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AN AUTOMATED TRIAXIAL SYSTEM FOR STRESS AND STRAIN PATH TESTING OF SOILS*

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ABSTRACT : This paper describes a computer controlled laboratory triaxial system for stress and strain path tests of soils. The automated system developed is capable of controlling both the stresses and deformations imposed on samples. The system incorporates internal load cell, local axial and radial strain measuring devices and mid-plane porewater pressure transducer. The system is simple to operate and provides a reasonably priced tool for research. Using the system, soil samples, 102 mm dia. and 203 mm high, can be subjected to stress or strain paths which more accurately represent field conditions, leading to acquisition of more realistic soil parameters. The system was used to carry out a wide range of stress path tests to investigate the yielding behaviour of fine Leighton Buzzard sand in triaxial stress space. The automated triaxial system was also used to perform stress and strain path tests to investigate tube sampling disturbance effects in reconstituted normally consolidated and overconsolidated London clay, and natural lightly overconsolidated Bothkennar clay. The system has been proved to be accurate and reliable and provided good quality data for research.

KEYWORDS: Automated triaxial test equipment, sress path test, strain path test

INTRODUCTION

The conventional triaxial apparatus (Bishop and Henkel, 1962) is the most common testing device for routine examination of soils for geotechnical design and for much current research. This is because the device is simple in design and cylindrical samples are relatively simply prepared by extrusion from sampling tubes or by trimming in a soil lathe. Soil, unlike many materials, is history dependent and path dependent, meaning that its behaviour is governed by the recent stress and strain history and by the current stress and strain changes. The stress history and the stress path applied in a conventional triaxial test are unlikely to be the same as those relevant to soil in the ground with the result that the

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soil properties measured in the laboratory may not apply to soil behaviour in the ground. Also it is difficult to use the conventional triaxial apparatus to impose the stress and strain paths normally encountered in various geotechnical problems. The difficulty arises because performing such complex stress or strain paths requires accurate and rapid control of the applied stresses or strains in order to follow the desired stress or strain paths. Besides, computer control is required because complex stress or strain paths may require longer test periods which may be beyond the capability of the operator.

There have been major developments in microcomputers, in electronic instrumentation and in control systems which have allowed automatic control and monitoring of stress paths in the triaxial apparatus with high accuracy and at reasonable cost. Hight (1983) developed a control system which is capable of applying precisely specified sequences of stresses or deformations to soil samples in various pieces of testing equipment, for example, in the hydraulic triaxial apparatus (Bishop and Wesley, 1975), the plain strain apparatus (Atkinson, 1973), and the hollow cylinder apparatus (hight, 1983). Microcomputer controlled stress path equipment developed at the City University, London has been described by Atkinson (1985) and Atkinson et. al. (1985). This paper describes a microcomputer based fully automated triaxial system for carrying out stress path and strain path tests of soils for research works.

BASIC FEATURES OF THE TEST EQUIPMENT

The equipment consists of four major parts, the microcomputer, the pressure controllers, the signal conditioning unit and the loading system. The data from a test is monitored by means of transducers monitoring axial load, cell pressure, back pressure, pore pressure at the base and mid-height of specimen and, axial and lateral deformations of specimen.

The Microcomputer

The microcomputer is the central controller of the whole system. Its basic function is to receive and store initial test information as assigned by the operator, receive digital output from the transducers, do the necessary calculations to convert these to engineering units; command the pressure controllers to supply the required loading pressures; print, plot and store data at the end of required intervals of time; and finally to process the data at the end of each test. A standard Hewlett-Packard 86 B microcomputer was used. Through an IEEE-488 interface, the computer was linked to the signal conditioning unit and to other peripherals such as the disc drive and printer.

The Pressure Controllers

Three pressure controllers were used, each to control one pressure unit, namely back pressure, cell pressure and axial pressure. Each pressure controller consists of a small stepper motor operating through a reduction gear box and a flexible coupling to provide the required mechanical rotations in order to drive a manostat air pressure regulator. Making the motor step in either direction causes the air pressure to increase or decrease. The stepper motor requires a 12 Volt DC power supply to operate and, therefore, a special voltage converter box was used for this purpose. The controllers were linked to the computer through an HP General Purpose Input and Output (GPIO) interface. This interface provides eight different hardware configurations for four 8 bit ports. In the system only one 8 bit port was used to control the three stepper motor driven air pressure regulators (for cell and back pressure, and deviatoric load) and two relay driven solenoid valves (for switching from triaxial compression to extension and vice versa). A typical relationship between the number of steps and the generated pressure for the pressure controllers is shown in Fig. 1. It can be seen that the relationship is linear up to a pressure of 500 kPa, above which a slight diversion appears with further increase in pressure. Each step by the motor was found to cause a change of air pressure of approximately 0.1 kPa which corresponds to about 0.07 kPa for the axial pressure on the sample. Time taken to perform one step is approximately 0.1 sec. Thus an application of an increment of 100 kPa cell pressure, for example, will take a minimum of approximately 143 seconds. Three Budenberg Standard Test Gauges were also used as manual check on air pressures.

