DYNAMIC TORSION TESTING OF SOILS

EPREUVES DE TORSION DYNAMIQUE DES SOLS

ИСПЫТАНИЕ ГРУНТОВ СПОСОБОМ КРУЧЕНИЯ ПРИ ДИНАМИЧЕСКИХ УСЛОВИЯХ

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SYNOPSIS An outline is given of the use of dynamic soil properties, particularly shear modulus and equivalent viscous damping factor, in estimating site response to earthquake motion. Both modulus and damping are found to be strongly amplitude-dependent. Methods of determining dynamic properties are enumerated and the features of torsion tests outlined. An improved apparatus is described, in which free torsional oscillation of a sample with added inertia is observed. From a single test, values of shear modulus and equivalent viscous damping factor can be obtained over a range of amplitudes. Test results for a variety of soils are presented and compared with previously published results. It is shown that dynamic properties may differ greatly from published average results, and that damping in clays at low amplitudes may be less than had previously been estimated.

INTRODUCTION

To enable structural engineers to design buildings adequately to resist earthquake it is necessary to estimate the probable earthquake motions at the foundation of the structure. It has become increasingly clear over the past decade or so that the nature of the subsoils at the site profoundly influences the motion. This was most graphically illustrated in the earthquake at Caracas, Venezuela, 1957, when blocks of apartments of almost identical construction behaved very differently, some collapsing completely, others remaining practically undamaged. The differences in behaviour could be attributed only to differences in the nature of the subsoils on which the buildings were founded.

In recent years, methods of analysing the response of soils to earthquake motion have been developed. Two basic methods currently in use, which may be applied to horizontal soil strata with a horizontal surface, are the multiple reflection theory (Duke and Leeds, 1962) and the shear deformation approach (Idriss and Seed, 1967). These are also described and compared by Tsai, (1969). When the geometry of the boundaries of the soil deposits is more complex the finite element method may be more appropriate (Dezfulian and Seed 1970).

Whatever method is used to analyse the response of soils to earthquake excitation, knowledge of the stress strain relationships for the soils is required. These relationships are usually expressed in terms of the shear modulus and the equivalent viscous damping factor. Both of these quantities are strongly amplitude-dependent.

The shear modulus of soil samples may be determined indirectly from dynamic axial compression tests if Poisson's ratio is known, or assumed (Parton and Smith 1971). Accurate determination of Poisson's ratio for soils is difficult. Direct determination of shear modulus, in simple shear or torsion tests is therefore preferable. An example of forced cyclic simple shear tests is provided by Thiers and Seed (1968) while the same equipment was used for free vibration tests in simple shear by Kovacs, Seed and Chan, (1971).

DYNAMIC TORSION TESTS

These may be classified as resonant, where a single degree of freedom system oscillates at its natural frequency; or non-resonant, where the material is subjected to (usually sinusoidal) angular strain, at any chosen frequency and the induced torque is measured.

An example of the latter type is the Weissenberg Rheogoniometer, (Krizek and Franklin, 1969) in which an attempt is made to overcome one of the disadvantages normally associated with torsion tests on non-linear materials, namely, that the shear strain varies from zero at the axis to a maximum at the sample periphery. The Weissenberg Rheogoniometer applies a forced torsional oscillation to a sample placed between end platens, one of which is flat, the other a truncated cone If the cone apex is at the face of the flat platen, the shear strain is uniform throughout the sample. This apparatus has the limitation, however, that only remoulded samples may be tested.

Resonant type torsion tests may be subdivided into those with added inertia, and those in which added inertia is kept to a minimum. Some of the first

resonant tests were described by Ishimoto and Iida (1937); cylindrical samples were mounted on a base torsionally oscillated by an electromagnetic drive and the frequency varied until the amplitude at the top of the sample reached a maximum. The principal was employed by Wilson & Dietrich (1960) and in a modified form by Hall & Richart (1963). This method has two basic disadvantages, however:
firstly, the amplitudes of vibration are small, not readily controlled, and in many cases not even evaluated;
secondly the resonant frequency is usually one or two orders of magnitude greater than frequencies encountered in earthquake engineering problems.

Frequency effects are known to be small over a limited range (0.1-30 Hz.) but may be significant if the results of tests at the natural frequency of a small sample are applied to earthquake problems.

