measurements is the shearing strain rates at which the measurements are made, and the ability of the torsional shear device to measure sensitively the effects of number of cycles of loading.

The high-amplitude testing procedure was designed to assess the effects of shearing strain amplitude, γ, shearing strain rate, $\dot{\gamma}$, and number of cycles of loading (degradation in this cohesive soil). To assess the effects of cyclic loading, torsional shear measurements were made before any resonant column measurements were performed because of the large number of loading cycles applied in the resonant column measurement (approximately 30 seconds times the resonant frequency). The usual measurements taken at each high-amplitude shearing strain were four sets of torsional shear measurements, each at a different frequency and one resonant column measurement. In the torsional shear measurements, records of the first 1.25, 3rd, 7th, and 10th loading cycles at four excitation frequencies, typically 0.03, 0.1, 0.3, and 1.0 hertz were made. The high-amplitude resonant column reading was then taken immediately after the torsional shear readings. After each set of high-amplitude readings, one low-amplitude resonant column reading was taken to measure any change in the low-amplitude shear modulus after high-amplitude cycling.

HIGH-AMPLITUDE RESONANT COLUMN DATA

All of the resonant column data are shown in a normalized shear modulus - shearing strain plot in Fig. 1. As shown in this figure, shear modulus is constant at shearing strains of 0.001 percent and below and decreases with increasing shearing strain above 0.001 percent. For purposes of comparison, the Seed-Idriss (1970) curve for sands and the Stokoe-Lodde (1978) curve for San Francisco Bay Mud from sites other than Hamilton Air Force Base are plotted in Fig. 1.

The typical long-term time effect on shear modulus is shown in Fig. 2. This figure shows the low and high-amplitude values of shear modulus at selected shearing strains as a function of the duration of confinement at a constant confining pressure. It can be seen that for the shearing strains shown, the change in shear modulus as a function of time is approximately equal for all shearing strain amplitudes. This observation is consistent with the findings of Lodde (1981) and Anderson (1974) and supports the arithmetic increase method of predicting field behavior from laboratory data up to strains of 0.1 percent as proposed by Anderson and Stokoe (1978).

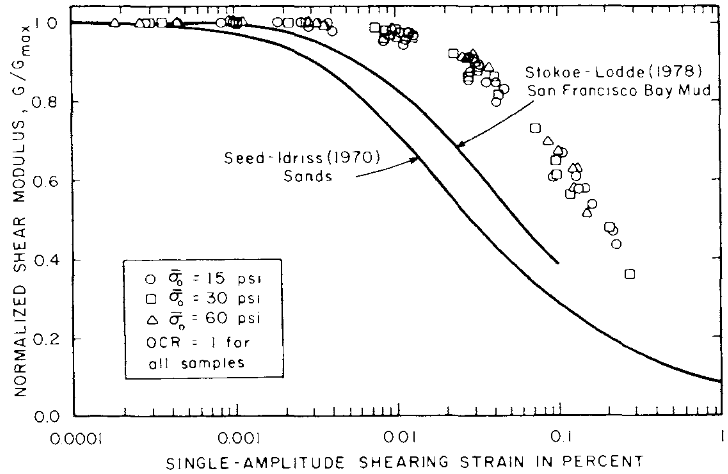

Figure 1 - Variation in Normalized Shear Modulus with Shearing Strain Amplitude from Resonant Column Tests

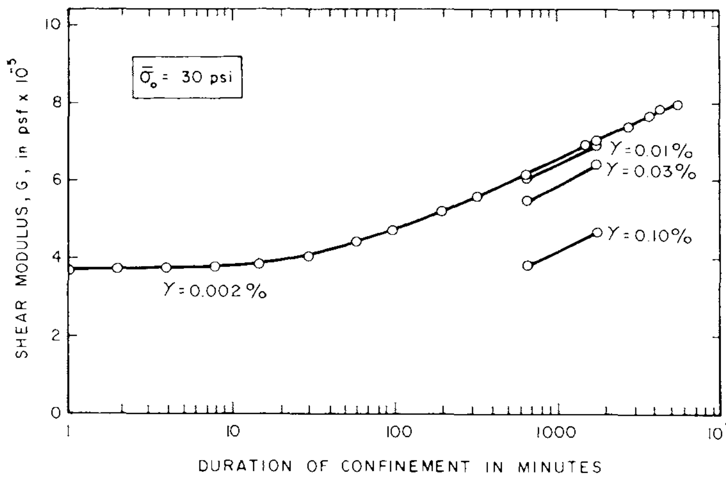

Figure 2 - Influence of Long-Term Time Effect on Shear Modulus Determined from Resonant Column Tests

