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A SERVO SYSTEM FOR CONTROLLED STRESS PATH TESTS

by K. T. Law

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SOMMAIRE

Dans le présent article, on décrit un servo-mécanisme capable d'imposer une trajectoire déterminée aux contraintes, lors de l'étude du comportement des sols au laboratoire. On a examiné diverses conditions: 1) des trajectoires des contraintes semblables à celles observées in situ, 2) le cisaillement produit par des déformations axiales et des déformations biaxiales, 3) l'état créé par une importante déformation ou l'état succédant à la rupture (ou à l'écoulement).

Le servo-mécanisme est constitué de deux parties principales: un mini-ordinateur et un transducteur électrique-pneumatique (E/P). Le mini-ordinateur recueille et traite les données pendant le déroulement de l'expérience. Les signaux électriques appropriés sont transmis au transducteur E/P, qui régularise la pression imposée à la conduite de contre-pression de l'appareil de mesure des déformations biaxiales ou triaxiales. Lorsque la charge axiale est appliquée à vitesse de déformation constante, il est possible de mesurer dans sa totalité le comportement contrainte-déformation, même lors de déformations élevées, le long d'une trajectoire prédéterminée des contraintes.

On a réalisé une série d'essais pour illustrer les possibilités du servo-mécanisme. Dans le cas particulier de l'analyse de la stabilité des pentes, on a effectué une autre série d'essais, qui ont permis d'obtenir les enveloppes de résistance en charge de pointe et ultérieure.

K. T. Law[1]

A Servo System for Controlled Stress Path Tests

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ABSTRACT: This paper describes a servo system capable of imposing a prescribed stress path for the study of soil behavior in the laboratory. Various conditions were examined: (*1*) stress paths resembling those in the field, (*2*) both axisymmetric and plane strain shearing, and (*3*) large strain or post failure (or yield) state.

The servo system is composed of two main parts: A minicomputer and an electric-pneumatic (E/P) transducer. The minicomputer collects and processes data while the experiment is in progress. The appropriate electrical signals are transmitted to the E/P transducer, which regulates the pressure connected to the back-pressure line of the triaxial or plane strain apparatus. With the axial load applied at a constant strain rate, it is possible to measure the complete stress-strain behavior, including that at large strains, along a prescribed stress path.

A series of tests was carried out to illustrate the capability of the servo system. For the particular case of slope stability analysis, another series of tests was conducted from which peak and post-peak strength envelopes were obtained.

KEY WORDS: servo system, computerized soil tests, controlled stress paths, triaxial tests, plane strain tests, strength envelopes, peak, post peak

Prediction of soil behavior under load is an essential requirement of engineering design. One way to improve such prediction is to examine the behavior of the soil by various test methods that yield results applicable under field conditions.

The stress path involved in shearing soils is an important factor influencing soil behavior and is receiving growing attention. A stress path, a line drawn through points on a stress plot, denotes the sequence of stress changes experienced by a soil element during the shearing process. Under field situations it starts from the point representing the *in situ* stress condition and proceeds to other points, as dictated by the type of structure being considered and the geometry and characteristics of the entire subsoil. The effects of stress path

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were recognized as early as 1948 when Taylor [*1*][2] pointed out the likelihood of being able to obtain the correct strength by reconsolidating soil specimens in the laboratory to the *in situ* pressures. Bozozuk and Leonards [*2*] and Bjerrum [*3*] provided evidence that such reconsolidated specimens do yield more consistent information than unconsolidated ones for estimating soil behavior under the loading condition. Following reconsolidation, shearing along different stress paths produces varying effects on different aspects of soil behavior. The general experience [*4-6*] has been that stress paths do not greatly influence cohesion (c') or the angle of internal friction (ϕ'); on the other hand [*7-9*], they strongly affect the deformational characteristics. Based on the second observation, Lambe [*10,11*] formulated the stress path method for solving deformation problems.

A number of methods have been used for shearing soils under a controlled stress path condition. Some have used the triaxial cell with minor modifications [*12-14*]. Others [*15-17*] have employed a special apparatus designed and built to test certain soil types. The above test equipment, however, permits only one mode of shearing; that is, incremental loading or controlled stress loading. It is not possible to shear soil specimens under a controlled strain rate condition as is required for study of rate effect and the post-peak stress-strain relation for a brittle soil. The equipment described in Ref *16* can impose constant strain rate shearing, but the control of stress path is lost. With computer technology it is now possible to build a system that is capable of controlling the stress path under controlled strain rate conditions in the shearing of soil specimens. Such a system is described herein.

Description of Apparatus

Figure 1 is a schematic diagram of the complete apparatus. Basically it consists of a servo system and a loading cell (triaxial or plane strain). The servo system is composed of two main parts: a minicomputer and an electric-pneumatic (E/P) transducer. Figure 2 shows a plane strain test conducted using the servo system.

