RHEOLOGICAL PROPERTIES OF A COHESIVE SOIL

M. G. Sharma[I] and M. C. Wang[II]
The Pennsylvania State University
University Park, Pennsylvania, U.S.A.

SYNOPSIS

It is generally accepted that ground motions generated by earthquakes impose severe inertia forces on structures, that are periodic in nature. These forces in turn may influence the load carrying capacity of the soil underneath structures. For a rational evaluation of soil-structure interaction, a complete knowledge of the constitutive relations for a given soil is imperative. This paper is concerned with an experiemental investigation for studying the rheological properties of a cohesive soil. Creep and creep recovery tests, stress relaxation, stress-strain tests at various strain rates ranging from 0.03 to 8 per sec. and dynamic tests with repeated application of triangular stress pulses were conducted. From the results a constitutive relation representing the elastic, viscoclastic and viscoplastic response of the material is obtained.

INTRODUCTION

During earthquakes the soils underneath the building foundation or any earth structure may be subjected to a series of vibratory stress applications of limited stress duration. It is well known that during the main shock of an earthquake, the ground may be subjected to a horizontal acceleration which may reach 15 to 20 times in a period of half a minute. The number of large vibratory pulses during the earthquakes may reach a number of 50. These pulses may in turn produce large shear stresses in the soil mass, which may exceed the shear strength of the material. In order to calculate the stresses and strains in the soil mass underneath a building foundation, due to earthquake loading, it is imperative to have a knowledge of three dimensional stress-strain relations for a given soil. Literature to date indicates that most of the stress analyses in the soil mass due to different loading conditions including that under earthquake conditions, is performed assuming the material as linear elastic. It is well known that soils display appreciable rheological properties which indicate that the response is rate dependent [1,2]. Therefore, for any realistic analysis for earthquake loading it is very essential to consider the rheological properties of the soils. This paper is concerned with a study for determining the rheological properties of a compacted soil. As part of this study, stress-strain tests, stress relaxation tests, creep tests, and dynamic tests with repeated application of stress pulses were conducted amd stress-strain relations representing the rheological properties were obtained. The effect of strain rate on the failure stress has been evaluated

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[I] Professor of Engineering Mechanics

[II] Associate Professor of Civil Engineering

MATERIALS AND METHODS

Specimen Preparation

The soil studied was a plastic clay that is abundant in Central Pennsylvania. The test soil has a liquid limit of 48 percent, a plastic limit of 20 percent, and a specific gravity of 2.72. It is classified as CL according to the Unified Soil Classification System. Test specimens had a diameter of 3.5 cm with a height of 7 cm. The test specimens were compacted in three layers, 55 tamps per layer, using the Harvard miniature kneading compactor. The water content and dry density were 18.5 percent and 105.5 pcf, respectively, which were equal to the optimum moisture content and maximum dry density obtained using the modified AASHO compactive effort. These compaction conditions are usually required for compacting foundation soil especially for highway pavement construction.

Experimental Procedure and Results

Rheological properties of the test soil were studied by conducting several types of tests with differing stress or strain histories. These included stress-strain tests conducted at controlled strain rates, stress relaxation tests, creep and creep recovery tests and dynamic tests involving repeated application of stress pulses.

Cylindrical samples of the test soil were subjected to monotonically increasing compressive loads at strain rates ranging for 0.03 to 8 per sec. in a standard Olsen machine. Figure 1 shows the results for unconfined specimens and specimens with the confining pressure of 10 psi.

Creep and creep recovery behavior of the material was studied by subjecting specimens to a stress that is applied for a certain duration $t_i - t_{i-1}$ and removed until recovery due to viscoelastic effects ceases. Any permanent strain is measured. The same history is repeated for different durations of stress. These tests were conducted for three values of stress namely, σ = 22.2, 33.3, and 44.4 psi and for unconfined specimens. Figure 2 shows the typical results from these tests for a stress level of 33.3 psi.

Stress relaxation behavior of the material was studied by subjecting specimens to a preselected value of strain that is held constant for a certain duration and the stress necessary for maintaining the strain is measured with time. Stress relaxation tests were conducted for various strains from 1 to 3 percent and for confining pressures 0 and 10 psi. Relaxation modulus representing the ratio of observed stress to the applied strain was obtained and was plotted against time for confining pressures 0 and 10 psi as shown in Figure 3. It can be seen for both cases the relaxation modulus is a function of time and is independent of strain indicating that the viscoelastic response of the material is linear.