HIGH-AMPLITUDE TORSIONAL SHEAR DATA

Two of the principal advantages of the torsional shear test are the capabilities of measuring the effects of shearing strain rate and number of loading cycles on shear modulus and hysteretic damping of soil. In fact, to understand properly dynamic soil behavior, one must understand the relative influences of shearing strain, shearing strain rate, and number of loading cycles on the soil response.

Typical torsional shear test results are shown in Fig. 3. In this figure, values of shear modulus at a given shearing strain are plotted as a function of the shearing strain rate in the torsional shear test. Also plotted in the figure are data obtained for the same specimen using the resonant column mode of testing. The shear modulus is shown to be a linear function of the logarithm of shearing strain rate. At shearing strains in excess of 0.01 percent, the influence of number of cycles of loading in lowering the shear moduli determined from the resonant column test is clearly seen.

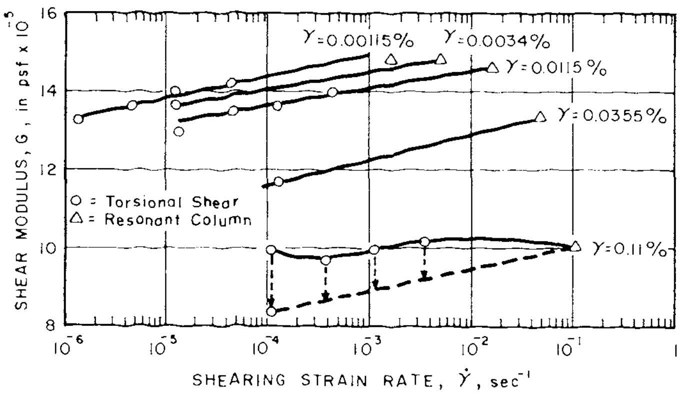

Figure 3 - Variation in Shear Modulus with Shearing Strain Rate

Effects of Shearing Strain Rate - As shown in Fig. 3, shear modulus at a constant strain amplitude can be approximated as a linear function of the logarithm of shearing strain rate. To quantify the influence of shearing strain rate on shear modulus, the factor $N^{\cdot}$ was developed. This factor is defined as:

$$N_{\dot{\gamma}} = \frac{G_2 - G_1}{\log_{10}(\dot{\gamma}_2/\dot{\gamma}_1)} \cdot \frac{1}{G \; @ \; \dot{\gamma} = 0.0001/\text{sec}} \qquad (1)$$

where $\dot{\gamma}_1$, $\dot{\gamma}_2$ = shearing strain rate at points 1 and 2 on a constant shearing strain line, respectively, and
G_1, G_2 = shear modulus at points 1 and 2, respectively.

This factor is simply the change in shear modulus per log cycle of shearing strain rate at a constant shearing strain amplitude normalized by the value of shear modulus at a shearing strain rate of 0.0001 sec^{-1}. The value of shearing strain rate of 0.0001 sec^{-1} was chosen arbitrarily because it fell approximately in the middle of all of the data. However, any shearing strain rate within a factor of ten could be used with little effect on the data.

Values of $N_{\dot{\gamma}}$ are plotted as a function of shearing strain amplitude in Fig. 4. The large amount of scatter in Fig. 4 and the fact that when shear modulus values for torsional shear tests are adjusted for cyclic degradation (as shown in Fig. 3) suggests that $N_{\dot{\gamma}}$ is independent of shearing strain amplitude, at least at strains less than 0.01 percent. It is believed that the scatter in Fig. 4 is the result of random experimental factors and variable soil specimens. To study the statistical distribution of the values of $N_{\dot{\gamma}}$, a histogram of the frequency of occurrence of the values of $N_{\dot{\gamma}}$ was made and is shown in Fig. 5. In this figure, the average of $N_{\dot{\gamma}}$ is 0.045, and the standard deviation is 0.016, which seems to indicate that the scatter is random below a shearing strain of 0.01 percent.