The Signal Conditioning Unit

The signal conditioning unit receives the output analogue signals from various measuring devices, amplifies and converts them to digital form, and then passes this information to the computer. The unit incorporated within the system is a strain gauge amplifier system (SGA 1100). The system produces a signed 12 bit (±4096 bits) digital output. Each logged device was calibrated within this range. A total of nine channels were used to monitor the signals from nine transducers within the system; three transducers to detect the back, cell and local pore pressures, an internal load cell to measure the axial deviatoric load, three local strain measurement devices, an external displacement transducer to measure the overall axial strain of the specimen and the volume change device. Each device was energized with 10 volts DC power supply. Any desired channel can be selected and to read the data from the corresponding device. A listing of the basic algorithm to scan data from various measuring devices is given in Appendix-A.

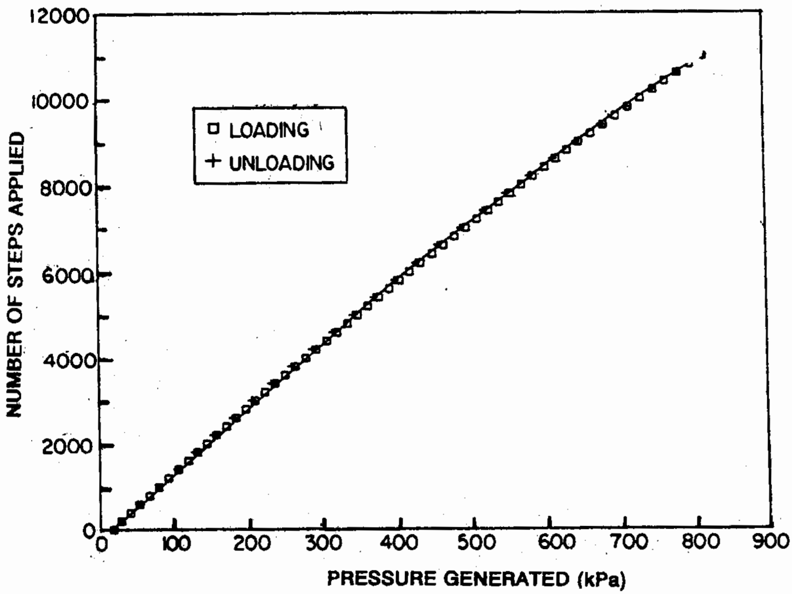

Fig 1. Typical pressure controller calibration characteristics

The Loading System

The loading system consists of a loading frame, an air actuator and a 102 mm triaxial cell mounted in a Wykeham Farrance triaxial machine. The loading frame is a two-post frame with adjustable cross bar and a flat plate base, used to provide reaction for vertical load application and to accommodate the 102 mm diameter triaxial cell. The actuator is a double acting Bellofram diaphragm air cylinder of 10 bar maximum pressure capacity, used to apply deviatoric stress. The two chambers behind the upper and lower Bellofram are filled with pressurized air and each of them is connected to one of the solenoid valves, which is in turn connected to the axial pressure controller. By controlling the opening and closing of the two valves both compression and extension stress controlled tests can be performed. During an extension test it is necessary to apply an upward force on the top cap which is transmitted to the sample. Measurement of this load required the load cell to be screwed to the top cap. The top cap arrangement (Bishop and Henkel, 1962) was used by Khatrush (1987) and Siddique (1990). Triaxial compression machine has a microprocessor controller and was linked to the microcomputer via an RS232 interface. Initially the system had the capability of controlling stresses only (Khatrush, 1987; Siddique, 1990). Subsequently, the system was modified to incorporate deformation control (Hopper, 1992).

