Capillary effects on shear modulus at high strains

Effets capillaires sur le module de cisaillement

SHIMING WU, Lecturer, Zhejiang University, Hangzhou, China
D. H. GRAY, Professor of Civil Engineering, University of Michigan, Ann Arbor, Michigan, USA
F. E. RICHART, JR., W. J. Emmons Professor of Civil Engineering, University of Michigan, Ann Arbor, Michigan, USA

SYNOPSIS Studies of the shear modulus at low-amplitude shearing strains, as developed using the resonant column device, showed a significant effect of capillarity for fine-grained cohesionless soils. This study considers the capillary effects when high-amplitude shearing strains were applied. These effects were still noted for shearing strains up to 0.25 percent, but they were reduced at the higher confining pressures.

INTRODUCTION

The shear modulus of a soil is a basic parameter needed to establish the dynamic response of a soil deposit, or dynamic soil - structure interaction. It is usually evaluated by measuring the shear wave velocity by laboratory or field testing methods, then calculating the shear modulus from the equation:

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

Insitu tests of the shear wave refraction, up-hole, down-hole, or cross-hole types are often used to measure the shear wave velocity at low -amplitude shearing strains. These results lead to evaluation of the low-amplitude shear modulus, G_o. The particular value of G_o established by the field test depends upon the stress conditions and soil characteristics at the test location. For cohesionless soils the average confining pressure is usually the factor which exerts the most influence on the value of the shear wave velocity.

Gravity stresses and surcharge stresses in the test zone can be calculated, but additional stresses due to capillarity may also exist. If there is a change in the water content of the soil between the time of field testing and prototype operation, the contribution of the capillary stresses may change, which will result in a change in the shear modulus of the soil.

A study was made (see Wu,et.al.,1984) to evaluate the effect of capillary stresses on the low-amplitude shear modulus of soils. Five fine -grained cohesionless soils were tested in Hall-Type low-amplitude torsional resonant column devices (see Richart, et.al., 1970) to determine the influence of degree of saturation on the low-amplitude shear modulus. Grain size distribution curves for the five soils are shown in Fig.1. From resonant column tests on these soils, a significant increase in G_o was observed for degrees of saturation from 5 to 20 percent, (see Wu, et.al., 1984). Glacier Way Silt had the finest grain sizes, and it showed the greatest influence of changes in the degree of saturation, as shown in Fig. 2. The peak increase occurred at a degree of saturation of about 18 percent, and the amount of increase in modulus was greater when the external confining pressure decreased.

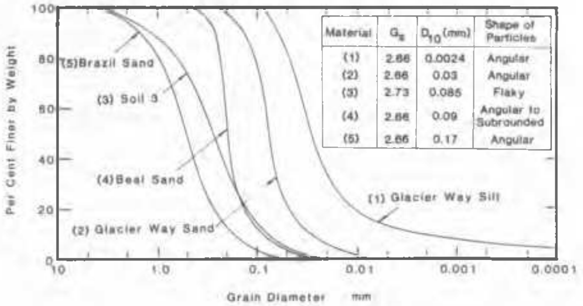

Fig.1 Grain Size Distribution of Soils Tested

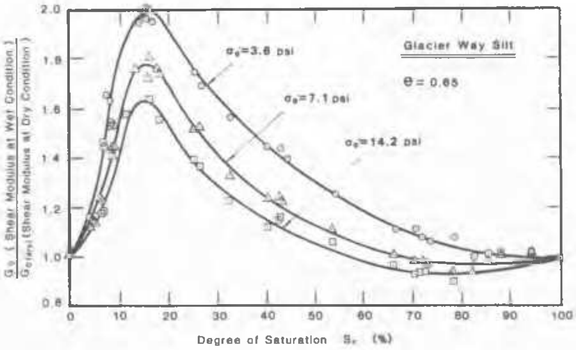

Fig. 2. $G_o/G_{o(dry)}$ vs. Degree of Saturation for Glacier Way Silt (from Wu, et.al. 1984) (1 psi = 6.9 kN/m^2)

Figure 3 shows the increase in shear modulus above that for the dry condition, for the five soils tested, as a function of D_{10} for these soils. Note that the modulus increase is a function of external confining pressure and effective grain size. Beal sand and Soil 3 did not fit on the trend lines because of grain shape effect introduced by flaky particles.

In the low-amplitude resonant column test, the maximum shearing strain was about 0.001 percent. The next question to be answered was whether the same effects of capillarity still existed when high-amplitude shearing strains were developed. This investigation describes the influence of capillarity on the shear moduli developed at shearing strains up to about 0.25 percent.