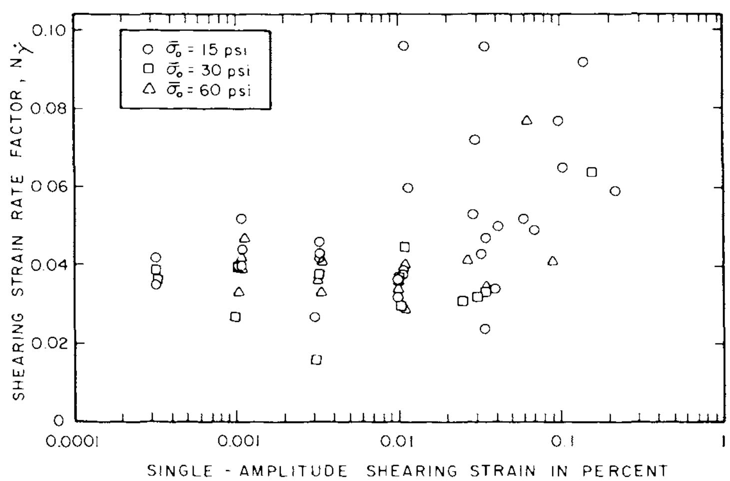

Figure 4 - Variation in Shearing Strain Rate Factor, $N_{\dot{\gamma}}$, with Shearing Strain Amplitude

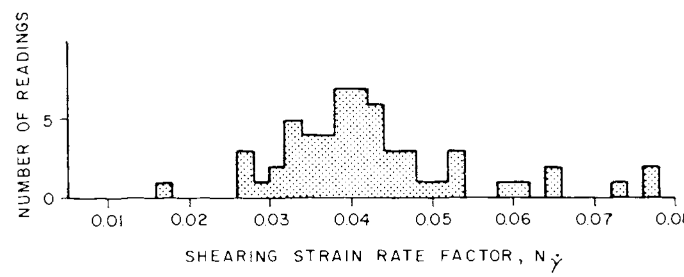

Figure 5 - Histogram of Shearing Strain Rate Factor, $N_{\dot{\gamma}}$.

Effects of Shearing Strain Amplitude - When shear modulus is plotted as a function of shearing strain amplitude at a constant value of shearing strain rate, plots like Fig. 6 are obtained. In this figure, the shear modulus - shearing strain curve is composed of two linear phases. At shearing strains below about 0.01 percent, the soil is nonlinearly "elastic"; that is shear moduli in this range do not experience any cyclic degradation (at least not in 500 cycles of loading). The second phase, which occurs at shearing strains above about 0.02 percent, represents "plastic" behavior. Shearing strains in this range result in cyclic degradation of shear modulus and possibly in the generation of excess pore water pressures.

The data shown in Fig. 6 and the shearing strain rate effect discussed above reveal an aspect of soil behavior that has not been detected before. In the torsional shear test, shear modulus at a constant shearing strain rate increases as the shearing strain amplitude decreases. No ultimate value of shear modulus is reached as in the resonant column test. When shear modulus values from the resonant column test are plotted in Fig. 6, they are found to fall on the same line as the corresponding torsional shear data. Thus, the data from the two modes of testing are found to be consistent with one another. It is believed that the reason why an ultimate value of shear modulus (G_{max}) is found in the resonant column test is that the increase in shear modulus due to decreases in shearing strain amplitude is approximately equal to the decrease in shear modulus due to decreasing shearing strain rate.

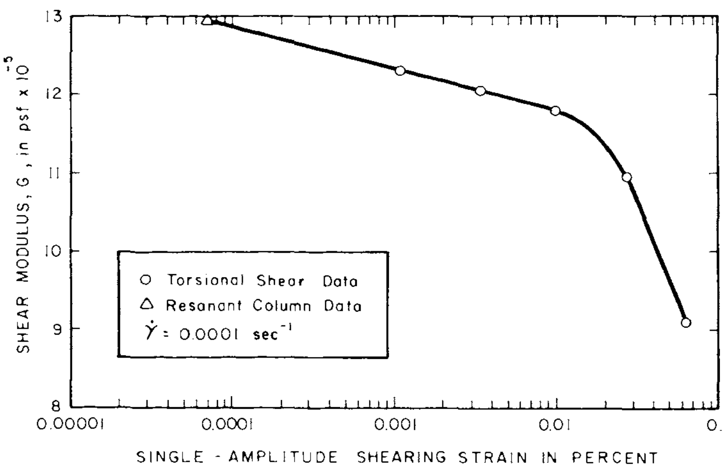

Figure 6 - Variation in Constant Shearing-Strain-Rate Shear Modulus with Shearing Strain Amplitude