These disadvantages are overcome in free vibration tests where rotational inertia is added to the free end of the sample. The combination acts as a single degree of freedom system, the sample providing the torsional stiffness and energy-dissipating parts of the oscillator. If the added inertia is suitably chosen, the resonant frequency may be reduced to a range appropriate for earthquake engineering problems The system is given a small angular displacement which initiates a free torsional oscillation decaying in amplitude with time. Zeevaert (1967) determined the dynamic shear modulus of sand and clay samples by this method.

DEVELOPMENT OF IMPROVED EQUIPMENT

In a free vibration tests in which shear modulus and damping properties of soils are to be determined, the following features are desirable:

1. The samples should preferably be tested in torsion to allow direct evaluation of the shear modulus.
2. The frequency of testing should be in the range of earthquake frequencies (0.1 - 10 Hz).
3. Strain amplitudes should be controllable and in the range of earthquake strains ($\leq$ 0.5%).
4. There should be some control over the effective consolidation pressures which could be applied.
5. There must be negligible friction in the apparatus to permit the evaluation of material damping from the decay of free vibrations.

The apparatus consists of a triaxial cell designed principally to accept 6" high by 3" diameter samples. A load ram, connected to the top platen, passes through a bearing in the cell top and is locked securely to an inertia beam as shown diagrammatically in Figure 1* The frequency of free vibration is controlled by adjusting the radius of a pair of weights secured to the beam.

The weight of the beam may be fully or partly counterbalanced using the cell pressure acting on the area of the load ram. Thus the vertical and horizontal stresses can be independantly adjusted. The sample back pressure is set to provide the desired effective stresses.

*Next Page.

At one end of the inertia beam, an actuating device consisting of a spring-loaded plunger running on a hand-operated cam provides a simple method of giving the sample an initial angular displacement. Four cams, giving shear strains of 0.06% to 0.7% are available.

At the other end, a linear variable differential transformer (LVDT) is used to measure the angular displacement of the inertia beam. The output of this transducer is applied to an ultra-violet recorder giving a trace on photographic paper of shear strain versus time. A reduced reproduction of an actual test record is shown in Figure 2.

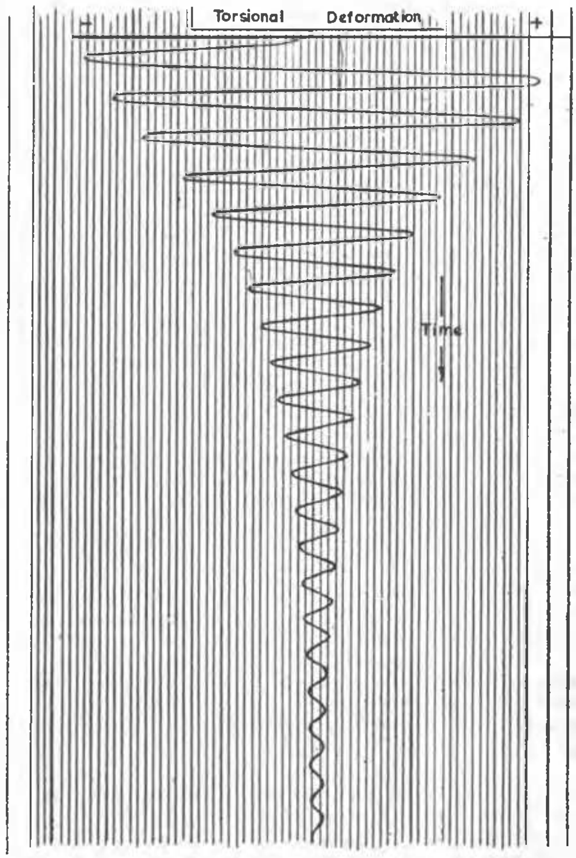

FIG. 2. Reduced Photographic Record.