Operation Principle

The principle of operation of the servo system can be illustrated by means of a constant strain rate test conducted along the stress path represented by a fourth-degree polynomial:

$$p' = \sum_{n=0}^{4} a_n q^n \qquad (1)$$

[2]The italic numbers in brackets refer to the list of references appended to this paper.

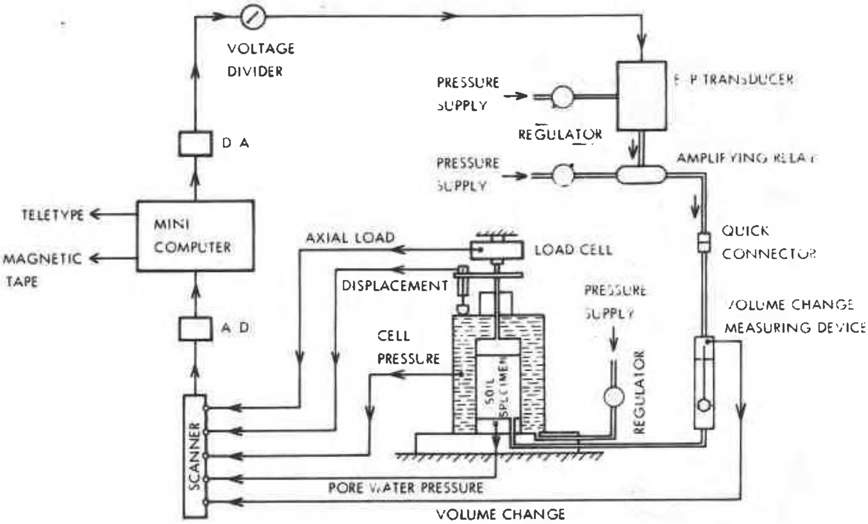


FIG. 1—*Schematic diagram of servo system for controlled stress path tests.*

where the *a*'s are the coefficients of the polynomial;

$$q = (\sigma_v' - \sigma_h')/2 \qquad (2a)$$

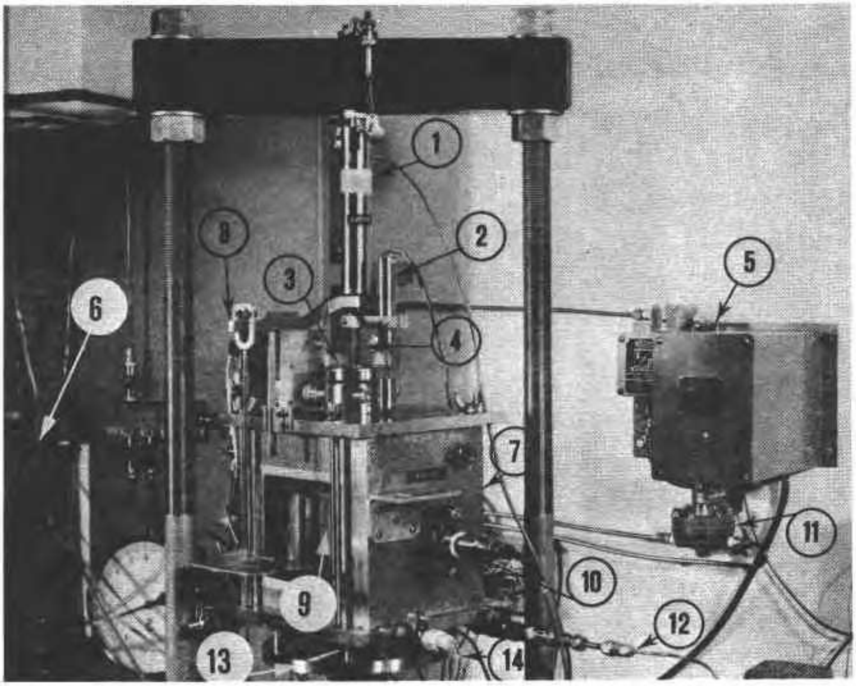
$$p' = (\sigma_v' + \sigma_h')/2 \qquad (2b)$$

and σ_v' and σ_h' are the vertical and horizontal effective stresses.

In a compression test σ_v' and σ_h' are the major and minor effective principal stresses σ_1' and σ_3', respectively; while in an extension test, they are σ_3' and σ_1', respectively. Defining p' and q in terms of σ_v' and σ_h' instead of σ_1' and σ_3' gives a sign convention to q that is positive in compression shearing and negative in extension shearing.

By assigning appropriate values for the coefficients in Eq 1, curved and linear stress paths can be applied to soil specimens. Some examples of compression and extension tests are shown in Table 1.