By providing a clamp to prevent movement of the ram on the air actuator, it was possible to use computer control to regulate deformations applied to specimens. Using the stepless compression machine, strain rates varying from 0.0005 to 5.99 mm/min were attainable.The algorithms used to control the compression machine are given in Appendix-B. Initially, the cell had the facility of single drainage only by providing high air entry porous ceramic disc embedded at the base pedestal (Khatrush, 1987; Siddique, 1990). Later, an aluminium top cap, with high air entry porous ceramic stone was used for providing the facility of double drainage (Hopper, 1992). The system also contains some additional peripheral devices interfaced to the computer, including a disc drive for storing data and loading programs, a printer for obtaining hard copies of the data. A general layout of the automated system and schematic details of the 102 mm triaxial cell are shown in Figs. 2 and 3 respectively. A general view of the triaxial system is shown in Fig. 4.

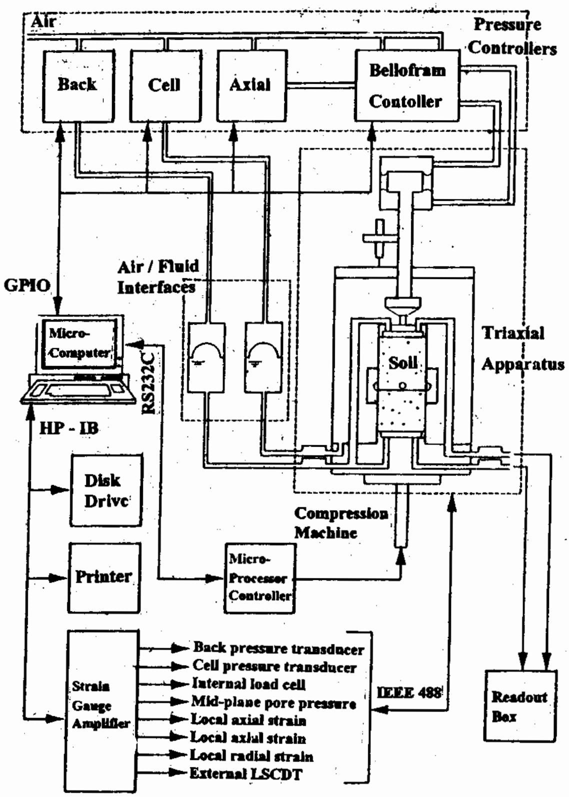

Fig 2. General layout of automated stress/strain path system

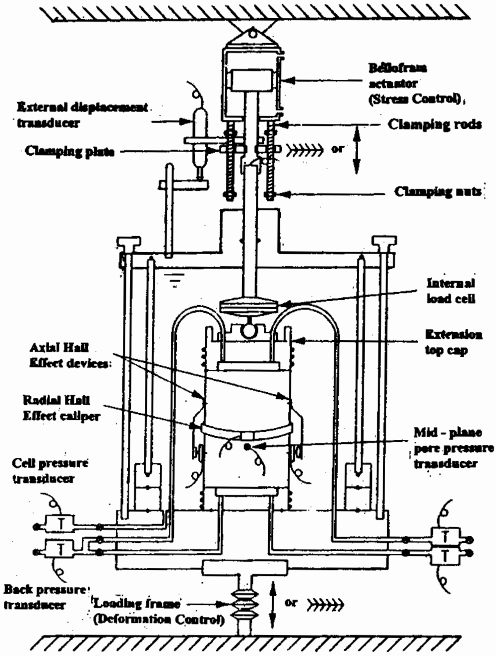

Fig 3. Schematic details of 102 mm triaxial cell

MEASUREMENT OF FORCES, STRESSES AND DEFORMATIONS

The measuring devices incorporated in the system include a load cell, cell pressure and back pressure transducers, a pore pressure transducer to measure pore pressure at the base of the specimen, an external displacement transducer, three local deformation measuring devices and a miniature local pore pressure transducer.

Load Cell, Cell Pressure and Back Pressure Transducers

A Wykeham Farrance 5000 N internal load cell was used to measure deviatoric load. The load cell was calibrated using a Budenberg dead load tester. A calibration of 1 N/bit was obtained which gave a resolution for the deviatoric stress of approximately 0.13 kPa/bit. The measurement of cell and back pressure was achieved by means of Druck PDCR 10 pressure transducers having an operating range of 0 to 1034 kPa. These were calibrated using the Budenberg dead load tester for a working range of 0 to 1000 kPa. The resolution of each transducer was 0.25 kPa/bit.

Pore Pressure Transducers

A Druck PDCR 81 miniature pore pressure transducer (Hight, 1982) was used to measure mid-plane pore pressure. For use as a piezometer in triaxial testing the transducer offered the following advantages:

(i) Small overall size and weight which enable it to be placed on the side of the specimen.