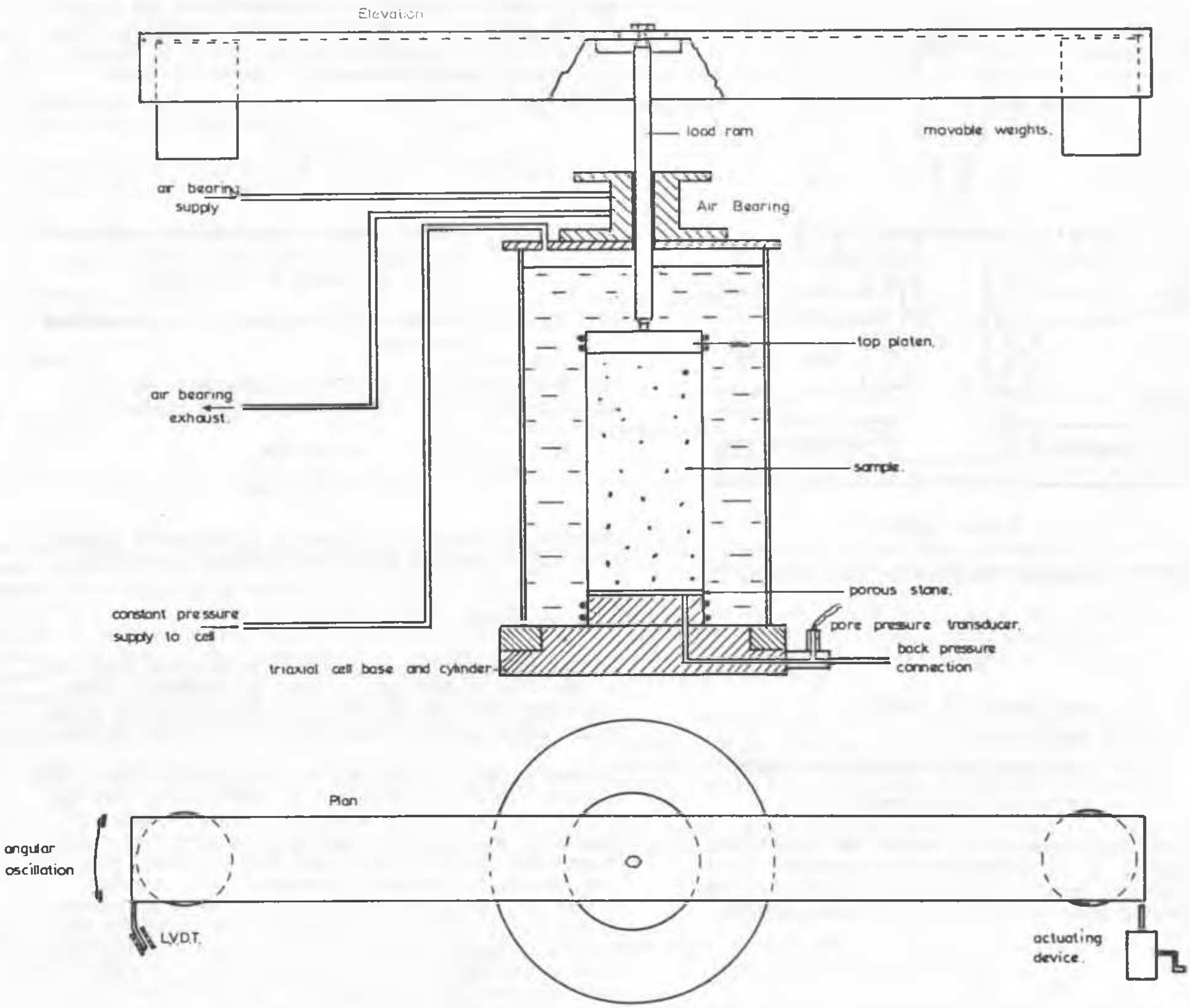

FIG. I Schematic Diagram of the Torsion Test Apparatus.

The problem of providing a bearing to support the load ram radially and yet be virtually frictionless and adaptable to a conventional triaxial cell was solved by using an externally pressurized gas bearing. This is shown schematically in Figure 3. Air under pressure enters the bearing, circulates in the supply manifold and passes through the ring of eight jets to enter the annular space between the load ram and housing. The air may escape upwards to the atmosphere or downwards through the exhaust chamber.

To overcome misalignment of bearing and sample axes a Hooke's joint, modified to allow a small amount of movement along each axis is incorporated in the top platen. This allows the top platen to be inclined by up to a few degrees from the horizontal and the platen axis to be up to 1/8" out of alignment with that of the air bearing, but at the same time transmits torsional movement without any lost motion.

A more detailed description of the equipment is given by Parton (1972).

THEORY

The shear modulus, G is determined from the observed period of oscillation using the following formula (Morley, 1956).