Unfortunately, the constant-shearing-strain rate shear modulus - shearing strain curves are not easily normalized as is the case for the high-amplitude resonant column data in Fig. 1. Instead, the equations describing the "elastic" and "plastic" phases of the constant-strain-rate curves were calculated. The form of the equation for the "elastic" phase is:

$$G(\gamma) = G_{ie} + M_e \ln(\gamma) \quad (2)$$

where $G(\gamma)$ = shear modulus at shearing strain γ,
G_{ie} = "intercept" shear modulus for elastic phase, at γ = 1.0 in./in., and
M_e = slope of $G - \ln(\gamma)$ curve for elastic phase.

The equation for the "plastic" phase is:

$$G(\gamma) = G_{ip} + M_p \ln(\gamma) \quad (3)$$

where G_{ip} = "intercept" shear modulus for plastic phase, at γ = 1.0 in./in., and
M_p = slope of $G - \ln(\gamma)$ for plastic phase.

Note that these equations are for shearing strain rates of 0.0001 sec^{-1}. To correct the shear moduli for a shearing strain rate that is different from 0.0001 sec^{-1}, the following correction should be used:

$$G(\gamma,\dot{\gamma}) = G(\gamma)\cdot(1+N_{\dot{\gamma}} \log_{10}(\dot{\gamma}/0.0001\ sec^{-1})) \quad (4)$$

Values of the parameters used in Eqs. 2 and 3 along with the intercept shearing strain where the elastic and plastic phases meet are listed in Table 1. Wherever values are omitted in Table 1 for the plastic phase, not enough data were available to evaluate G_{ip} and M_p with confidence.

Table 1 - Curve Fitting Parameters for Constant Shearing-Strain-Rate Shear Modulus - Shearing Strain Curves

Test	$\bar{\sigma}_o$* (psi)	"Elastic" Curve		"Plastic" Curve		Intercept Shear Strain %
		G_{ie} ksf	M_e ksf	G_{ip} ksf	M_p ksf	
1	15	361	- 1.2	-189	- 64.2	0.020
	60	1198	-20.1	-925	-274	0.023
2	15	361	- 1.5	-218	- 67.9	0.029
	30	396	-21.4	72.9	- 56.3	0.010
	60	814	-41.1	-	-	-
3	15	403	-12.3	-400	-105.5	0.018
	30	760	-15.8	260	- 67.2	0.006
	60	1210	-27.9	-	-	-
4	15	166	-13.4	-473	- 92.1	0.030
5	15	278	- 7.3	-199	- 62.7	0.019

*time of confinement varies from 1 to 4 days

Long-Term Time Effect - As in the case for the high-amplitude resonant column data, the long-term time effect can have substantial influence upon the high-amplitude torsional shear test results as shown in Fig. 7. In this figure, the long-term time effect is seen to be approximately equal for all shearing strains in the elastic range below 0.01 percent. In the plastic range, the long-term time effect is seen to decrease with increasing shearing strain amplitude. If the plastic range curves are extrapolated to large shearing strains, the curves will cross at shearing strains of approximately one percent, which seems to indicate that the long-term time effect is minimized at this and higher strains.

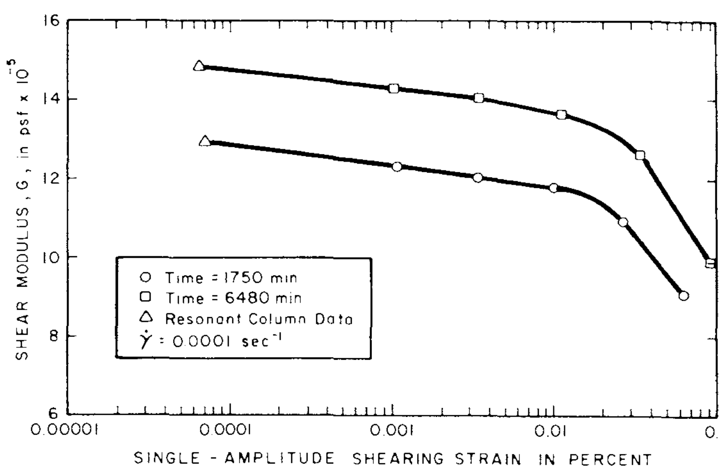

Figure 7 - Influence of Long-Term Effect on Constant-Shearing-Strain-Rate Shear Modulus