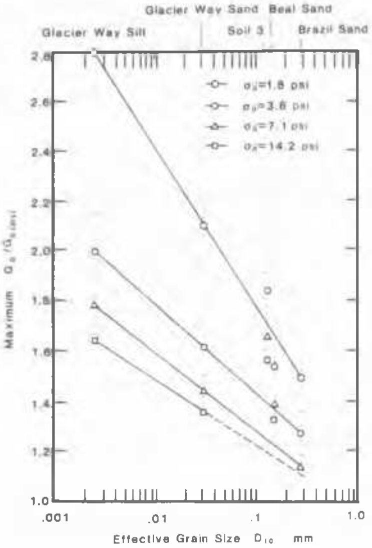

Fig.3. Relationship Between Maximum Value of $G_o/G_{o(dry)}$ and D_{10} for Five Test Materials. (from Wu,et.al., 1984)

(1 psi = 6.9 kN/m^2)

TESTING PROCEDURES

Solid, cylindrical soil samples 3.57 cm. diameter and 8.0 cm. in height were tested in the Drnevich Long-Tor high-amplitude resonant column device. Two values of uniform confining pressure were used, 24.8 and 98 kN/m . Each of these pressures were applied to samples having 10 different degrees of saturation. One sample was needed for each degree of saturation.

Sample Preparation

The sample were prepared by mixing a preselected amount of distilled water with previously air - dried soil and storing this mixture in an air - tight container for at least 24 hours to obtain uniform moisture distribution. Then the soil samples were compacted in a standard mold, 3.6 cm. inner diameter and 8.0 cm. in height, which was lined with a rubber membrane. The mold was located on the pedestal of the resonant column device before compaction began. Samples were compacted close to the required density by changing the compaction effort. The specimens were sealed with a top cap and membrane; then a weak vacuum was temporarily connected to the drainage line and the mold was taken apart. A second greased membrane was placed outside the sample, and 0 - rings were placed to seal the membranes against the top cap and bottom support.

Capillary stresses are very sensitive to temperature changes, therefore changes in environmental temperature would affect the test results. To eliminate the temperature effects, the room temperature was maintained at 72^{o}F +/- 1^{o}F.

Testing Device

The Drnevich Long - Tor resonant column device is capable of applying longitudinal or torsional oscillations to the top end of the soil sample. In these tests only the torsional oscillations were used. The amplitude of torsional motion which could be developed depended on the torsional stiffness of the sample. For low confining pressures acting on samples of cohesionless soils the device can develop shearing strains in the sample of 0.2 to 0.3 percent.

During the initial phase of the test program, the shear wave velocity vs. time relationship was established at low - amplitude torsional shearing strains. The results from tests using the Drnevich Long-Tor device were nearly identical to those previously obtained using the Hall-Type resonant column device, and reported in Wu, et.al. (1984). Comparable samples tested in the two devices showed similar values for the optimum degrees of saturation, with Long-Tor values 2 to 4 percent lower. The magnitudes of shear moduli varied by 8 or 9 percent at the optimum value of saturation (with the Long-Tor values lower). It should be noted that an experimental error of 10 percent is not unusual for this type of test, even when using one type of device. At other degrees of saturation the test data overlapped, except for greater than 80 percent degree of saturation, where again the values from the Long-Tor device were lower by about 15 percent. In these tests the shearin strain amplitudes were approximately 0.0001 percent.

Correction for Void Ratio Differences

It was not possible to reproduce exactly the same void ratio when preparing samples at different degrees of saturation, although with practice a good approximation was obtained. The final void ratio and degree of saturation for each sample were determined after each test was completed. Then, if necessary, the value of shear modulus obtained was corrected for the void ratio difference by using Hardin's void ratio function (Hardin, 1978).

$$f(e) = 0.3 + 0.7\,e^2 \qquad (2)$$

The test shear modulus was multiplied by the ratio of f(e) (target) / f(e)(test) to determine the shear modulus corresponding to a void ratio of e = 0.65 (target).

High Amplitude Test Pattern

The confining pressure was applied to the sample, and was maintained constant throughout the test. Low-amplitude shear wave velocities were measured at intervals of time until the plot of shear wave velocity vs. logarithm of time exhibited a constant secondary slope (usually found at about 1000 min). Then the high-amplitude sequence was started.