(ii) A rapid response time even with clays of very low coefficient of consolidation (e.g., Londonclay, Bothkennar clay).

(iii) High output which reduces loss of resolution in high speed logging.

(iv) Lack of hysteresis, making it especially suitable for measurements of pore pressure changes during unloading from compression to extension.

(v) Considerable savings in testing time as it is unnecessary to wait for equalisation of pore pressures throughout the specimen height.

The transducer was calibrated for a working range of 600 kPa by placing it in the triaxial cell and applying known increments of pressure with the Budenberg dead load tester. The resolution of the transducer was 0.25 kPa/bit. In addition to this mid-plane pore pressure transducer, two other pressure transducers were used to measure pore pressure at top and bottom of specimen. The pressure transducers were either Bell and Howell or DRUCK PDCR 10 pressure transducers (operating range of 0 to 150 psi). These were calibrated for a working range of 0 to 1000 kPa, using the Budenberg dead load tester. The resolution of these transducers was 1 kPa/bit. These pressure transducers were not connected to the strain gauge amplifier system but to stand-alone signal read-out box.

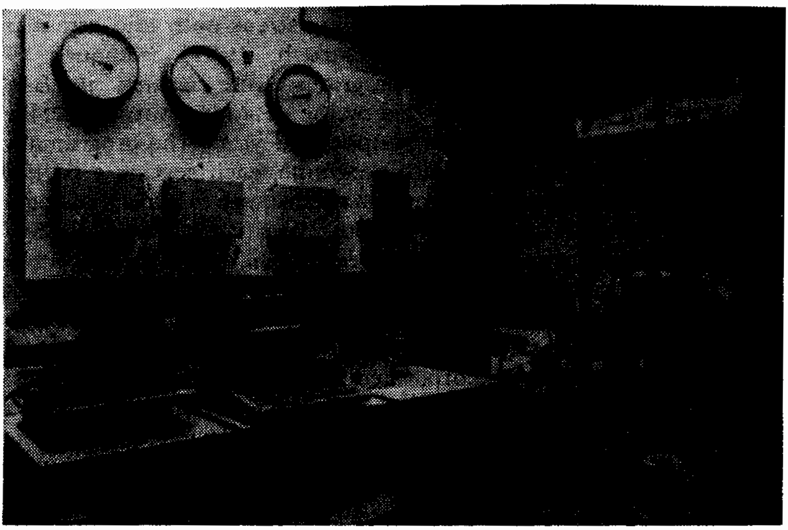

Fig 4. Photograph showing general view of stress/strain path system

Axial and Radial Deformation Measuring Devices

Overall deformation of a specimen was measured by means of a linear strain conversion displacement transducer (LSCDT). The transducer was calibrated over its travel range of 25.4 mm (1 inch). The resolution of the transducer is approximately 6.35 μm/bit. To obtain accurate measurements of deformations, local deformations were measured using Hall effect devices (Clayton and Khatrush,1986; Khatrush, 1987; Clayton et. al., 1989; Siddique, 1990; Hopper, 1992). Two axial Hall effect devices having gauge length of 70 mm, and one radial caliper were used. The resolution of these axial strain and radial strain devices was about 1 μm/bit and 0.5 μm/bit respectively.

Volume Change Measurement

Various devices have been developed in order to record volume change. A comprehensive review of various volume change measuring devices was carried out by Alva-Hurtado and Selig[13]. However, the accuracy of these volume change devices does not depend only on their electrical characteristics, since in addition their are some other errors which take place. The nature of these errors has been discussed by Khatrush (1987). From various stress path test results he concluded that the use of local measurements of axial and radial deformations achieved the greatest accuracy. All volume change measurements were, therefore, calculated on the basis of local measurements of axial and radial strains.

THE SOFTWARE

Computer programs were developed for stress path and strain path testing in the triaxial apparatus (Khatrush, 1987; Siddique, 1990; Hopper, 1992). The computer programs were written in BASIC. Additional special commands provided by the HP-input/output ROM were used to communicate with various peripheral devices. The programs were constructed as a series of block sub-programs, each serving a particular function. These were developed in an interactive way to allow a dialogue to take place between the computer and the user via a video display. All information and data appear on the screen so that the user has a choice of either keeping or correcting these. The flow chart showing the general layout of the programs is illustrated in Fig. 5. Using programs, the system is capable of performing any desired stress and strain path test. The other special features which were incorporated in the programs are as follows:

(i) Control of the rate of application of stress for each stress path and the rate of deformation for each strain path as desired by the user.