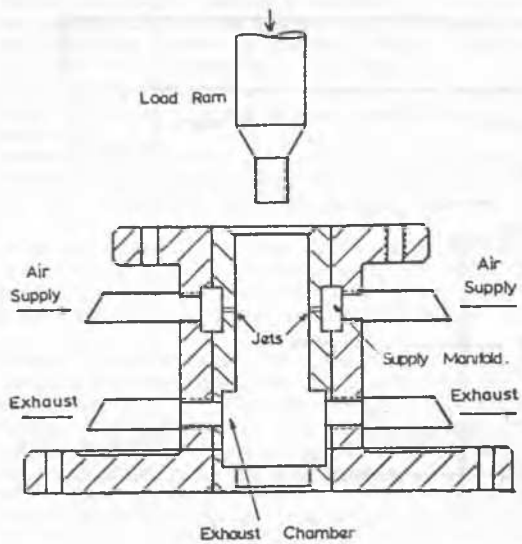

FIG. 3 Schematic Diagram of Air Bearing.

$$G = \frac{4\pi^2 JL}{I_p T_o}$$

where J = mass moment of inertia

L = sample length

I_p = polar moment of inertia of sample

T_o = period of free vibration.

From the displacement-time record the logarithmic decrement, δ is determined for successive cycles. The standard result is used which for small values of damping gives the equivalent viscous damping factor,

$$\lambda_{eq} = \frac{\delta}{2\pi}$$

where δ is the natural logarithm of the ratio of successive excursions in the same direction.

These methods of analysis have been used by Zeevaert (1967), Kovacs, Seed and Chan (1971) and others. These previous workers took average values of logarithmic decrement and period of oscillation over 3-5 cycles to obtain single values of modulus and damping factor. (Friction in his apparatus prevented Zeevaert from evaluating soil damping).

With the improved equipment it has been found possible to evaluate shear modulus and damping factor for each successive cycle of oscillation. It is found that the period of oscillation decreases as the amplitude decays and that the logarithmic decrement decreases also. These changing parameters reflect the non-linear soil properties and hence, from a single test, values of modulus and damping may be evaluated over a range of strains.

As shear strain varies from zero on the axis to a maximum at the periphery of a solid cylindrical torsion test specimen, it is sometimes considered that such a test is unsuitable for determining the stress strain characteristics of non-linear materials. However, a simple correction may be applied to account for non-uniformity of strain. It can be shown (Taylor, 1971) that

$$G(\gamma_R) = G_e + \frac{\gamma_R}{4}\frac{dG_e}{d\gamma_R}$$

where $G(\gamma)_R$ is the value of shear modulus which corresponds to the shear strain, γ_R at the periphery of the sample

G_e is the effective modulus, as determined previously.

The most useful form of this relationship, for use when strain is plotted on a logarithmic scale is:-

$$G(\gamma_R) = G_e + \frac{0.109\ d\ G_e}{d(\log_{10}\gamma_R)}$$

Despite the strong non-linearity of the soils tested, this correction has never been found to exceed 5%.

TEST PROGRAMME

It was considered most important to evaluate that part of the total calculated damping, as determined from the logarithmic decrement of the free vibration decay, which could be attributed to friction in the equipment.

Generally, metals have low damping, compared with soils and are linearly elastic in the strain range .001 to 1%. Thus from a free vibration test on a metal it should be possible to determine a damping factor which represents the friction in the test equipment plus the low damping in the metal specimen. This damping correction could be subtracted from the gross damping factor evaluated for soil specimens to determine the true soil damping factor. To this end, a steel specimen approximately 3 in. long and 1/8 in. diameter (to give the same test frequency as for soil tests) was fitted by means of special clamps to the normal top and bottom platens. An initial shear strain of .075% produced free oscillations which continued for approximately 500 cycles before the amplitude reduced to a low level. Tests at higher strains, up to 0.4%, produced similar results.

A constant damping factor of 0.001 and a shear modulus of 11.6 x 10^6 p.s.i., both independent of amplitude, were determined from the decay record. Morley (1956) gives the shear modulus of mild steel as 11- 12 x 10^6 p.s.i. Lazan (1968) gives damping factors for torsion tests on mild steel in the range 0.0002-0.0005. As damping factors for soil in the strain range tested are typically 0.02-0.10 the correction for damping in the apparatus was considered negligible.