The application of q on the soil specimen is achieved by straining the soil specimen at a constant rate on the load press. The horizontal effective stress, σ_h', is applied using the servo system in such a way that p' and q closely satisfy Eq 1. In the present test system σ_h' is equal to the difference between the cell and the back pressures. While the cell pressure is kept constant, the back pressure is regulated by the servo system to produce the appropriate σ_h'. This procedure eliminates the need to correct for any load applied to the piston as a result of cell pressure changes. The back pressure regulation will also affect σ_v' ($\sigma_v' = 2q + \sigma_h'$) and hence p', resulting in an actual stress path somewhat different from the prescribed one (Fig. 3). The allowable deviation ϵ be-



1. Load cell 2. Displacement transducer 3. Rotating bushing 4. Piston 5. Electric/pneumatic transducer 6. Volume change transducer 7. Plane strain cell 8. Hanger for anisotropic consolidation 9. Specimen 10. σ_2-transducer 11. Pressure amplifying relay 12. Back-pressure line 13. Load press 14. Cell pressure line

FIG. 2—*A controlled stress path plane strain test.*

tween the stress paths, however, can be reduced to a tolerable value to be given in a later section.

The complete task of regulating $\sigma_h{}'$ in accordance with Eq 1 involves three steps: (*1*) monitoring responses, (*2*) processing data, and (*3*) changing the back pressure.

Response Monitoring

Electrical transducers (Figs. 1 and 2) are used to monitor load, pressure, axial displacement, and volume change during the experiment. These quantities, measured in terms of voltage, are transmitted through an analogue/digital (A/D) converter to the minicomputer for processing. A load cell far more rigid than the soil specimen is used to remove possible problems arising from loading system flexibility, particularly when measuring post-

TABLE 1—*Examples of tests conducted using the servo system.*

NOTE: $*K = \sigma_{ho}'/\sigma_{vo}'$; $1\sigma_{ho}', \sigma_{vo}'$ = horizontal and vertical effective stresses at end of consolidation; $p' = \Sigma_{n=0}^{4} a_n q^n$.

Test				Coefficients				
No.	Type	Stress Path	*K	a_0	a_1	a_2	a_3	a_4
1	triaxial compression	constant p'	>1.0	$\frac{1\sigma_{vo}'}{2}(1 + K)$	0	0	0	0
2	triaxial compression	constant σ_{oct}'	<1.0	$\frac{\sigma_{vo}'}{3}(1 + 2K)$	1/3	0	0	0
3	triaxial compression	constant stress ratio	<1.0	0	$\frac{1 - K}{1 + K}$	0	0	0
4	triaxial extension	constant p'	<1.0	$\frac{\sigma_{vo}'}{2}(1 + K)$	0	0	0	0
5	triaxial extension	constant stress ratio	>1.0	0	$\frac{1 - K}{1 + K}$	0	0	0
6	plane strain	constant p'	>1.0	$\frac{\sigma_{vo}'}{2}(1 + K)$	0	0	0	0
7	plane strain	constant σ_v'	1.0	σ_{vo}'	−1.0	0	0	0
8	plane strain	nonlinear	1.0		all values to be assigned			

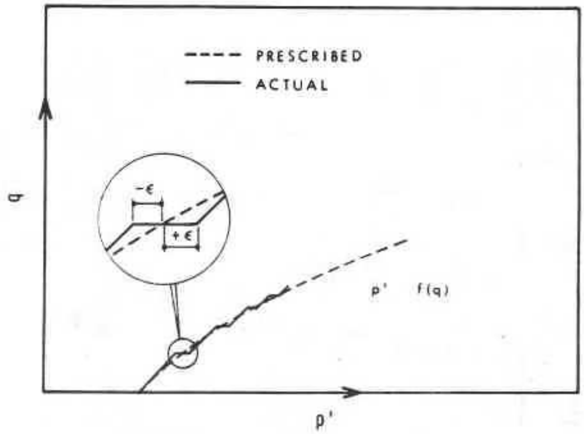


FIG. 3—*Prescribed and actual stress paths in a controlled stress path test under constant strain rate.*

peak behavior. This load cell can take compressive and tensile loads so that both compression and extension tests can be carried out. The cell and back pressures are registered using pressure transducers of the unbonded strain gage type. Both transducers yield values of absolute pressure and the effect of barometric pressure changes is cancelled out because σ_h' is equal to the difference in back and cell pressures. The axial displacement is recorded by means of a direct-current differential transformer (DCDT) transducer, the volume change by a float-displacement instrument as described by Mitchell and Burn [*18*].