(ii) Reporting of test specimen's status at specified time intervals. Current values of stresses and strains are displayed on the screen and stress or strain path and stress-strain curves are also plotted on the graphics display as the test proceeds.

(iii) The test data for each stress or strain path is printed in a tabular form at regular intervals of time as specified. The test data are finally stored on disc at the end of each test.

(iv) Safety features have been included in the software, so that none of the transducers may exceed their maximum operating range.

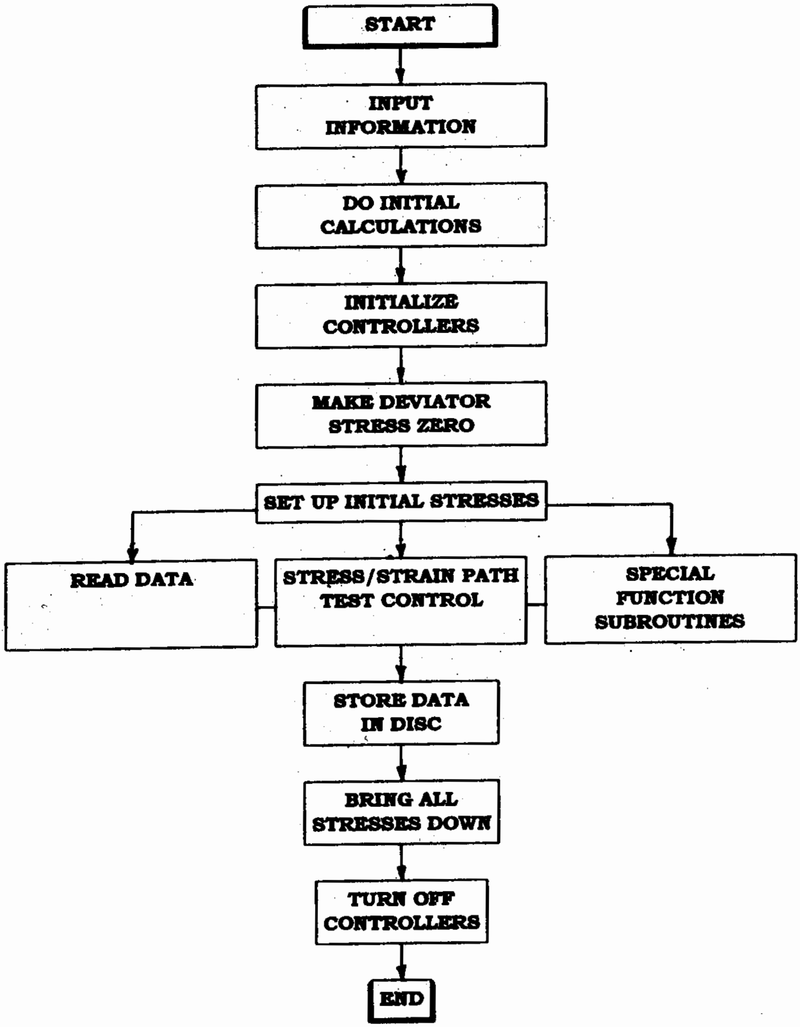

Fig 5. Flow chart showing general program layout

ILLUSTRATIVE EXAMPLES OF STRESS PATH AND STRAIN PATH TESTS USING THE AUTOMATED TRIAXIAL SYSTEM FOR RESEARCH

The automated triaxial system was used for a number of research works carried out at the University of Surrey, England. The system has been proved to be very effective for carrying out a wide range of stress and strain path tests on triaxial samples to obtain good quality data.

Khatrush (1987) conducted stress path tests to investigate the yielding behaviour of fine Leighton Buzzard sand in triaxial stress space. The shape of the yield loci, both in triaxial compression and extension have been investigated. Having established the shape of the yield loci, series of stress path tests were also carried out to investigate the effect of stress reversal (i.e., from extension to compression and vice versa) on the position of the yield surface. Typical examples of the sequence of stress paths and the corresponding stress-strain data to examine the effect of stress reversal on previously established yield loci are presented in Figs. 6(a) and (b).

