A Cyclic Triaxial Facility for Loading a Silty Clay

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SYNOPSIS: A digital control servo-hydraulic triaxial test facility with full data acquisition has been developed at Nottingham University as part of the UK Science and Engineering Research Council initiative in earthquake engineering. This apparatus is currently being used to investigate the response of a coarse silt contaminated by kaolin clay to cyclic stress and strain. High quality deformation data is generated by on sample instrumentation and enables the stiffness at very low strain levels to be determined accurately. This paper describes the development of the facility and presents some results of the tests carried out to date.

INTRODUCTION

Analogue controlled servo hydraulic systems for carrying out triaxial tests have been in use at Nottingham since the early 1960s. They were extended during the 1970s for cyclic loading problems associated with offshore structures (Hyde 1974) and have been further extended to study the behaviour of materials used in road construction (Loach 1987). Most recently the system was upgraded as part of the SERC initiative in earthquake engineering including the development of a new control and data acquisition facility.

The facility provides for the testing of 76mm diameter samples. The Instrumentation described by Brown et al (1980) is located in the middle third of the test sample to reduce the effect of end restraint. Instrumentation mounted on the test sample allows accurate measurement of axial and radial deformation. Pore pressures are monitored by a small pore pressure transducer consolidated into the central region of the test sample.

The loading system (Fig. 1) comprises two linear actuators, which control the deviator and confining stresses and enable them to be cycled. Feedback from any monitored parameter can be used to control the applied loading. Hence, for example, sample consolidation can follow K_O conditions using feedback from radial strain transducers to control the applied stress ratio. Strain and stress controlled tests use feedback from the axial LVDT transducers and the strain gauged diaphragm load cell respectively.

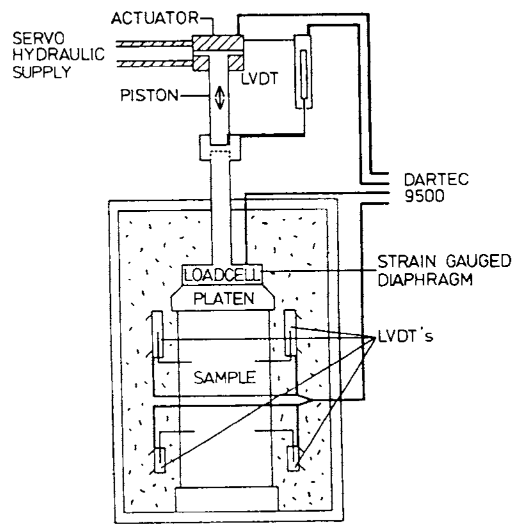

Fig. 1a Servo System - machine 1.

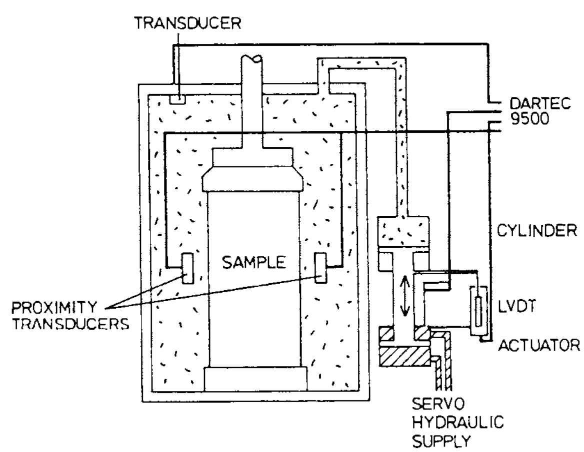

Fig. 1b Servo System - machine 2

TRIAXIAL TEST FACILITY

DIGITAL CONTROL SYSTEM

The proprietary digital control system (Fig. 2), supplied by Dartec Limited, Stourbridge, UK, comprises two sets of four channel microprocessor control systems programmed by a Texas Instruments professional computer.

Fig. 2 Digital Control System

Proprietary software provides for setting appropriate gains for the system, analysing frequency response, programming complex waveforms and setting various trips. The data acquisition facility available commercially was too limited for the requirements of the work being undertaken and an alternative system was developed.

TRIAXIAL APPARATUS

The triaxial apparatus (Fig. 3) was first developed by Lashine (1971). Subsequent developments have brought the equipment to the state described below:

Fig. 3 Triaxial Apparatus

<u>Axial Load:</u>

Deviator stress is measured by load cells designed and built at Nottingham University. They are disc load cells and consist of a loaded web shaped to give an approximately linear strain profile with radius. The load cell is attached to a top platten by means of vacuum permitting extension or compression loading.