Finally, repeated triangular pulses were applied to specimens and the resulting plastic strain accumulation with the number of stress pulses is obtained. These tests were conducted for four levels of stress. Figure 4 shows the plastic strain versus accumulated time duration of loading.

INTERPRETATION OF RESULTS

The test results indicate that the soil tested displays elastic, viscoelastic, and viscoplastic response under a variety of stress and strain histories. This suggests that any stress-strain relationship should describe these responses of the material. This can be achieved by assuming the observed strain for an applied stress pulse as made up of the following components

$$\varepsilon(t) = \varepsilon_e + \varepsilon_{VE} + \varepsilon_p \qquad (1)$$

where

ε_e = Elastic strain

ε_{VE} = Viscoelastic strain

ε_p = Viscoplastic strain

Elastic strain is the time independent and reflects the elastic properties of the material. This strain is completely recoverable. The viscoelastic strain is time dependent and represents the combined elastic and viscous response of this material and recoverable a finite time after the stress is removed. The viscoplastic strain is the strain that is irrecoverable after the stress is removed and represents permanent strain. It can have both time independent and time dependent components. Using the creep and creep recovery data, the strain components as indicated in Equation (1) were separated and using the standard curve fitting procedure the following creep strain-stress-time relationship was obtained:

$$\varepsilon(t) = [D_0 + D\,(1-e^{-\frac{t}{\lambda}})]\,\sigma + kt^m\,\sigma^n \qquad (2)$$

where

D_0 = Elastic compliance (5.3×10^{-5} psi^{-1})

D = Viscoelastic compliance (2.45×10^{-2} psi^{-1})

λ = Retardation time (0.42 sec)

k = 1.5×10^{-7} psi^{-1}, $m = 0.93$ and $n = 1.67$ are constants associated with plastic strain for level of stress up to 33 psi

t = time.

The relaxation modulus versus time as indicated earlier was independent of strain level. Therefore, the response of the material is linear viscoelastic. It was found that the data conformed to the following equation:

$$E(t) = Ee^{-\frac{t}{\tau}} + E_e \qquad (3)$$

where

$E(t)$ = relaxation modulus

E = Decay Modulus (135 psi, 370 psi)

E_e = Equilibrium modulus (700 psi, 800 psi)

τ = Relations time (0.34 sec., 0.31 sec.)

The numbers in parenthesis refer to constants for 0 and 10 psi confining pressures respectively.

The results of the dynamic tests involving repeated application of stress pulses were examined and the permanent strain accumulation with the number of cycles were obtained for about 100 pulses. Knowing the period of each of the pulses, the plastic strain accumulation with time was obtained. The plastic strain variation with time and stress conformed to the following law up to a stress level of 33.3 psi.

$$\varepsilon_p = Kt^m \sigma^n \qquad (4)$$

Based upon the results of the dynamic tests the following constants were found for the material for 0 confining pressure

$$K = 5.78 \times 10^{-5} \left(\frac{1}{\text{psi}}\right), \; m = 0.36, \; n = 0.91$$

From the dynamic tests the ratio of amplitude of stress to the amplitude of strain was evaluated and this was found to be independent of stress and slightly dependent on the frequency of the pulses.

As Equation (3) represents the linear response, it can be generalized to obtain stress-strain relationship for any strain hisotry using the Boltzmann Superposition principle [3] as follows:

$$\sigma = \int_0^t E(t-t') \frac{d\varepsilon}{dt'} \, dt' \qquad (5)$$

Assuming a sinusoidal strain history $\varepsilon = \varepsilon_0 e^{i\omega t}$ (where $i = \sqrt{-1}$, ε_0 = strain amplitude) and using equation (5) the storage modulus, the loss modulus and the absolute value of the complex modulus were caculated. Figure 5 shows the computed value of the dynamic moduli plotted against frequency for 0 and 10 psi confining pressures.

The failure stress obtained from stress-strain tests at various constant strain rates when plotted against the strain rate indicated a linear relationship for both 0 and 10 psi confining pressures (see Fig. 6). This indicates that the failure stress is rate dependent.