Minicomputer

The minicomputer performs two main tasks: (*1*) data acquisition and processing, and (*2*) transmission of a pertinent electrical signal to the E/P transducer. Raw experimental data are accepted at a certain frequency controlled by a variable to be fed into the computer. Engineering quantities such as stress and strain are computed following the standard method [*12*]. Values of p' and q are deduced using Eqs *2a* and *2b*.These engineering quantities are displayed on a teletype or stored on a magnetic tape. Substituting q in Eq 1 yields the theoretical value p_t' required to follow the prescribed stress path. The difference between p' and p_t' is evaluated and compared with the allowable limits $\pm\epsilon$. If the difference exceeds the limits, a numerical increment ξ is added to or subtracted from the current number being sent through the digital/analogue (D/A) converter to the E/P transducer. Consequently, the pressure from the E/P transducer to the back-pressure line will be modified in accordance with the change in the current number. As the checking for deviation from the prescribed stress path and the subsequent pressure modification (if necessary) are done sufficiently frequently, it is not necessary for the E/P transducer to behave linearly. This has proved to be very useful because usual problems such as nonlinearity, hysteresis, or minute drifting in characteristics will impose no effect on the overall performance of the servo system.

Electric-Pneumatic Transducer

The E/P transducer, also shown schematically in Fig. 1, is a device that regulates pressure in proportion to the voltage it receives. A voltage divider is installed between the D/A converter and the E/P transducer to reduce the voltage to an acceptable range. The basic E/P transducer delivers a pressure ranging from 20 to 100 kPa, and for practical purposes a pressure-amplifying relay is used to expand it to 80 to 400 kPa. The basic device and the relay are each supplied by a constant pressure about 30 kPa higher than the respective maximum output pressures. That from the relay is the back pressure supplied to the soil specimen via a quick connector, which facilitates switching the servo system from one shearing apparatus to another.

At present three E/P transducers have been installed. Three controlled stress path tests can therefore be run at the same time, along with seven conventional triaxial or plane strain tests, all linked to the minicomputer.

Operation Frequency and Other Parameters

The operation of the servo system may be performed at a frequency of up to once per second. Between operations, the voltage on the E/P transducer and hence the back pressure remain at the level of the last operation. The minicomputer and the E/P transducer use an a-c power of 105 to 125 V at 50 to 60 Hz, and both are equipped with standby batteries that immediately cut in and maintain operation in the event of power failure.

The frequency of operation, allowable deviation ϵ, and numerical increment ξ (which controls the size of change in $\sigma_h{}'$) are all adjustable, depending on the behavior of the soil specimen during shear. By adjusting them together the prescribed stress path can be closely followed. In testing Leda clay, for instance, the specimen responds relatively rapidly in the early part of the test and the following have been found adequate:

frequency	1 operation/30 s
allowable diviation ϵ	0.25 kPa
size of back pressure change	0.3 kPa

At the later stage of testing the frequency may be reduced to once every 1 to 5 min while the other two parameters remain unchanged.

Test Description and Results

Two test series were conducted: (*1*) to illustrate the capability of the servo system in soil testing, and (*2*) to obtain strength envelopes for stiff Champlain Sea clay for natural slope stability considerations. The majority of tests in the first series were carried out along linear stress paths, although curved ones were also possible by assigning appropriate values to the coefficients of the polynomial (Eq 1).

All specimens were trimmed from 127-mm-diameter Osterberg samples and were enclosed in thin Ramses rubber membranes; all were 80 mm high and 36 mm in diameter for triaxial tests, and 36 by 36 mm in cross section for plane strain tests. Side drains were provided and a strain rate of 3.5 percent axial strain per day (calculated by the method of Bishop and Henkel [*12*]) was used to allow adequate pore pressure equalization within the specimen.

A Geonor triaxial cell with a rotating bushing to reduce piston friction was employed in the triaxial compression and extension tests. Specimen preparation and mounting were identical to preparation for an ordinary triaxial test. No cell modification was required in the compression tests, but some accessories were made for the extension tests.

The arrangement for triaxial extension tests is shown schematically in Fig. 4. Fastened to the piston is a circular plate on which weights are placed to balance the cell pressure acting on the piston. The piston is screwed to the top stainless steel loading platen for application of pulling force. After consolidation, a coupling is mounted to connect the load cell to the piston, and shear can be started by lowering the load press at a constant rate. The coupling is designed to allow for possible small misalignment between the piston and the load cell. A correction of 0.75 kg is made in the data processing to account for the top platen weight and extension of the rubber membrane.

The cell for performing plane strain tests has been described in detail by Bozozuk [*19*]. It is similar in principle to the triaxial cell except that provisions are made to maintain zero strain in the intermediate principal stress direction. This is done by mounting in the cell two side blocks that can be brought into contact with the specimen. Load cells are installed at the end of the blocks for measuring the intermediate principal stress during the test. Again, anisotropic consolidation can be applied, but only plane strain compression tests are possible.

