

A SIMPLE  $K_0$  TRIAXIAL CELL

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R. G. Campanella and Y. P. Vaid

Department of Civil Engineering, The University of British  
Columbia, Vancouver, B.C.

PREPRINT

to be Published

Canadian Geotechnical Journal, Vol. 9, No. 3,  
August 1972.

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Dept. of Civil Engineering, The University of British Columbia,  
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## ABSTRACT

The need to reproduce the same stress path in the laboratory as in the field is emphasized - especially for initial consolidation which in most cases is under  $K_0$  conditions. A simplified  $K_0$  triaxial cell is described which permits initial  $K_0$  consolidation without any adjustments. A loading system is described which permits a variety of stress paths during shear (either passive or active, compression or extension, by strain control or stress control loading, under drained or undrained conditions).

The ease of sample preparation and test procedure are pointed out and characteristics of the new apparatus are described. Typical data is presented during both consolidation and loading under all possible stress paths which demonstrates the consistency of results, the flexibility of the new apparatus, and the variation in soil behaviour as a function of stress path.

## INTRODUCTION

Isotropic stress conditions are almost always used in routine triaxial testing of soils. In the ground, however, sedimentary clay strata have most likely been consolidated under conditions of no lateral strain ( $K_0$  - consolidation). Thus, in order to understand and correlate field behaviour of natural deposits, it is necessary to study laboratory samples which have been consolidated under the same conditions, i.e.  $K_0$  - consolidation.

The behaviour of clays consolidated under  $K_0$ -condition has not been studied as extensively as those of clays consolidated isotropically. One of the main reasons contributing to this appears to be the generally complicated procedures and apparent long times required to affect  $K_0$ -consolidation. Furthermore, much of the emphasis has usually centred on determination of angle of shearing resistance which, in many clays, has been found relatively insensitive to the type of consolidation (Simons 1960, 1963, Skempton and Sowa 1963, Ladd 1965). However, the stress-strain behaviour of a  $K_0$ -consolidated clay is very different from the behaviour of the same clay consolidated isotropically (Skempton and Sowa 1963, Ladd 1965). For example, for the Haney clay reported herein the peak deviator stress in undrained tests occurs at about 3% axial compression for initial isotropic consolidation as opposed to about 0.3% for  $K_0$  - consolidation. Therefore, in practical problems dealing with natural clays where deformations are of major concern laboratory consolidation to in-situ  $K_0$  - stresses is a first requirement if any meaningful stress-strain data

is desired.

In this paper a new type of triaxial apparatus is described which permits  $K_0$ -consolidation with the same simplicity and speed as isotropic consolidation. In addition, the apparatus has the important capability of being used as a one dimensional oedometer which is free of side friction problems and allows lateral stress measurements, thus providing information on  $K_0$  values. A special type of loading system is used, which makes possible strain controlled tests in which a monotonic decrease or increase of cell pressure is involved.

#### CURRENT METHODS OF $K_0$ -CONSOLIDATION

The most common method of consolidation under conditions of no lateral yield consists of a slow increase in cell pressure accompanied by an interrupted application of axial load (Bishop and Henkel 1962). A lateral displacement sensing device is used around the sample which actuates the axial loading mechanism when lateral deformation tends to occur. An automatic pneumatic procedure for  $K_0$ -consolidation has also been described by Saada (1970). His method operates on the principle that the ratio of water expelled from the sample to its vertical deformation equals the initial cross sectional area. Both these methods are rather complicated and usually require excessively long consolidation

times. For the range of stresses commonly used in triaxial testing of clays, consolidation times extending to 2 weeks are not uncommon.

## NEW APPARATUS

### Concept.

The condition of no lateral strain during consolidation is developed in the new apparatus by both preventing any volume change in the cell-water system surrounding the sample and by using an axial loading ram of the same area as the sample. Of course this technique only works on saturated samples. Thus, when the loads are applied and pore water drainage lines opened the sample volume will change only if the sample height changes. An essential requirement of this method is an extremely low compliance cell-water system, thus, minimising any lateral strain due to expansion of the system when a pressure change occurs during the progress of consolidation.

### Considerations governing design.

Some of the desirable features in a triaxial apparatus are outlined below. All of these features were incorporated in the apparatus described herein.