DISCUSSSION

The results indicate that the rheological constitutive relation for soils can be obtained from creep, stress relaxation and dynamic tests. Although the stress-strain tests at various controlled strain rates indicate rate dependent behavior, the data cannot be easily interpreted for the description of the rheological properties. Figure 2 indicates that the creep and creep recovery test is the ideal test for the development of rheological stress-strain relationship that represents the observed elastic, viscoelastic and viscoplastic response of the material. The dynamic test involving the repeated application of stress pulses is also a convenient test for the description of the elastic and plastic response, but has the limitation of inaccurate evaluation of viscoelastic response. The stress relaxation tests (see Figure 3) provide sufficient information about the elastic and viscoelastic properties of the test material. They are inadequate for the description of viscoplastic response.

REFERENCES

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Figure 1. Stress Versus Strain Curves

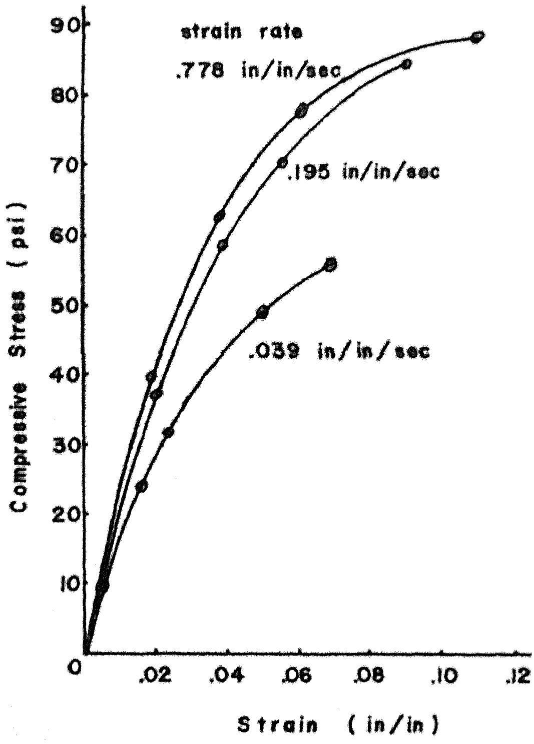
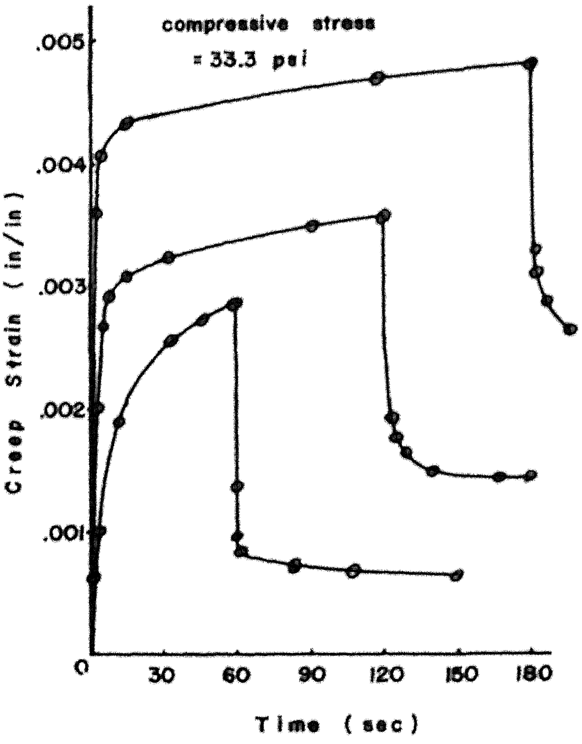