The bush device which guides the load ram is detachable from the outer cell enabling soft samples to be assembled without the risk of failure during preparation.

<u>Pressure Transducers:</u>

Cell and base porewater pressure are monitored using strain-gauged silicon transducers manufactured by Druck Limited, Leicester, UK. Internal porewater pressure is monitored by a minature strain gauged silicon transducer introduced in to reconstituted samples at the initial consolidation stage. Back pressure on the volume change line is monitored using strain-gauged diaphragm transducers manufactured at Nottingham University. They are larger devices than the Druck transducers and are mounted adjacent to the volume change device remote from the sample.

<u>Volume change:</u>

A 100ml capacity volume change device made by Soiltech Ltd is used in which a DC linear variable differential transformer (LVDT) is attached to the side of a piston connected to a rolling diaphragm, producing a linear response with volume.

<u>Deformation:</u>

Radial deformation is measured using two proximity transducers. The transducers are mounted on a frame imparting no load to the sample. A 12 micron thick metal foil target is secured to the sample inside the membrane.

Axial deformations are measured 'on-sample' using four LVDT displacement transducers. The accuracy of this system at low strains particularly when determining damping ratios has been critically examined.

<u>Data Acquisition:</u>

Data obtained from cyclic triaxial tests has previously been recorded on X-Y or linear time chart recorders which tend to introduce significant damping both electrically and mechanically. Transition from an analogue to a digital system was essential but was accompanied by problems. Previously smooth stress-strain loops were clouded by electrical noise.

Various software techniques were employed to analyse the nature of the noise and attempt to reduce its significance. The noise on our system was a combination of intrusive signals from A-C power supplies, both mains and transducer excitation, random noise from electronic components and radiated interference from other equipment in the vicinity. Several techniques for manipulating the noisy data were studied. Straightforward mathematical averaging and rolling weighted averages were found to round of peaks and obviously would not work if the noise was greater than the signal. A sophisticated software package using Fast Fourier Transforms was examined. This highlighted the problem by revealing significant energy levels at 50hz (mains) and also at 1hz (the test frequency). By passing the noisy data through appropriate filters (eg Butterworth low pass filters) a smooth response resulted (Fig. 4).