- (i) Frictionless seal - When the applied axial load is measured outside the triaxial cell, the provision of a frictionless seal on the

loading ram is a very desirable requirement. What appears to be a relatively small amount of ram friction can result in considerable error in the determination of angle of shearing resistance  $\phi'$ , particularly during extension shear. The axial stress during such a test is the minor principal stress and a small error in its estimate can cause a large error in the principal stress ratio  $\sigma_1/\sigma_3$  and hence in  $\phi'$ .

- (ii) Double drainage - This provides flexibility in consolidation and drained shear by either permitting drainage from both ends or drainage from one end and pore pressure measurements at the other. The latter technique for drained shear helps to make certain that excess pore pressure at failure are essentially zero and, in strain controlled consolidation tests provides data to evaluate the permeability and compressibility of the soil.
- (iii) Flexibility of operation - The apparatus should be suited to consolidate samples isotropically or under  $K_0$ -condition in about the same time duration. This is an essential requirement when the behaviour of isotropically and  $K_0$ -consolidated samples is to be compared, as it eliminates possible ageing effects in  $K_0$ -consolidated samples associated with much longer consolidation times required by existing techniques (Bjerrum and Lo 1963).

It should be possible to induce failure of the sample under any desired stress path possible in the triaxial apparatus, using either stress controlled or strain controlled loading. In the

conventional apparatus it has not been possible to load samples in active compression (axial stress held constant, cell pressure decreased) using strain controlled loading, even though this stress path is representative of many field problems. Strain controlled loading is mandatory when post peak strength information is required.

#### Description of main components.

Fig. 1 shows the apparatus, with all essential details. Except for the loading head and frictionless seal the remaining components are similar to those in a conventional triaxial cell. The cylinder is machined from heavy wall stainless steel pipe in order to keep the compliance of the cell-water system to a minimum. The loading ram is guided in its vertical motion by a pair of super precision stainless steel linear Thompson Ball Bushings and is sealed to the head by means of a rolling diaphragm (called a Bellofram) having an effective area equal to the area of the sample. An essentially frictionless vertical movement of the ram is obtained as the flexible Bellofram simply rolls on or off the inner periphery of the head. The friction in the guide bushings is negligible unless lateral loading becomes excessive.

Measurements of total friction through the loading ram gave a maximum recorded value of 50 gm and an average value of the order of 25 gm. The friction measurements were independent of cell pressure