The high-amplitude sequence of tests involved applying 1000 cycles of the next step of shearing strain amplitude, measuring the shear wave velocity, and then letting the sample rest until the low-amplitude shear wave velocity had recovered its original value. The silt-sized soils demonstrated a time-dependent recovery of the low-amplitude shear wave velocity similar to that found for clays (see Anderson, 1974). The 1000 cycles of high-amplitude straining did not cause any significant changes in subsequent low-amplitude shear wave velocities, when measured after a sufficient period of rest. This pattern of cycling, measurement, and recovery period was followed for shearing strains of 0.001, 0.0025, 0.004, 0.0055, 0.007, 0.0085, 0.01, 0.025, 0.05, 0.10, and 0.2 or 0.3 percent. A schematic diagram of this test procedure is shown in Fig. 4. The distribution of shearing strains gave enough data points to establish reliable curves of G/G_0 vs. shearing strain amplitude for each degree of saturation and confining pressure.

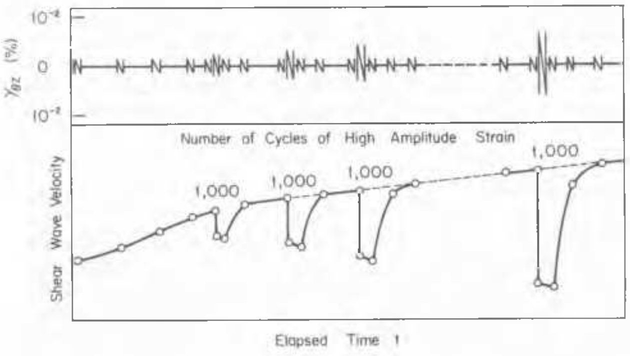

Fig. 4. High Amplitude Test Sequence

TEST RESULTS AND DISCUSSIONS

Figures 5 and 6 show the results of the high-amplitude tests for the confining pressures of 25 kN/m^2 and 98 kN/m^2, respectively. The test data in each figure have been expressed as the ratio of the modulus actually obtained from the tests, G, divided by the low-amplitude shear modulus obtained for the dry soil. The effects of capillarity are evident in both figures, but for the lower confining pressure (Fig. 5) an increase in shearing strain amplitude to 0.25 percent almost eliminated the capillary effects. For the higher confining pressure (Fig. 6) the curve still shows the influence of capillary stresses in the 10 to 30 percent degree of saturation range, even for the highest shearing strain amplitude obtainable. The overall trend is that an increase in shearing strain amplitude reduces the capillary effects on the shear modulus.

For the five soils tested at the low-amplitude shearing strain level, it was found consistently that the shear modulus at 100 percent degree of saturation was the same as that for the dry samples. This is also illustrated in Figs. 5 and 6. However, Fig. 5 and 6 show that for the higher shearing strain amplitudes the shear modulus is lower for the completely saturated samples than it was for the dry samples. This was probably due to the build-up of pore pressures in the sample, even though the drainage line was open. The time required to develop 1000 cycles depends on the stiffness of the sample, but it is on the order of 10 to 20 seconds. This much time is needed to make the readings. Because the Glacier Way Silt has a low permeability, the pore pressures would build up faster that they could be dissipated.

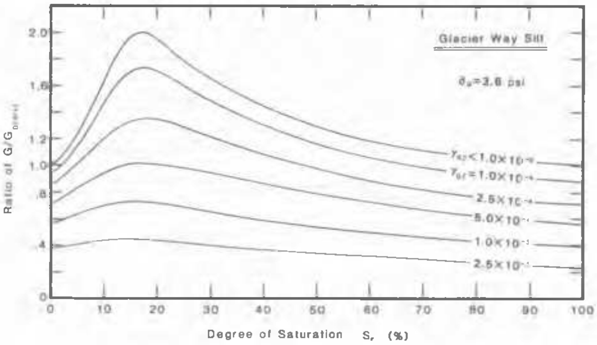

Fig. 5. Ratio of $G/G_{o(dry)}$ vs. Degree of Saturation for Different Shearing Strain Levels Under Confining Pressure of 3.6 psi (25 kN/m^2)

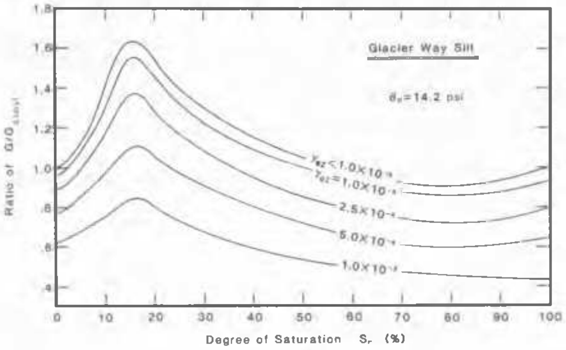

Fig. 6. Ratio of $G/G_{o(dry)}$ vs. Degree of Saturation for Different Shearing Strain Levels Under Confining Pressure of 14.2 psi (98 kN/m^2).