The equipment was used to determine the dynamic characteristics of a variety of local soils, undisturbed samples of which were obtained in 4 inch diameter thin-walled sampling tubes. Details of these materials are given in Table 1.

TABLE 1

No.	Location	Depth to top of sample	Description	Natural water content %	Liquid Limit	Plastic Limit	Plasticity Index
1	Human Sciences Building site, Univ. of Auckland	7 ft	silty clay, medium whitish-grey	40	79	30	49
2	Science Block Stage D site, Univ. of Auckland	12 ft	silty clay, grey	46	62	24	38
3	Abbots Way, Auckland	10 ft	silty clay, grey	51	69	31	38
4	Waikato University Library site	30 ft	sensitive silty clay, white with ash particles	97	68	42	26
5	Huntly	20 ft	loose pumice sand $D_{60}/D_{10} = 6.7$	-	-	-	-
6	Huntly	23 ft	partly cemented pumice sand $D_{60}/D_{10} = 10.0$	-	-	-	-

Seed and Idriss (1969) have published a set of average curves relating equivalent viscous damping factor and dynamic shear modulus to amplitude of shear strain. The curves, with suitable correction factors applied to them, have been widely used by Idriss and Seed in computer analyses of the response of horizontal soil layers to earthquake excitation. The relationships between modulus and strain for saturated clays have been normalized by dividing modulus values by the undrained shear strength of the soil. For sands, moduli curves have been resolved into a single curve by dividing by the cube root of the effective overburden pressure.'

The same parameters are used in this presentation of test results.

Results for clays are shown in Figures 4 and 5 while those for sands are given in Figures 6 and 7. The numerous points from two tests at different initial amplitudes were plotted and a smooth curve drawn through them. The correction for non-uniformity of strain, described previously, was then applied to give the modulus curves shown.

Without exception, the shear moduli of the soils tested were strongly strain dependent. Below a strain amplitude of 0.01% material properties tend towards linear elastic behaviour.

The damping factor exhibits strong amplitude dependence, values increasing with increasing strain amplitude. Generally damping values tend to a constant lower limit, of approximately 2%, below strain amplitudes of 0.01%., and rise to about 10% at 0.5% strain amplitude.

The results obtained for clays are compared in Figures 4 and 5 with those of Seed and Idriss (1969) and Kovacs, Seed and Chan (1971). It is seen that the observed moduli are considerably less than those given by the curve of Seed and Idriss, which is intended to be an average value for clays.

Results of Kovacs et al are for a remoulded clay mixture which may account for the low moduli recorded.

Damping values were found to be lower than those presented by Seed and Idriss The damping curves follow the same trend as Seed and Idriss' but are displaced vertically.

The results of Kovacs et al indicate lower damping values at high strains. At low strains the damping factors obtained using the improved equipment are significantly less than those published previously.

The moduli determined for sands are shown in Figure 6 in which

$$K = G/(\sigma')^{1/3}$$

where σ' is the effective vertical overburden pressure (lb/sq.ft).

The observed modulus values were adjusted for relative density using the relationship given by Kiefer, Seed and Idriss (1970). It is seen that, at low strains, observed values are about one fifth of those presented by Seed and Idriss. This may be attributed to the high vesicular pumice content of the sand tested.

Observed values of damping shown in Figure 7 closely approximate those of Hall and Richart (1963) at small strain amplitudes, but are considerably less than those presented by Seed and Idriss over a wide strain range.

SUMMARY AND CONCLUSIONS

The development of a free vibration torsion test has been described and representative results for saturated clays and pumice sands presented. The following conclusions are drawn:-