Anisotropic consolidation can be applied by different methods (Fig. 5). For vertical consolidation pressure exceeding the horizontal, the standard Geonor hanger system (Fig. 5A) may be used, but it requires frequent adjustments to keep the arm of the hanger level. It is simpler to put appropriate weights on the piston (Fig. 5B) in addition to those for balancing cell pressure. For horizontal pressure greater than the vertical, the position of the Geonor hanger system is modified (Fig. 5C) so that a pulling force can be in-

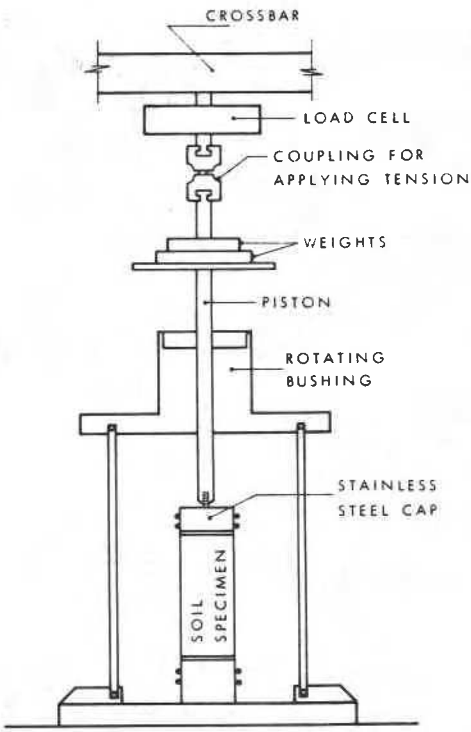


FIG. 4—*Arrangement for triaxial extension tests.*

troduced to the piston. This method again necessitates frequent adjustment of the hanger arm. A simpler method is to take away appropriate weights from the pistons (Fig. 5D) already in use for balancing cell pressure. (It should be noted that there is one advantage in using the hanger system: larger loads can be more easily applied because of the moment arm ratio.)

The tests in the first series for illustrating the capability of the servo system are summarized in Table 1, and the corresponding stress paths are shown in Fig. 6. Except for Test 8, all tests were conducted on a stiff, fissured, and brittle Champlain Sea clay from Rockcliffe, Ottawa, Canada. Its moisture content ranged from 65 to 70 percent; other detailed characteristics have been given by Mitchell [*20*]. In Tests 1, 4, and 6, the consolidation ratio K of the horizontal to vertical consolidation pressures was assigned a value greater or less than 1.0, with a subsequent shearing across the p'-axis. This resulted in a reversal of shear stress direction or a 90-deg rotation in principal stress. Anisotropic behavior can be studied and it is possible to simulate, in the laboratory, the stress paths corresponding to situations such as building embankments on soft clays and cutting slopes in stiff clays.