COMPARISON OF RESONANT COLUMN AND TORSIONAL SHEAR DATA

The results of torsional shear tests on San Francisco Bay Mud are found to be consistent with resonant column tests results when the effects of shearing strain rate and cyclic degradation are taken into account. In the resonant column test, shearing strain rate typically varies with shearing strain amplitude in the manner shown in Fig. 8. In this figure, shearing strain rate is shown to be a linear function (indicated by the 45 degree slope on the $\log \gamma$ - $\dot{\gamma}$ log plot) of shearing strain amplitude at strains below about 0.001 percent. This is the same range of shearing strains over which G_{max} is measured in the resonant column test. At shearing strains above about 0.001 percent, the shearing strain rate - shearing strain amplitude curve gradually bends downward as the dynamic response of the soil specimen becomes nonlinear.

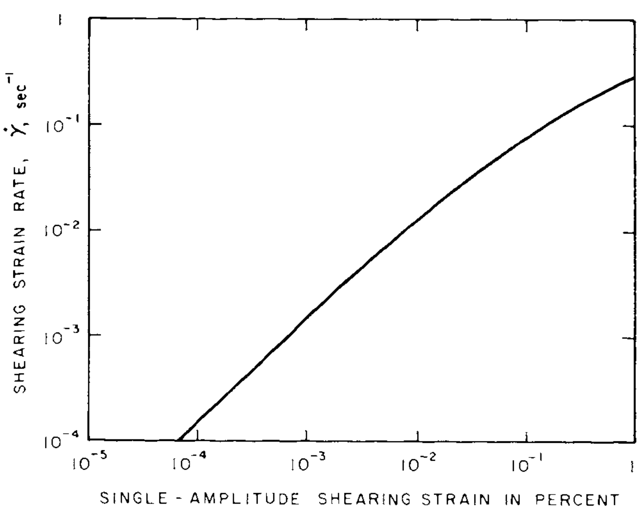

Figure 8 - Variation in Shearing Strain Rate with Shearing Strain Amplitude in the Resonant Column Test

The combined effects of shearing strain amplitude, shearing strain rate, and cyclic degradation on shear modulus as determined in the torsional shear test are shown by the five thin lines in Fig. 9. At shearing strains below about 0.01 percent (the "elastic" range), the constant-shearing-strain-rate curves are approximately parallel and straight because of little or no cyclic degradation in this range. At shearing strain amplitudes above 0.01 percent (the "plastic" range), the constant-shearing-strain-rate curves are curved concavely downward due to the cyclic degradation effect increasing with increasing shearing strain amplitude.

When the curve in Fig. 8 is cross-plotted in Fig. 9, the resulting curve is found to be a typical resonant column shear modulus - shearing strain amplitude curve and the effects of strain rate and cyclic degradation on resonant column data are clearly shown.

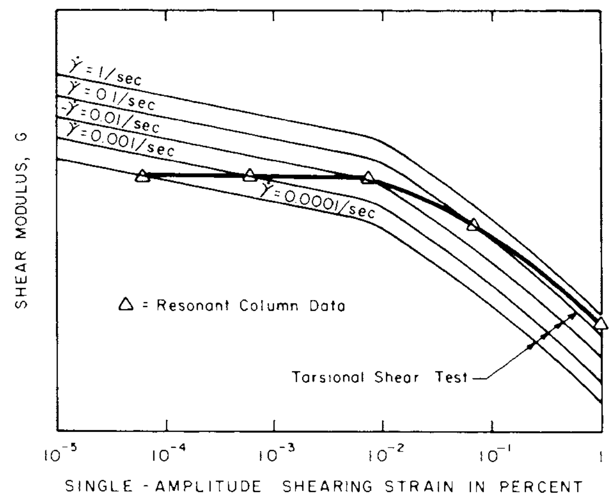

Figure 9 - Combined Parameter Effects on Shear Modulus

SUMMARY AND CONCLUSIONS

The effect of shearing strain rate on the shear modulus of cohesive soils is a subject that has received little attention in the past. This has been due primarily to the lack of an appropriate laboratory testing device. With the development of the torsional shear/resonant column (TSRC) device, these difficulties have been overcome. The TSRC device is capable of both torsional shear and resonant column measurements on the same soil specimen simply by changing the frequency of excitation. The TSRC device is capable of testing over a shearing strain range from below 0.001 percent to in excess of 0.1 percent and over a range in shearing strain rate from below 0.0001 percent per second to in excess of 10 percent per second.