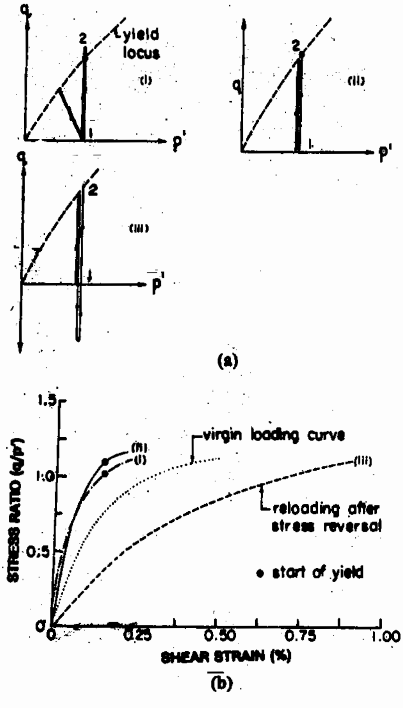

Fig 6. Effect of stress reversal on yielding of Leighton Buzzard sand (a) sequence of stress paths (b) stress-strain curves

Using the automated system, Siddique (1990) investigated the effect of tube penetration disturbances on the undrained stress-strain-strength, stiffness and pore pressure characteristics of K_0-normally consolidated reconstituted soft London clay. The sequence of stress path and strain paths applied to samples are shown in Figs. 7(a) and (b). Examples of normalized stress paths and stress-strain curves for a typical test which simulated application of tube penetration disturbances are presented in Figs. 8(a) and (b) respectively.

Hopper (1992) examined the effects of ideal tube sampling (Baligh et. al., 1987) disturbance on lightly overconsolidated natural Bothkennar clay and overconsolidated reconstituted London clay. Sequences of stress and strain paths applied to Bothkennar clay and London clay samples are shown in Fig. 9(a) and (b), respectively. Figs. 10(a) and (b) show stress paths and stress-strain curves for a typical test modelling ideal sampling disturbances on Bothkennar clay and reconstituted overconsolidated London clay, respectively.

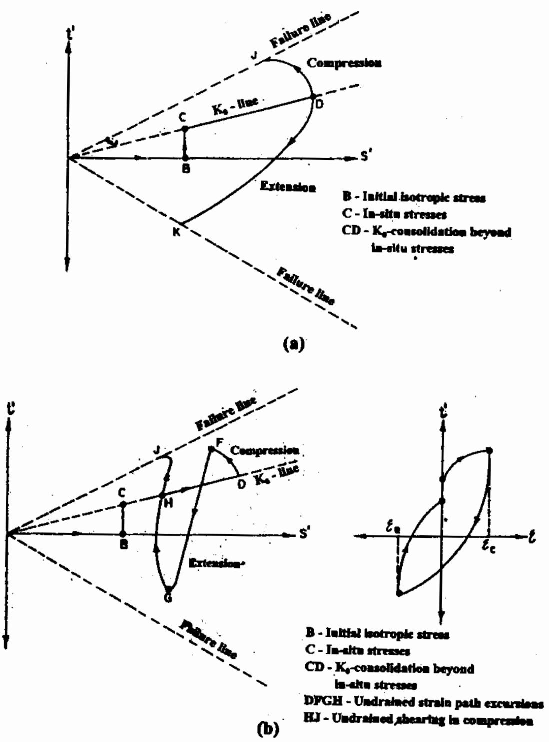

Fig 7. Stress and strain paths applied to normally consolidated London clay samples (a) stress paths for "undisturbed" samples (b) Stress and strain paths simulating tube penetration disturbances

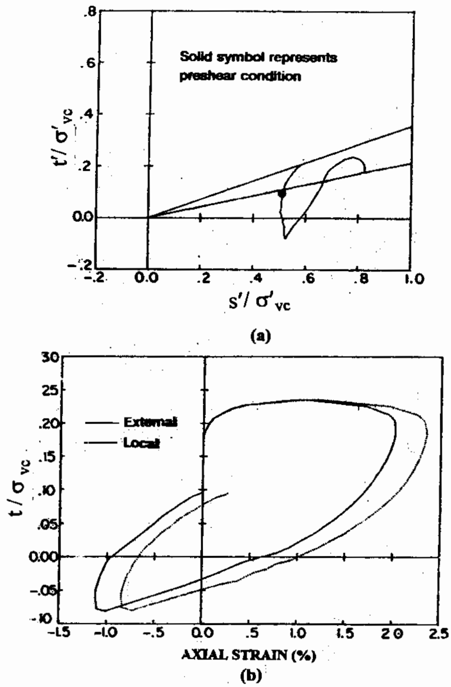

Fig 8. Stress paths and stress-strain curves for a typical test modelling tube penetration disturbances applied to normally consolidated London clay (a) stress paths (b) stress-strain curves

The stress paths and strain paths applied to triaxial samples in a number of research programme, as mentioned above, indicate that the computer controlled triaxial system is capable of executing quite a variety of stress and strain paths. The tests provided accurate and reliable results which were used in a number of research works carried out at the University of Surrey, England.