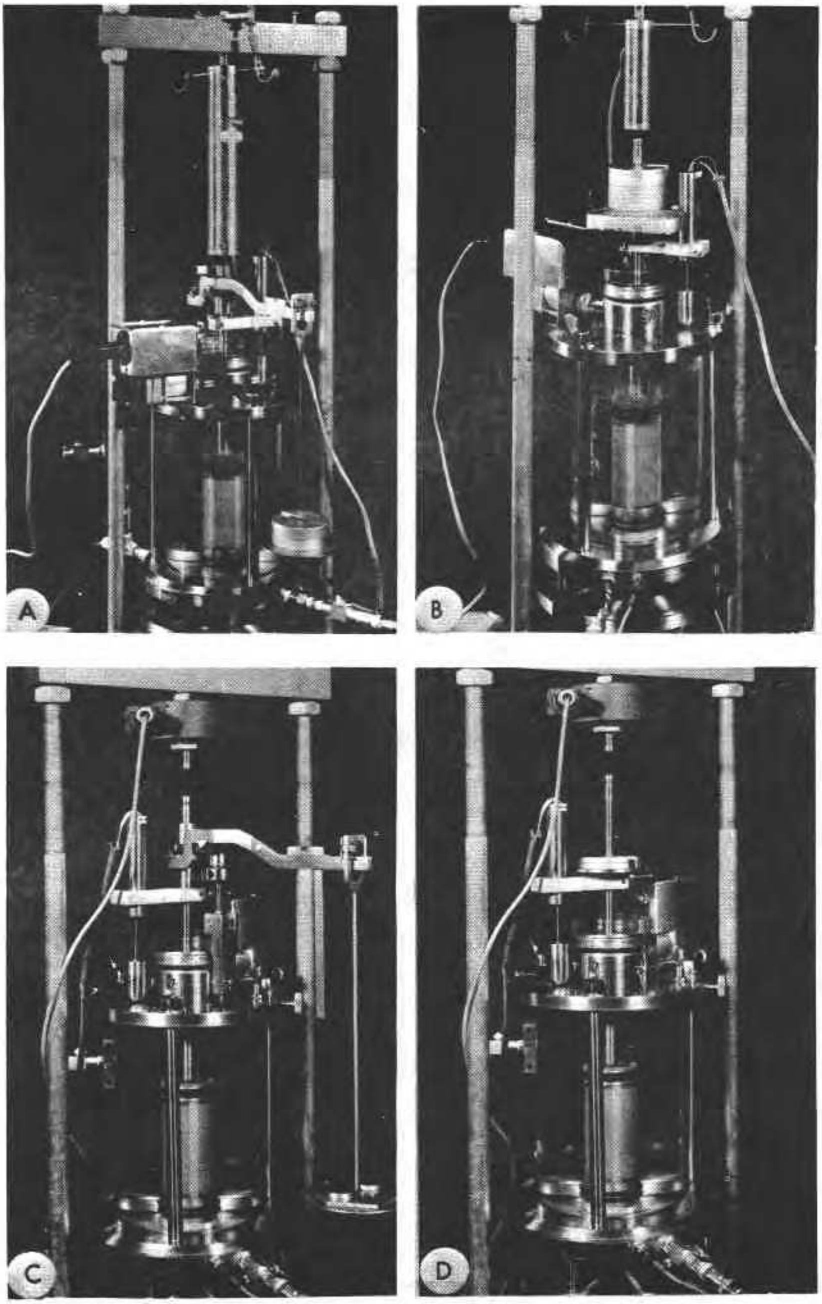


FIG. 5—*Methods of applying anisotropic consolidation pressures.*

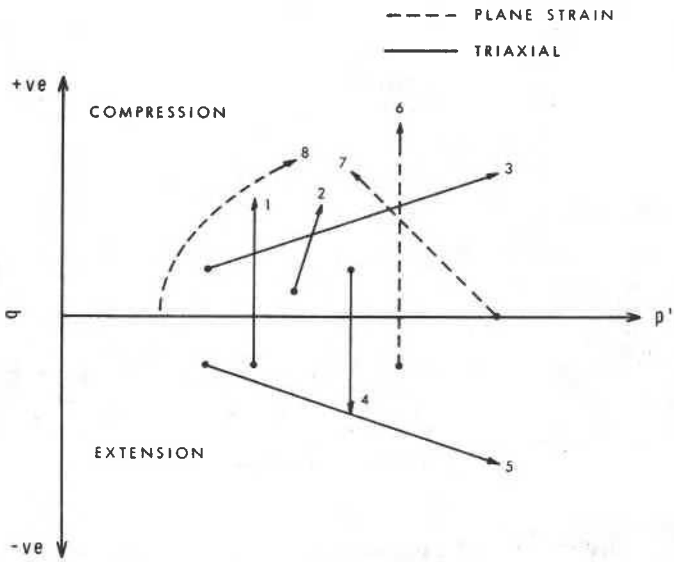


FIG. 6—*Examples of stress paths conducted by means of the servo system.*

Test 7 is a plane strain test with the vertical stress held constant. It is applicable to a long vertical cut, either standing freely or supported by a retaining structure that allows the active pressure to develop.

Test 2 is a constant σ_{oct}' compression test; Tests 3 and 4 are constant stress ratio tests in both the compression and extension stress space. All are useful for studying the fundamental behavior of the clay.

Typical p'-q plots for triaxial and plane strain tests (Tests 5 and 6) are shown in Fig. 7. They are computer plots showing the entire stress path realized during the tests. Deviation from the prescribed stress path is negligible so that the objective of controlling the stress path is achieved. The same is also true of all the other tests listed in Table 1.

Test 8 involved a nonlinear stress path and was performed on an undisturbed, soft, sensitive marine clay (its properties have been given by Bozozuk and Leonards [*2*]). This test was designed for studying the *in situ* behavior of clay subjected to a self-boring pressuremeter test, as described by Eden and Law [*21*]. The nonlinear stress path (Fig. 8) was deduced from the *in situ* test for the soil at the pressuremeter-soil interface, where the strains, radial pressures, and pore pressures were monitored by means of electronic transducers. In the laboratory the soil specimen was trimmed horizontally and mounted in the cell in such a way that plane strain condition was maintained in the original *in situ* vertical direction, as was true also in the pressuremeter test. After consolidation, appropriate values were assigned to the coefficients