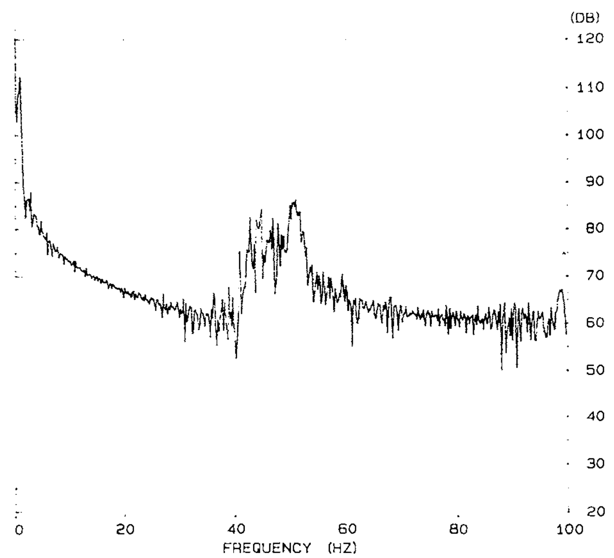

Fig. 4a Energy Spectrum from LVDT

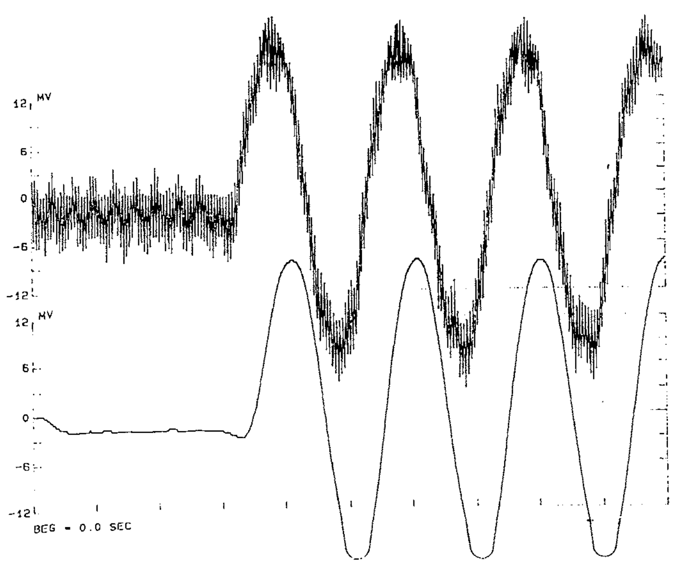

Fig. 4b Raw and Processed Data

Manipulating data post test is time consuming and obviously does not permit real-time servo control. A system which performed real time filtering was provided by CIL Ltd, Worthing, UK. Their α block A-D system is used in which all signals are filtered using a low pass technique before being amplified to a level approaching 5 volts. All data is converted to ASCII format and transferred to a proprietary spreadsheet for manipulation. This system has been used satisfactorily for the past 18 months.

The facility at Nottingham comprises three fully instrumented triaxial cells equipped as described above. The digital controlled servo-hydraulic system provides for the cyclic loading of one of these. A switching unit developed at Nottingham University allows manual monitoring of parameters from the two cells containing samples in various states of preparation while data from the one sample on test is recorded digitally.

EXPERIMENTAL RESULTS

A test programme is currently being undertaken to investigate the response of a coarse silt (Attenborough silt) contaminated by clay, in this case kaolin. This area of research was chosen as previous work tended to concentrate on sands or clay. While some work on clean silts has been undertaken previously as well as on silty clay, the topic of clay contamination has not been addressed.

Isotropic and K_O over consolidated samples have been tested with 100% SILT - 25% CLAY contents. It is intended to extend this range to include 50% SILT - 50% CLAY samples.

Seed (1963) suggested that a typical magnitude 5 earthquake could reliably be simulated as 5 cycles lasting 8 seconds. A trace of the recent Bishop's Castle earthquake in the UK (M = 5.1) is shown in Fig. 5 which suggested that

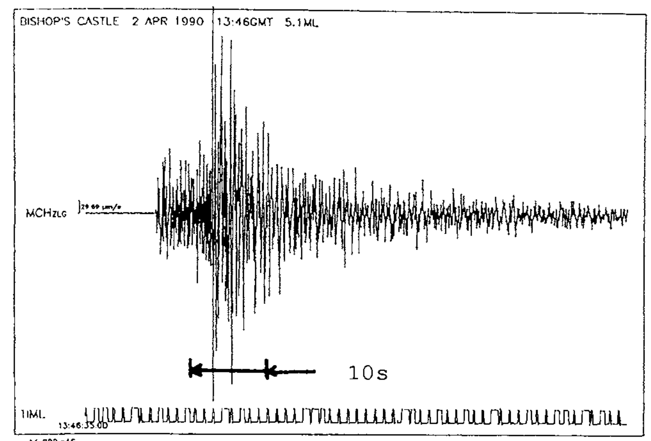

Fig. 5 A seismogram of the Bishop's Castle Earthquake (courtesy British Geological Survey)

this is approximately correct. The cyclic load tests which were performed undrained involved applying 5 cycles over a range of times. The loading frequencies used were 1Hz (T = 5s), 5 cycles at 0.5Hz (T = 10s) and a much slower test 5 cycles at 0.1Hz (T = 50s) to minimise the effect of pore pressure lag behind deviator stress. Degradation of stiffness, development of plastic and elastic strains and frequency dependency have been specifically examined.

CLASSIFICATION

Classification data of the sample combinations are shown in Fig. 6. The silt is very coarse which is consistent with high angle of internal shearing resistance. The silt is obtained from a local gravel pit and only material passing the 75μm sieve is used. The nominal 100% silt sample contains a small amount of clay size particles whose presence enabled a value of plastic limit to be determined. The inclusion of 25% clay did not appear to affect plasticity characteristics as measured in the Atterberg tests performed under BS1377:1975.

Sample	ϕ'	C_c	C_s	W_L	W_p	I_p
100% silt	38	0.118	0.015	30	20	10
75% silt	33	0.150	0.04	30	20	10