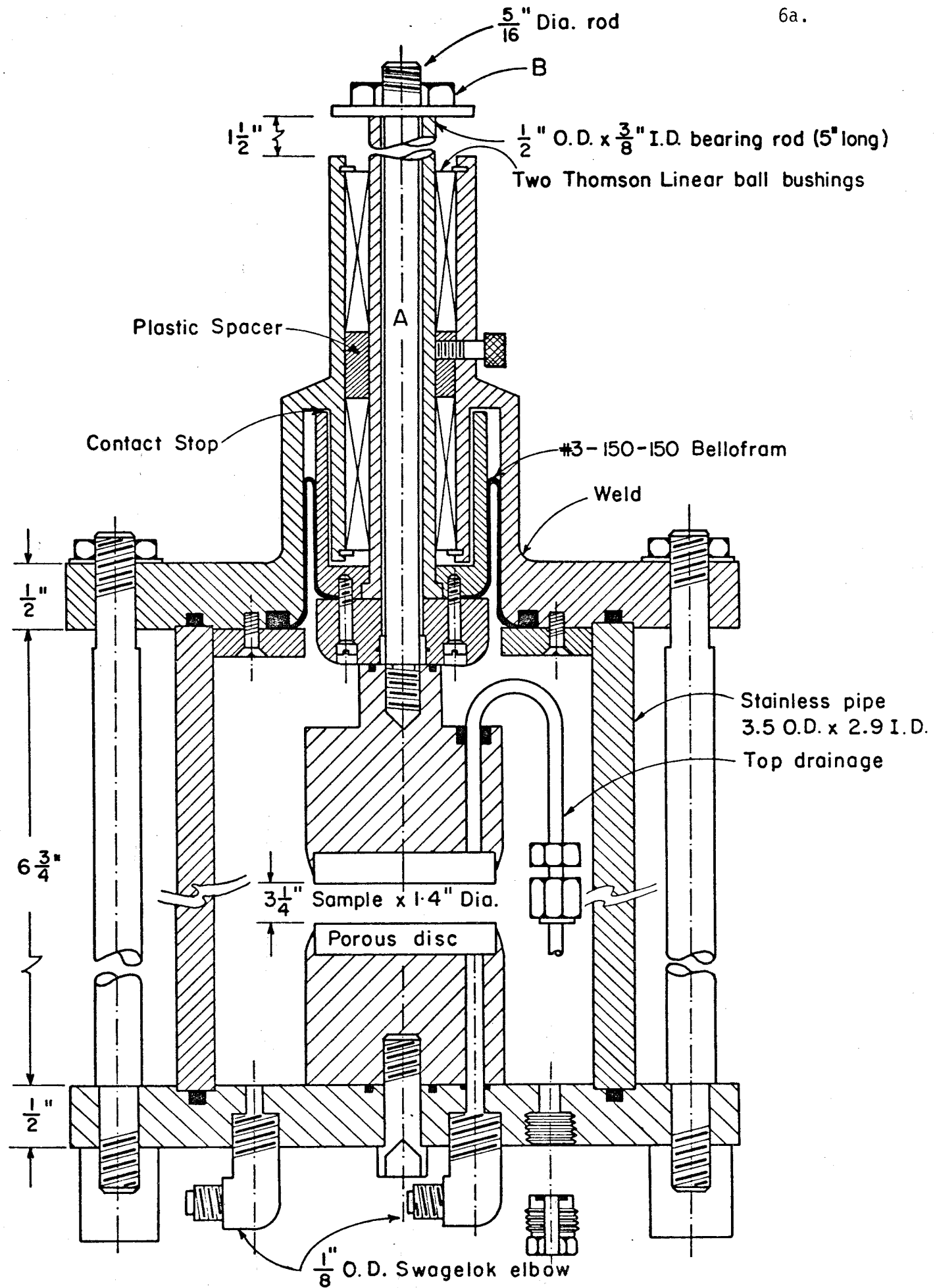


Fig.1.  $K_0$  - TRIAXIAL APPARATUS

over a test range from 1 to 6 kg/cm<sup>2</sup> for the Bellofram in two different locations. A total friction error of 50 gm is indeed negligible since it gives an error in axial stress of only 0.005 kg/cm<sup>2</sup> for a 1.4 in. dia. sample.

A schematic layout of the load, pressure, displacement and volume change measuring system is shown in Fig. 2. The vertical load is applied through a rolling diaphragm double acting piston which is completely saturated with water. Each side of the piston is connected to the saturated displacement plunger and also to the air pressure supply. All air pressures are controlled by precision regulators which have a measured accuracy of  $\pm 1/2$  in. of water. Similarly, the cell-water system is connected to an air pressure supply and to the same displacement plunger. All lines are 1/8" dia. copper tubing and all valves are Whitey non-displacement ball valves. A constant load is applied to the sample, eg. during one increment consolidation, by applying a pressure to the top side of the Bellofram piston through the regulated air pressure applied to the reservoir, while the water pressure on the bottom side of the piston is a constant small value maintained by the plastic reservoir. The displacement plunger is activated by the strain drive made up of a Canadian Duff-Norton miniature jactuator (1000 revolutions for 1 in. travel, capacity 1000 lbs.) and Motomatic variable drive which provides a constant torque over the electrically adjustable range of about 1.5 rpm to 0.0006 rpm.

A constant strain rate compression loading is obtained when the displacement plunger pushes water into the top side of the loading