CONCLUSIONS

A computer controlled laboratory testing system for triaxial stress and strain path tests has been developed. The fully automated system is capable of controlling both the stresses and deformations imposed on samples. Using the system, it is possible to conduct a wide range of stress path and strain path tests on 102 mm dia. by 203 mm high specimens. For accurate measurements of stresses and strains, the system has been incorporated with internal load cell, local axial and radial strains measuring devices, and mid-plane porewater pressure transducer.

The system is versatile, simple to operate and provides a reasonably priced tool for research. Soil samples can be subjected to stress or strain paths which more accurately represent field conditions, leading to more realistic stress-strain-strength, stiffness and pore pressure parameters. The system has been used to carry out a variety of stress path tests to investigate the yielding behaviour of fine Leighton Buzzard sand in triaxial stress space. The system has also been used to perform stress and strain path tests to investigate tube sampling disturbance effects in reconstituted London clay, and natural Bothkennar clay.

The system developed, therefore, is capable of modelling stress paths and strain paths for a number of materials, e.g., sands, reconstituted clays and naturals clays. The system has been proved to be accurate and reliable in measuring stresses and deformations in sands and clays and provided good quality data for research.

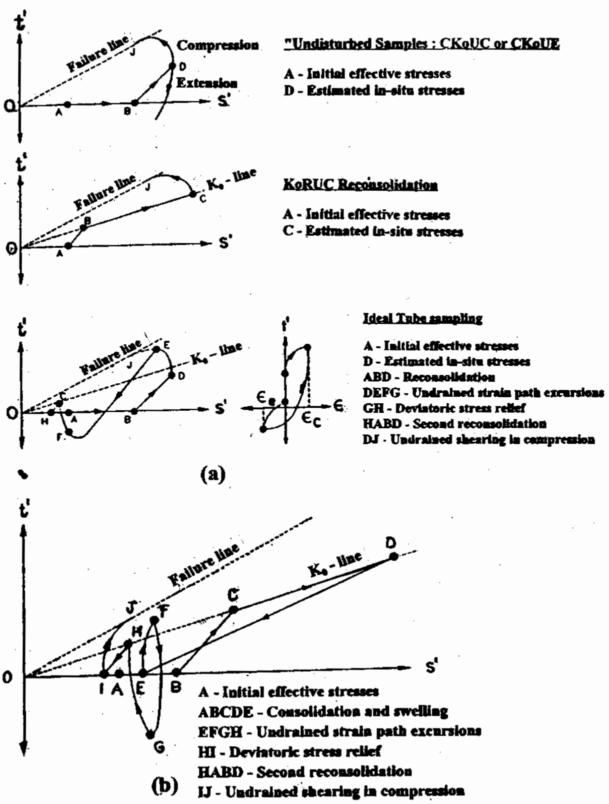

Fig 9. Sequence of stress paths for modelling ideal sampling disturbances
(a) undisturbed lightly overconsolidated Bothkennar clay
(b) overconsolidated reconstituted London clay

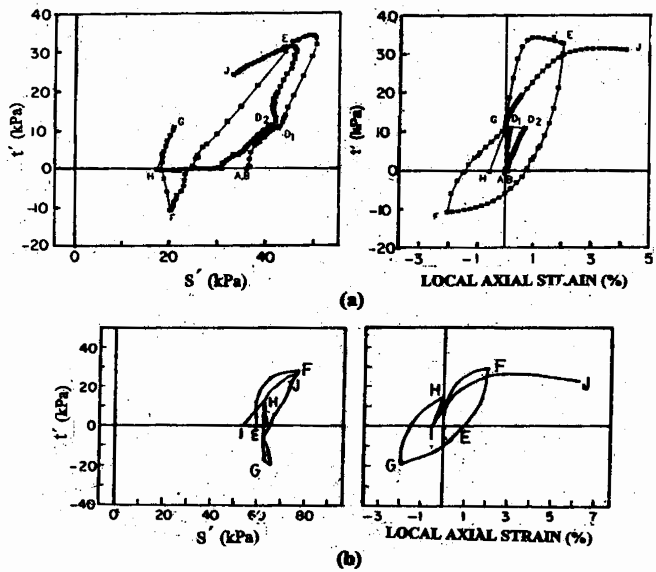

Fig 10. Stress paths and stress-strain curves for typical tests modelling tube penetration disturbances (a) undisturbed Bothkennar clay (b) reconstituted London clay