ϕ' - maximum angle of internal shearing resistance,

C_c - gradient of normal consolidation line in e - log σ'_v space

C_s - gradient of swelling line is e - log σ'_v space

W_L - Liquid Limit %

W_p - Plastic Limit %

I_p - Plasticity Index %

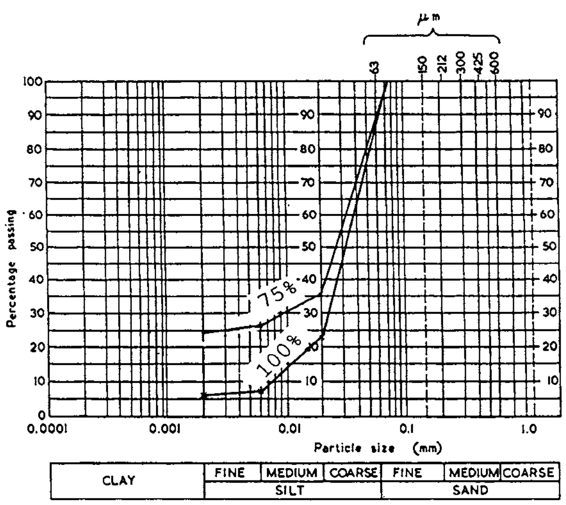

Fig. 6 BS1377:1975 Grading Curves

SAMPLE PREPARATION

Air dried combinations of silt and clay are continuously mixed with de-aired water for 2 days to form a slurry with a moisture content of about 1.8 times the Liquid Limit. The slurry is then gently poured into 78mm internal diameter 300mm high perspex cylinder sitting on a vibrating table. This process assists in eliminating trapped air. A previously de-aired miniature pore pressure transducer is inserted into the slurry via one of the two porous loading platens inserted at either end of the cylinder. The cylinder is mounted vertically in a loading frame as K_o consolidation is effected. A dial gauge mounted on the loading ram and the internal pore pressure transducer monitors the state of consolidation.

Having reached a predetermined consolidation state the sample is extruded from the cylinder and set up in the triaxial cell. The predefined state adopted in the work presented here is a vertical effective stress of approximately 150kPa.

Consolidation is further effected in the triaxial cell either isotropically (stress controlled) or anisotropically (stress and strain controlled) using feedback from the proximity transducers to maintain constant sample diameter. After consolidation the sample is subjected to a series of controlled stress and strain excursions. Due to the sensitivity of the axial strain devices stress controlled tests only are performed until a minimum strain of 100mε is reached. Thereafter control can alternate between strain and stress control until the sample reaches a predetermined failure criteria.

K_o CONSOLIDATION

Fig. 7 shows the stress path followed in q p' space during K_o consolidation in the triaxial apparatus for the 100% silt sample where

$$p' = \frac{1}{3}\left[\sigma_1' + 2\sigma_3'\right]$$

$$q = \sigma_1' - \sigma_3'$$

This is compared with the Mayne and Kulhawy (1982) model $K_o = (1 - \sin\phi)\ OCR^{\sin\phi'}$ using a value of $\phi' = 38°$ which indicates significant similarity.

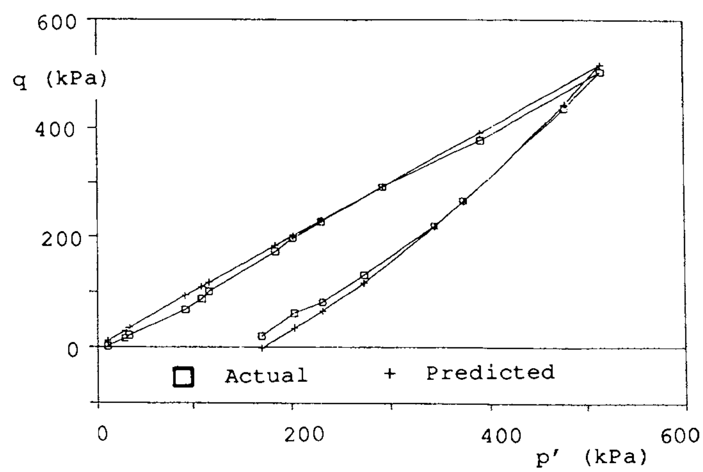

Fig. 7 K_o Consolidation Stress Path

CYCLIC LOAD TESTS

Figs. 8a-c show typical stress-strain curves produced from cyclic load tests using shear strain ε_s: $\varepsilon_s = 2/3\ (\varepsilon_a - \varepsilon_r)$. Fig 8a indicates the limitations of the axial deformation device (4×10^{-5} strain ≈ 2 microns). Whereas Figs 8b and 8c, show hysteresis loops at higher strain levels for stress and strain control respectively.

The secant shear modulus was determined using a value of Poissons's ratio of v = 0.5 ie assuming no volume change. Although the on sample instrumentation did monitor values of v approaching 0.6 due probably to local barelling caused by end restraint particularly at high strains.