Figure 2. Creep and Creep Recovery Curves



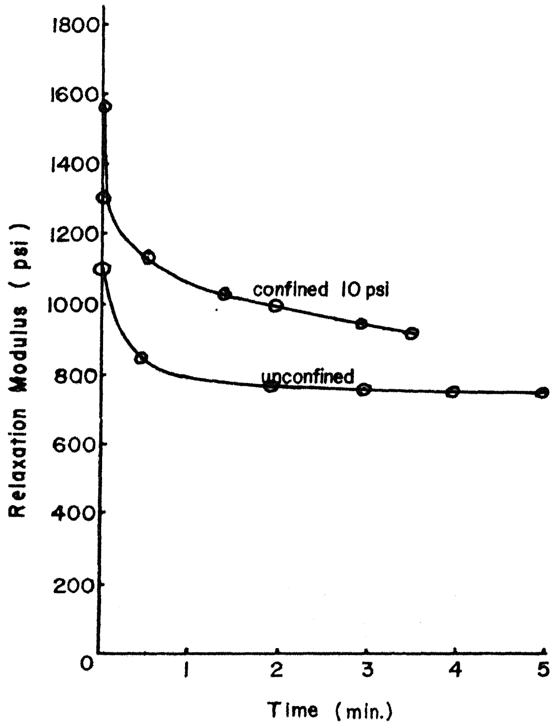


Figure 3. Relaxation Modulus Variation With Time

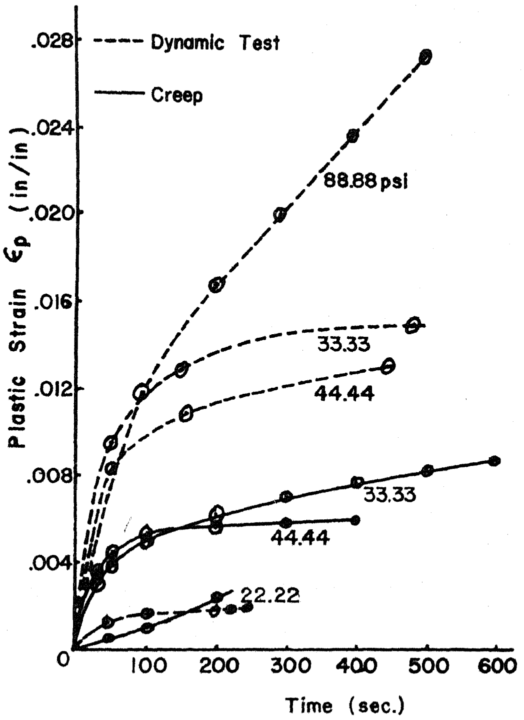


Figure 4. Plastic Strain Variation With Time

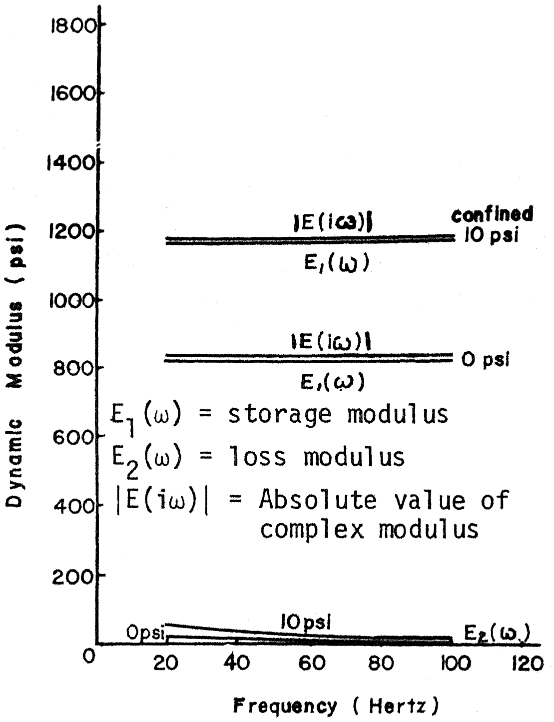


Figure 5. Dynamic Modulus Variation With Frequency

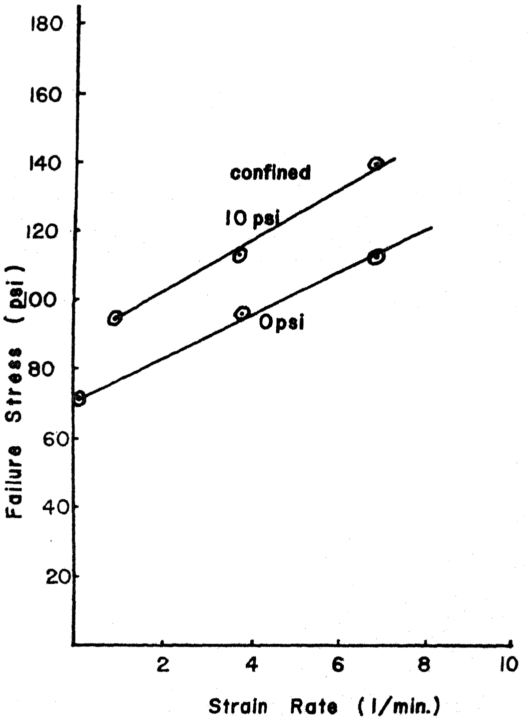


Figure 6. Failure Stress Variation With Strain Rate