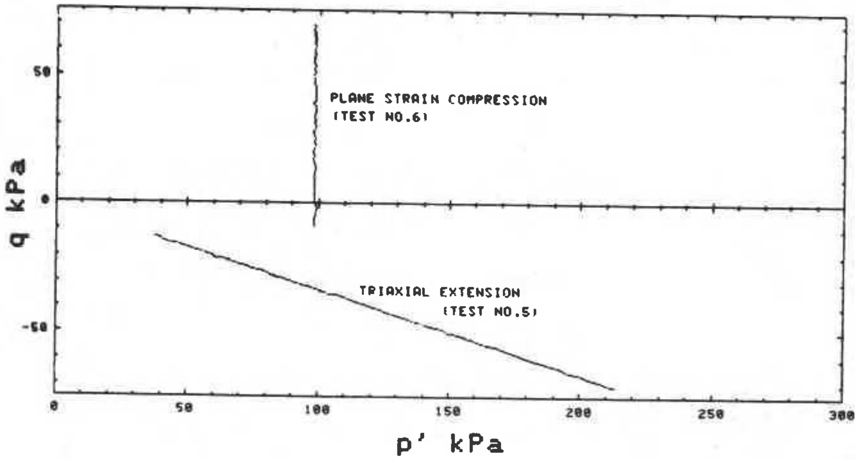


FIG. 7—*Typical stress paths during tests.*

in Eq 1, causing the subsequent shear to follow the nonlinear stress patn (Fig. 8). Figure 9 shows the stress-strain and volume change-strain curves for the laboratory test (Test 8). A significant volume change was found to take place. Although it is not possible to measure volume change during a pressuremeter test, the laboratory test indicates that shearing along the observed effective stress path involved some drainage. This is in contrast with the usual assumption of undrained shear for this *in situ* test. The deduced pressuremeter strength will therefore be generally higher than the undrained strength and will yield an unsafe design if used directly for some engineering applications.

The second test series was also carried out on Rockcliffe clay. Plane strain and triaxial tests were conducted in a relatively low stress range, in which most natural slope failures occur. Various stress paths were used to simulate those possible in the field [22]. All specimens were sheared to a large strain (about 8 percent) for observing post-peak behavior.

Typical stress-strain and volume change-strain curves for triaxial and plane strain tests conducted at constant p' are shown in Fig. 10. Dilatancy exists around the peak strength, which is followed by a drop to post-peak strength. The peak and post-peak values for all the tests are presented on a p'-q plot in Fig. 11. Two distinct strength envelopes can be obtained, one for peak and the other for post-peak. They do not appear to depend on the stress paths or on the mode of straining, plane strain, or axisymmetric strain. For natural slope stability considerations they can be characterized by

$$\phi_f' = 48 \text{ deg}, c_f' = 5.5 \text{ kPa}$$

$$\phi_r' = 40 \text{ deg}, c_r' = 0 \text{ kPa}$$

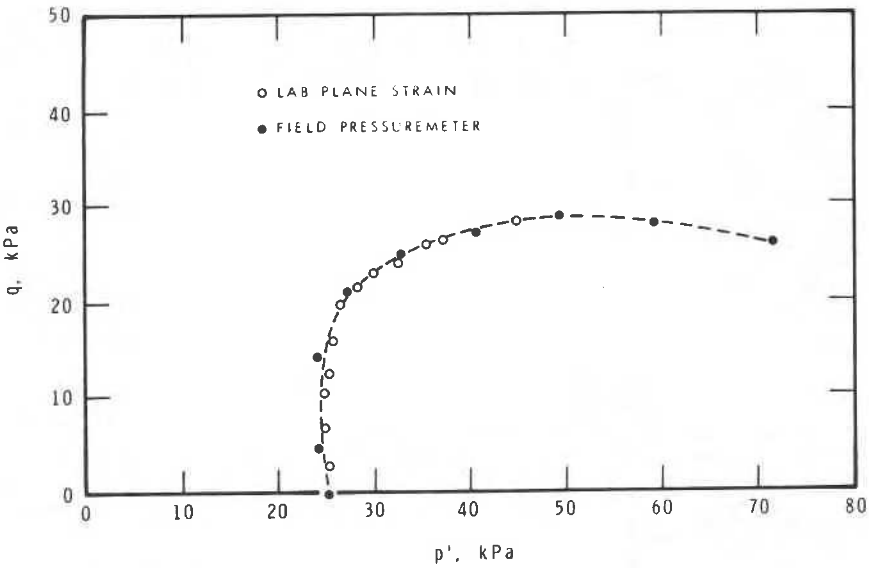


FIG. 8—*Effective stress paths for laboratory and field pressuremeter tests.*

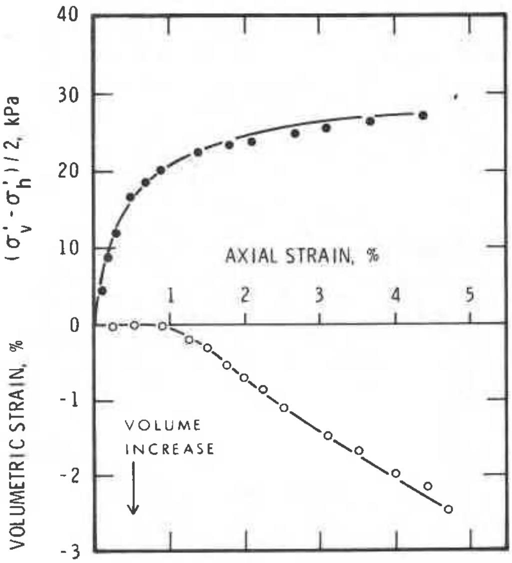


FIG. 9—*Shear stress-axial strain and volumetric strain-axial strain relations during curved stress path test under plane strain condition.*