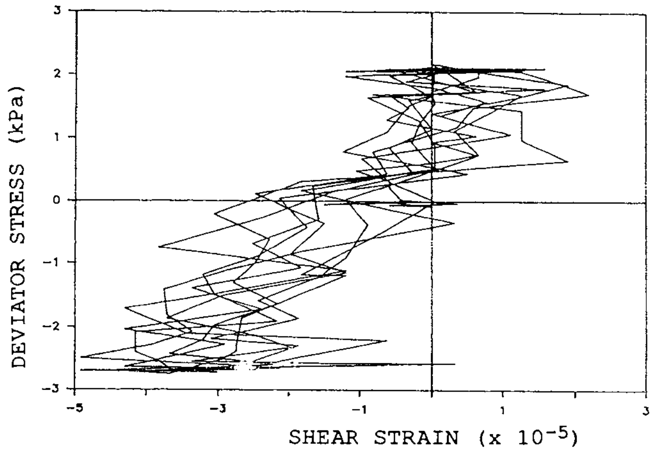

Fig. 8a Stress-Strain Response at Very Small Strain Levels

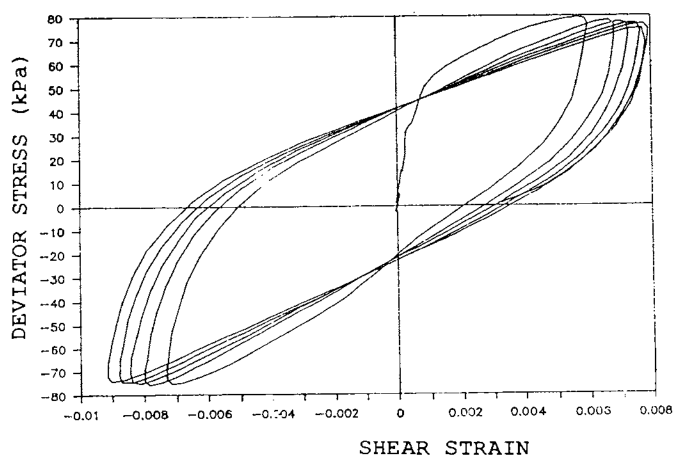

Fig. 8b Stress Controlled Test

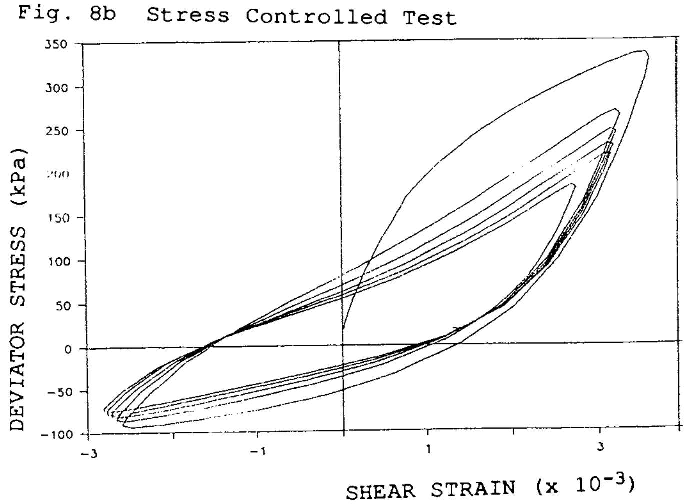

Fig. 8c Strain Controlled Test

It has been found that for both sample combinations the degradation of secant shear modulus is not affected by the type of consolidation history (ie one dimensional or isotropic). Fig. 9 shows the normalised shear modulus G/p' against shear strain for all four cyclic load tests highlighting the apparent insignificance of type of consolidation history and showing as expected a higher stiffness for the coarser material for any given level of repeated shear strain and also reveals the different shapes of the degradation curves.