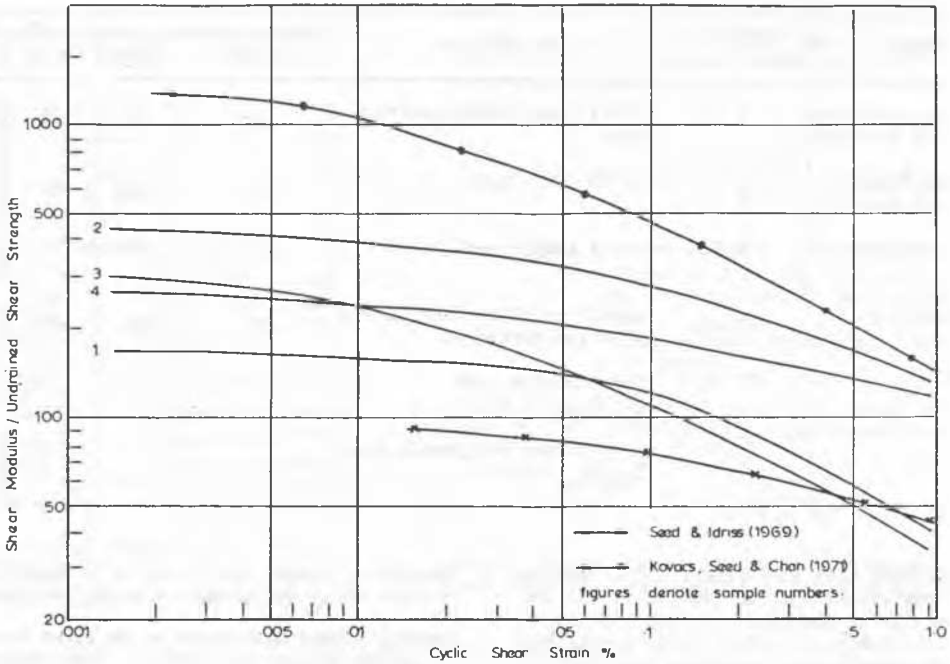

FIG. 4 Variation of Modulus with Strain
Saturated Clays.