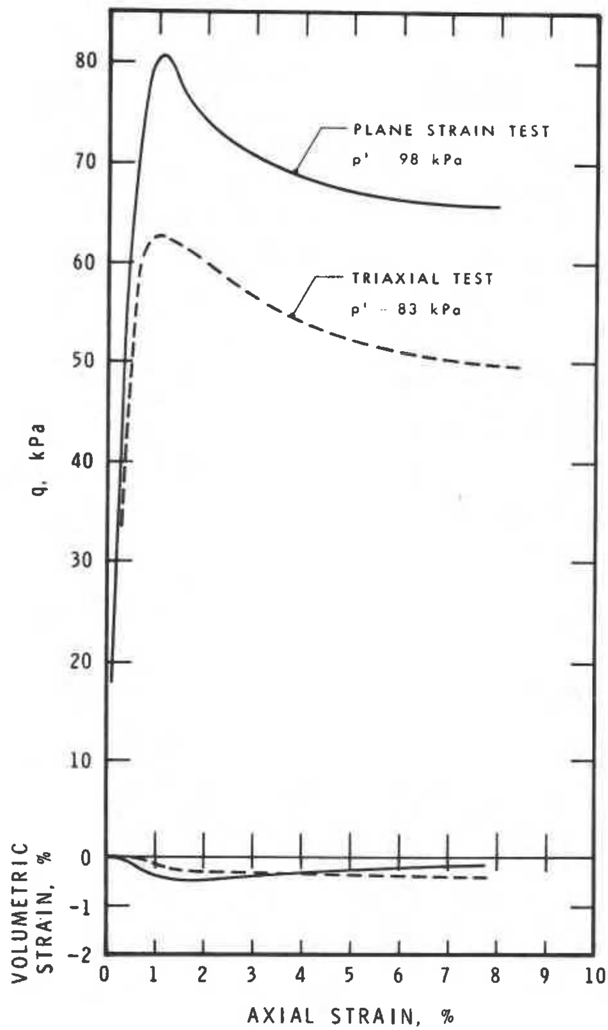


FIG. 10—*Typical stress-strain and volume change-strain curves.*

where ϕ' and c' are the angle of internal friction and cohesion in terms of effective stresses, respectively; and subscripts f and r refer to peak and post-peak stages.

Summary and Conclusions

A description is given of a servo system for shearing soil specimens along linear or curved effective stress paths, as defined by a fourth-degree polyno-

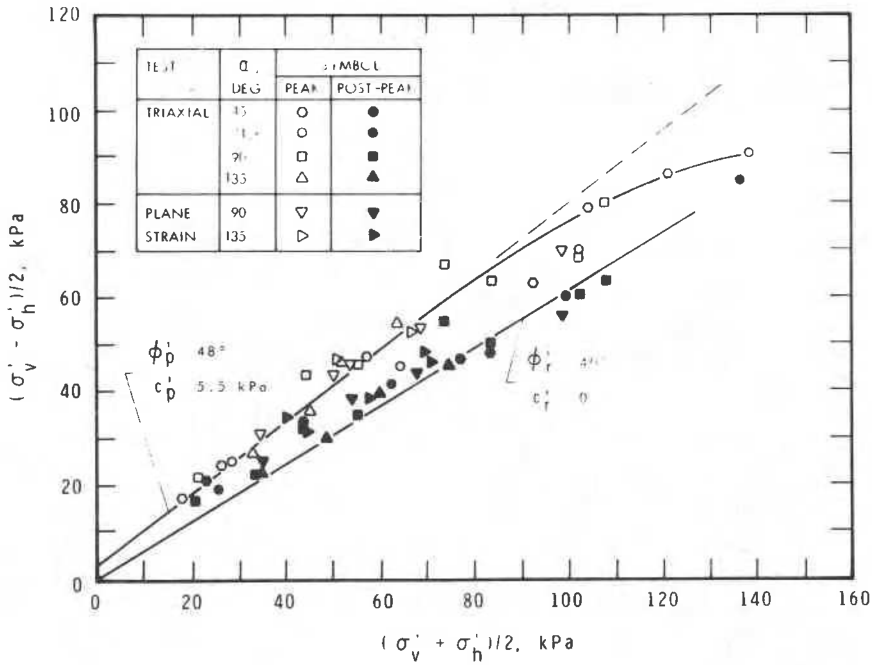


FIG. 11—*Summary of test results of Rockcliffe clay.*

mial. The servo system comprises a minicomputer and an electric-pneumatic transducer. It can be conveniently connected to the conventional triaxial and plane strain cells in such a way that compression and extension tests can be performed at constant strain rate under the axisymmetric or plane strain mode of straining. Tests on a stiff Champlain Sea clay yielded the following observations:

1. The stress paths realized closely followed the given paths.
2. The post-peak stress-strain relation was determined for this brittle clay along various stress paths.
3. Peak and post-peak strength envelopes were obtained for natural slope stability considerations. These envelopes are independent of stress paths and modes of straining.

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