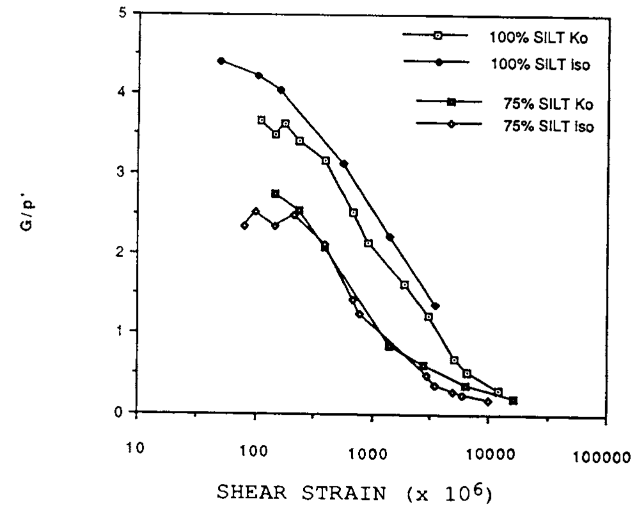

Fig. 9 Degradation of Normalised Shear Stiffness v Shear Strain

Although the secant shear modulus appears to be independent of the type of consolidation history, the development of plastic strains is significantly different. The K_o consolidated sample appears to develop shear strains equally in extension and compression. Fig. 8b whereas the isotropically consolidated sample yields only in extension. This point is shown graphically in Figs. 10a and 10b.

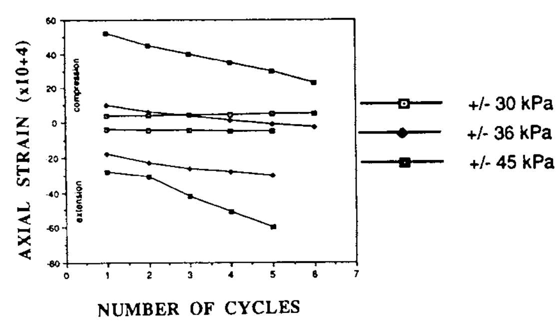

Fig. 10a Development of Axial Strain - Isotropic Consolidation

The effect of frequency is also considered. Fig. 11 shows the degradation of shear modulus and development of viscous damping at three frequencies for the isotropically deconsolidated 100% silt sample. Indicating higher stiffnesses and lower damping for the faster tests.

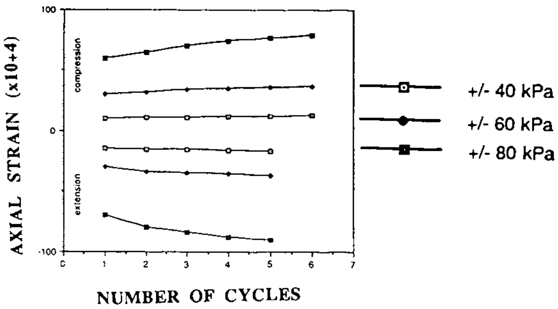

Fig. 10b Development of Axial Strain - K_o Consolidation

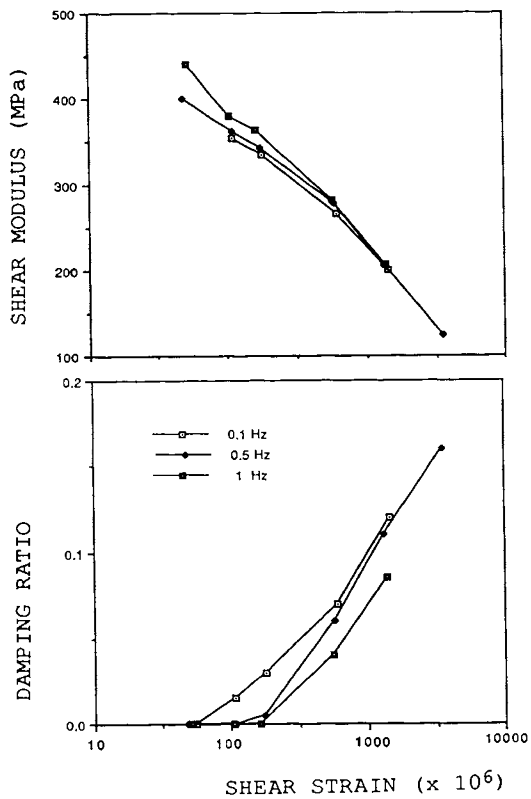

Fig. 11 Frequency Affects on Degradation of Shear Modulus and Development of Damping Ratio v Shear Strain

CONCLUSION

The triaxial test facility developed at the University of Nottingham has enabled high quality data to be generated on the deformation characteristics of clay contaminated silt samples subject to cyclic stress and strain.

This paper has described the development of the test facility and presented some of the data generated from the current research project. This illustrates the ability of the equipment to accurately produce K_o overconsolidated samples in the triaxial configuration and the ability to determine accurate values of shear modulus at strain levels similar to those which are imposed by the resonant column apparatus. Further, the results reported appear to indicate that the shear modulus degradation is independent of where consolidation history is K_o or isotropic.

ACKNOWLEDGEMENTS

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