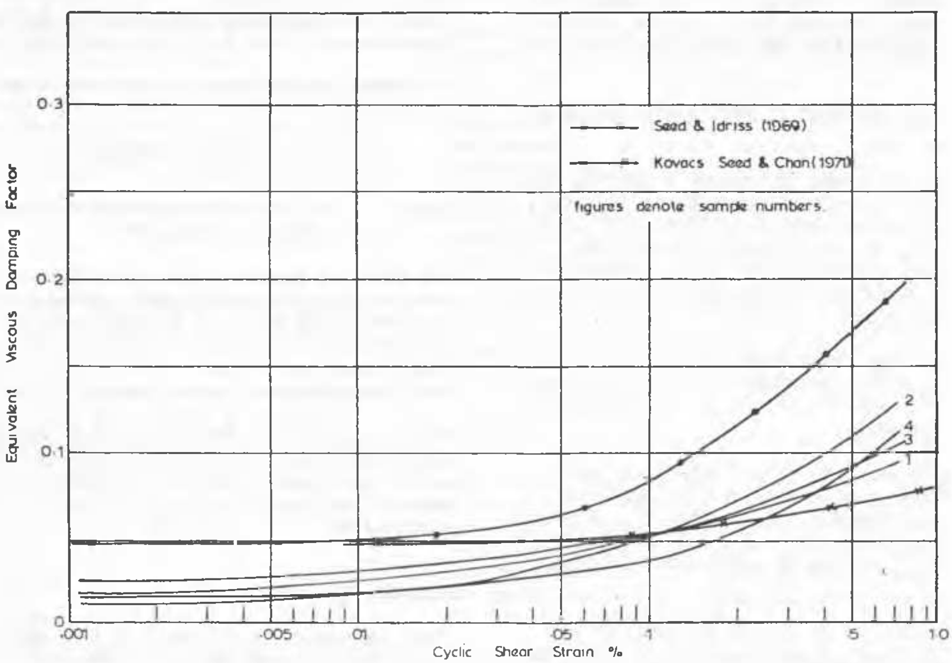

FIG. 5 Variation of Damping Factor with Strain
Saturated Clays

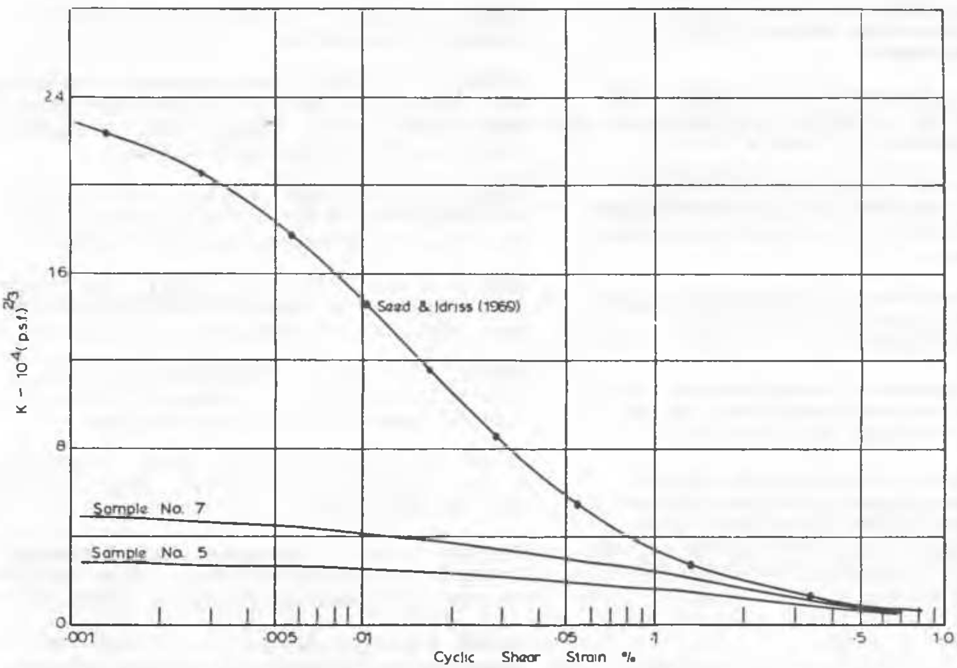

FIG. 6 Variation of Modulus with Strain.
Medium Sands, Relative Density 80 %.

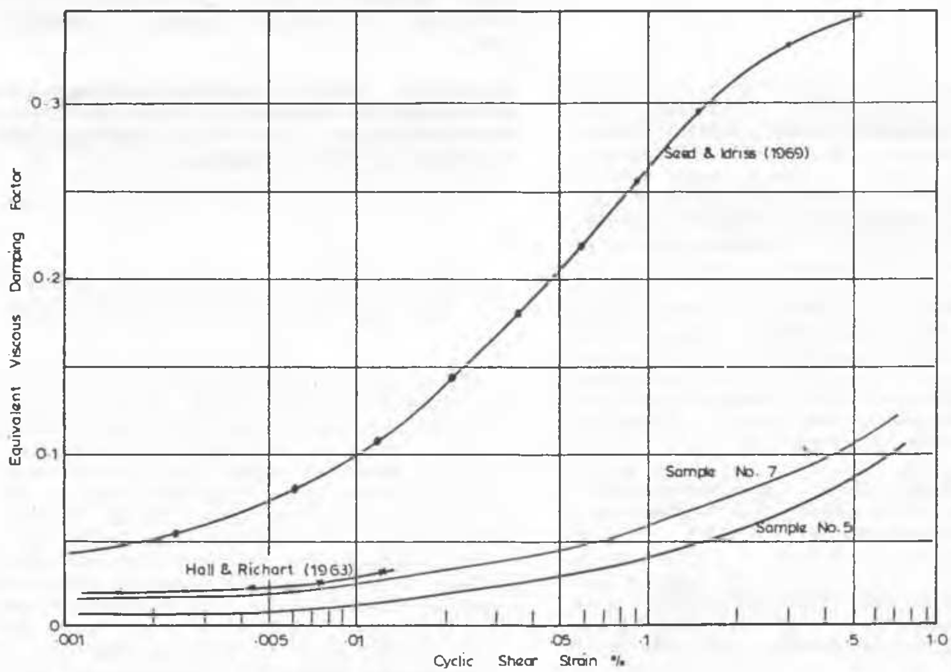

FIG. 7 Variation of Damping Factor with Strain.
Medium Sands, Relative Density 80 %

(1) Values of shear modulus are strongly strain-dependent, modulus values decreasing with increasing shear strain.

(2) Below a strain amplitude of approximately 0.01% the behaviour of the materials tested changes, and becomes approximately linearly elastic.

(3) Values of equivalent viscous damping factor evaluated are found to be strongly strain dependent, damping factors increasing with increasing strain amplitudes.

(4) Below a strain amplitude of approximately 0.01% values of damping factor are found to be approximately constant.

(5) For clays, the equivalent viscous damping factor, particularly at low strain amplitudes, may be lower than had previously been estimated.

(6) The range of dynamic soil properties observed in practice appears to be so wide that the use of average parameters for a broad soil group such as 'sands' or 'clays' can give only a rough approximation to the actual dynamic properties of a particular soil.

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