The effects of shearing strain amplitude and shearing strain rate on the shear modulus of intact, normally consolidated specimens of San Francisco Bay Mud were studied with the TSRC device. Conclusions from this study are:

1. Shear moduli determined by resonant column measurements are essentially constant below a shearing strain amplitude of 0.001 percent and decrease with increasing shearing strains above 0.001 percent. This behavior is similar to that found in other studies, although the normalized modulus-strain curve shown in Fig. 1 exhibits a "stiffer than normal" shape (normalized curve shifted to the right on the graph).

2. Shear moduli at shearing strains equal to or less than 0.1 percent increased with time at a constant mean effective normal stress. This increase with time, known as the long-term time effect, was approximately equal for all shearing strains less than 0.1 percent as shown in Fig. 2 which agrees well with other studies.

3. At a constant shearing strain amplitude, shear modulus increased as the logarithm of the shearing strain rate increased as shown in Fig. 3. Typically, for this soil, the variation in shear modulus with shearing strain rate at a constant shearing strain amplitude was about four percent per log cycle of shearing strain rate.

4. The influence of shearing strain rate on shear modulus was found to be independent of shearing strain amplitude (for strains up to 0.01 percent), mean effective normal stress, and duration of confinement at constant mean effective normal stress.

5. When shearing strain rate is taken into account, a maximum value of shear modulus was not found at low-amplitude shearing strains (below 0.001 percent) at a constant shearing strain rate as shown in Fig. 6. Therefore, G_{max} measured in the resonant column test is a special case in which the decrease in shear modulus due to lower shearing strain rates is counterbalanced by an increase in shear modulus due to lower shearing strain amplitudes as shown in Fig. 9.

ACKNOWLEDGEMENTS

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REFERENCES

Anderson, D. G. (1974), "Dynamic Modulus of Cohesive Soils," Ph.D. Dissertation, University of Michigan, 311 pp.

Anderson, D. G., and Stokoe, K. H., II (1978), "Shear Modulus: A Time-Dependent Material Property," Dynamic Geotechnical Testing, ASTM STP 654, 1978, pp. 66-90.

Hardin, B. O., and Drnevich, V. P. (1972) "Shear Modulus and Damping in Soils: Design Equations and Curves," Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 98, No. SM7, July 1972(b), pp. 667-692.

Isenhower, W. M. (1979), "Torsional Simple Shear/Resonant Column Properties of San Francisco Bay Mud," M.S. Thesis, The University of Texas at Austin, 1979, 307 pp.

Lodde, P. F. (1981), "Shear Moduli and Material Damping of San Francisco Bay Mud," M.S. Thesis, The University of Texas at Austin, 1981.

Seed, H. B. and Idriss, I. M. (1970), "Soil Moduli and Damping Factors for Dynamic Response Analyses," Report No. EERC 70-10, University of California, Berkeley, September, 1970.

Stokoe, K. H. and Lodde, P. F. (1978), "Dynamic Response of San Francisco Bay Mud," Proceedings of the Conference on Earthquake Engineering and Soil Dynamics, ASCE, Pasadena, June 19-21, pp. 940-959.

APPENDIX - NOTATION

G = secant shear modulus
G_{ie} = "elastic" shear modulus intercept
G_{ip} = "plastic" shear modulus intercept
G_{max} = low-amplitude shear modulus
G_1 = shear modulus at point 1
G_2 = shear modulus at point 2
M_e = slope of "elastic" shear modulus - log shearing strain curve
M_p = slope of "plastic" shear modulus - log shearing strain curve
$N\dot{\gamma}$ = shearing strain rate factor
OCR = overconsolidation ratio
TSRC = torsional shear/resonant column test
γ = single-amplitude shearing strain
$\dot{\gamma}$ = shearing strain rate
$\dot{\gamma}_1$ = shearing strain rate at point 1
$\dot{\gamma}_2$ = shearing strain rate at point 2
$\bar{\sigma}_o$ = mean effective normal stress