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NOTATION

K_0	coefficient of earth pressure at rest
p'	mean effective stress $(\sigma_a' + 2\sigma_r')/3$
q	deviatoric stress
q'	$\sigma_a' - \sigma_r'$
s'	$(\sigma_a' + \sigma_r')/2$
t'	$(\sigma_a' - \sigma_r')/2$
ε	axial strain
ε_c	axial strain in compression
ε_e	axial strain in extension
σ_a'	axial effective stress
σ_r'	radial effective stress
σ_{vc}'	vertical effective stress at the end of K_0-consolidation
CK_0UC	K_0-consolidated (up to in-situ stresses) undrained compression
CK_0UE	K_0-consolidated (up to in-situ stresses)undrained extension
K_0RUC	K_0-consolidated (up to twice in-situ stresses) undrained compression

APPENDIX - A

BASIC ALGORITHM FOR SCANNING SIGNALS FROM VARIOUS MEASURING DEVICES

```
20 ON ERROR GOTO 50
30 LOADBIN "UTIL/1"
40 OFF ERROR
50 REM ******** READ SIGNALS FROM SGA BOX ********
60 DIM R(13), S(13), U$(13), D$(13)
70 U$(0)="NOT USED  "
```

```
80 U$(1)="BACK PRESS " @ U$(2)="CELL PRESS " @ U$(3)="AXIAL PRESS"
90    U$(4)="H.E.CALIPER"@U$(5)="H.E.GAUGE13"@ $(6)="H.E.GAUGE12"
100 U$(7)="L.S.C.D.T." @ U$(8)=VOL.CHANGE " @ U$(9)="PORE PRESS "
110 GOTO 230
120 FOR JJ=1 TO 9
130 SEND 7 ; UNL UNT MLA TALK 9 SCG JJ
140 ENTER 7 USING #,B,B ; S1, S2
150 S3=BINAND (S2,15)
160 S(JJ)=S1+256*S3
170 IF BINAND  (S2,32)=0 THEN S(JJ)=-S(JJ)
180 R(JJ)=S(JJ)
190 D$(JJ)=VAL$ (R(JJ))
200 I=JJ
210 FAST LABEL 80, 30+I*10, D$(I)&"      ",0
220 NEXT JJ @ GOTO 120
230 GCLEAR @ GRAPH
240 FAST LABEL 5,0, "OUTPUT  READINGS  FROM  SGA  100" ,1
250 FOR I=1 TO 9
260 FAST LABEL 0, 30+I*10, "CHANNEL NO. "&VAL$ (I)&"     "&U$(I),1
270 FAST LABEL 90, 30+I*10,"BITS" ,1
280 NEXT I
290 GOTO 120
300 END
```

APPENDIX - B

BASIC ALGORITHM FOR CONTROLLING COMPRESSION MACHINE

```
10 REM ************************************************
20 REM THIS PROGRAM CONTROLS THE CLASSIC TRIAXIAL
30 REM   COMPRESSION MACHINE
40 REM ************************************************
50 REM *** CONTROL COMMANDS ***
60 CONTROL 10,3 ; 15
70 CONTROL 10,4 ; 30
80 REM *** KEY LABELS ***
90 ON KEY£ 1,"UP" GOSUB 200
100 ON KEY£ 2,"DOWN" GOSUB 300
110 ON KEY£ 3,"STOP" GOSUB 400
120 ON KEY£ 4,"END" GOSUB 500
130 KEY LABEL
140 GOTO 130
200 REM *** PLATEN UP ***
210 OUTPUT 10 USING "£,K" ; CHR$ (15)
220 OUTPUT 10 USING "£,K" ; CHR$ (0)
230 OUTPUT 10 USING "£,K" ; CHR$ (6)
240 OUTPUT 10 USING "£,K" ; CHR$ (5)
250 OUTPUT 10 USING "£,K" ; CHR$ (14)
260 GOTO 140
300 REM *** PLATEN DOWN ***
310 OUTPUT 10 USING "£,K" ; CHR$ (15)
320 OUTPUT 10 USING "£,K" ; CHR$ (0)
330 OUTPUT 10 USING "£,K" ; CHR$ (6)
340 OUTPUT 10 USING "£,K" ; CHR$ (5)
350 OUTPUT 10 USING "£,K" ; CHR$ (12)
360 GOTO 140
400 REM *** STOP PLATEN ***
410 OUTPUT 10 USING "£,K" ; CHR$ (13)
420 GOTO 140
500 REM *** END PROGRAM ***
510 END
```