Another peculiarity of the curves shown in Fig. 6 is the dip in the curves at high degrees of saturation. This was discussed by Wu, et.al. (1984), as indicated below.

> A possible explanation for this follows from the method of constructing the samples on the pedestal of the resonant column device at the preselected water content. Because the soil-air-water systems for fine-grained soils at relatively high degrees of saturation were of the air-closed or air-discontinuous type, the air bubbles in the compacted specimen were isolated and compressed. This resulted in an increase in air bubble pressure above atmospheric. Also, the higher confining pressures caused greater volume changes in the specimen, which increased air bubble pressure and caused the resultant effective stress to be lower than the external confining pressure.

Modulus Degradation

The reduction in shear modulus with increasing shearing strain amplitude is shown in Figs. 5 and 6. Another way of representing this information is to use the low-amplitude shear modulus (G_0) at a particular degree of saturation as the reference, then with the shear modulus (G) determined at a higher shearing strain amplitude - and at the same degree of saturation-calculate the ratio of G/G_0. Results are presented this way in Figs. 7 and 8 to show the influence of degree of saturation at each of the shearing strain amplitudes.

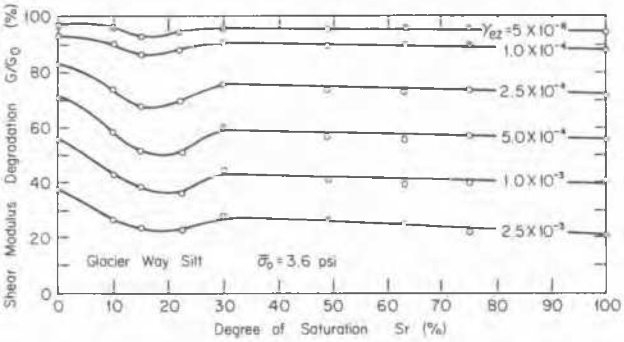

Fig. 7. Relationship of Shear Modulus Degradation vs. Degree of Saturation for Glacier Way Silt under Confining Pressure of 25 kN/m^2

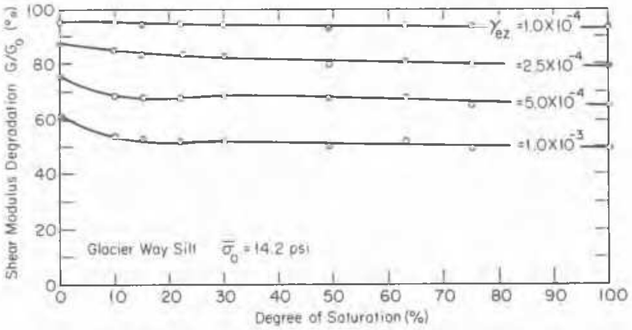

Fig. 8. Relationship of Shear Modulus Degradation vs. Degree of Saturation for Glacier Way Silt under Confining Pressure of 98 kN/m^2

Figure 9 shows the shear modulus degradation as a function of the shearing strain, which is the usual way of illustrating this type of information. These curves represent the modulus degradation for a sample having 10.4 percent degree of saturation. Similar curves can be developed from Figs. 7 and 8, using values for each degree of saturation.

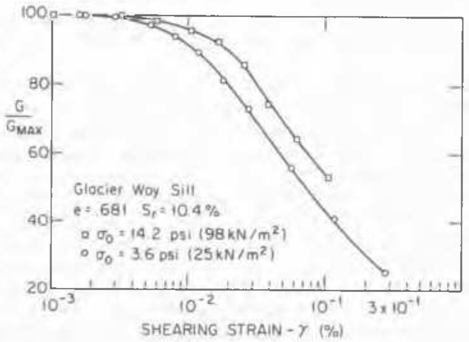

Fig. 9. Reduction of Shear Modulus with Increasing Shearing Strain

CONCLUSIONS

For fine-grained cohesionless soils, capillarity in the water-air-soil particle system causes significant increase in the low-amplitude shear modulus. The shear modulus in the completely dry condition is approximately the same as that for the fully saturated or nearly saturated conditions, because little capillarity exists for these conditions. For partially saturated soils there exists a degree of saturation at which a maximum increase is a function of the average confining stress on the soil, and the effective grain size, D_{10}.

Further tests using high-amplitude shearing strains produced results which were similar to those found for the low-amplitude tests. There was a maximum increase in shear modulus at a particular degree of saturation, at a value of about 18 percent for the Glacier Way Silt reported herein. This maximum increase was reduced as the shearing strain amplitude increased, with the decrease being more significant at the lower confining pressure. Further tests on different materials are suggested to better define this behavior.

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