**LEGEND :**

⊗ Whitey Ball Valve

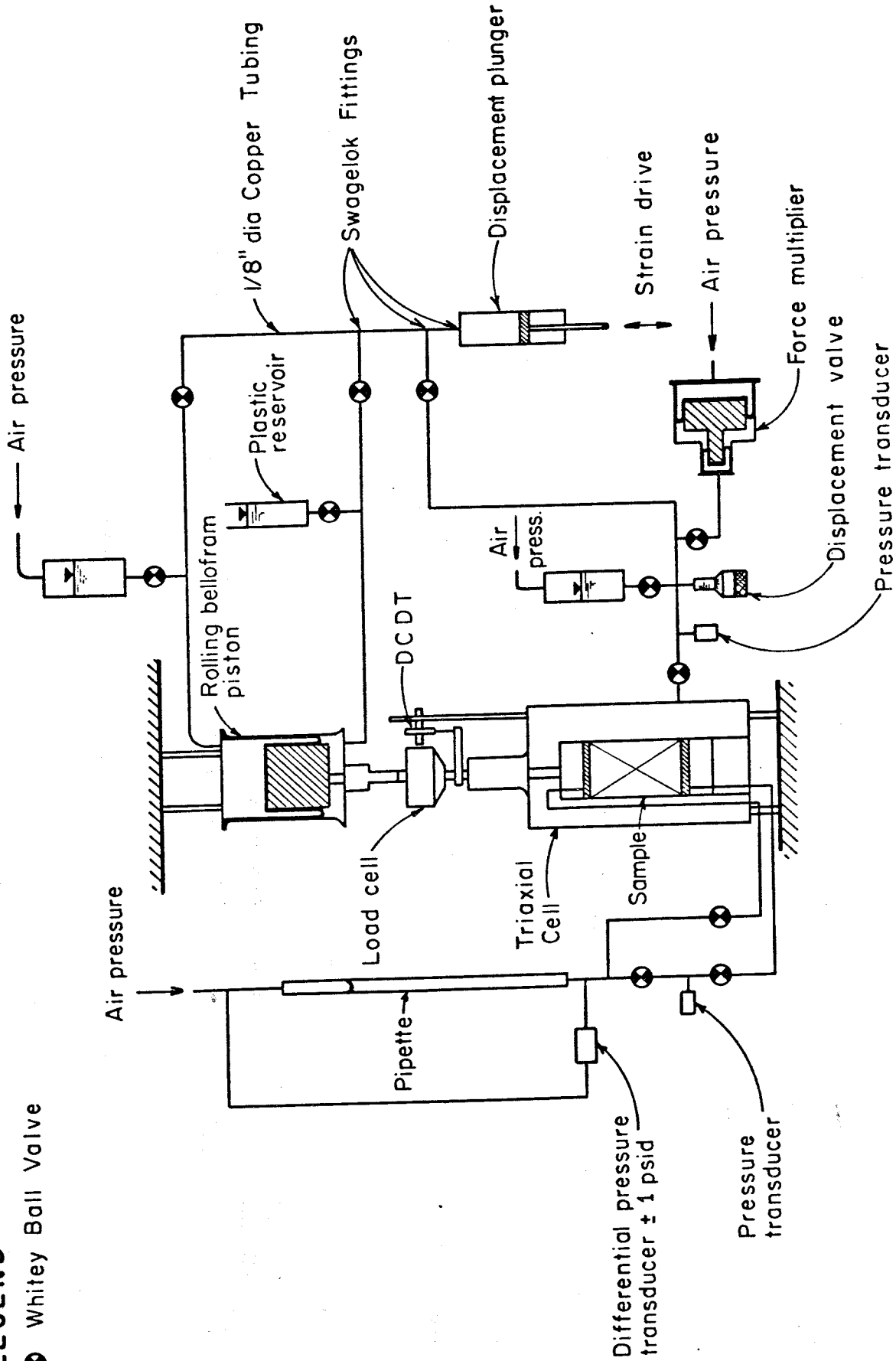


Fig.2. SCHEMATIC LAYOUT OF LOADING, DISPLACEMENT, VOLUME CHANGE AND PRESSURE MEASURING SYSTEM.

piston at a constant rate while the bottom side freely drains. An extension test is obtained by keeping the top side of the loading piston at the constant pressure used for consolidation while the plunger is used to push water at a constant rate into the bottom side of the loading piston which reduces the load on the sample.

A constant lateral pressure can be applied to the sample through the cell water during axial loading or unloading. During  $K_0$ -consolidation the cell water is undrained and lateral pressures measured by the pressure transducer. A constant strain rate extension test (increasing lateral pressure) can be run by maintaining a constant axial load and pushing water at a constant rate into the cell with the displacement plunger. On the other hand a compression test (decreasing lateral pressure) can be run by maintaining a constant axial load and withdrawing water from the cell with the same displacement plunger. The force multiplier, a piston 'floating' between two rolling Belloframs of different areas, is used to safely generate constant cell pressures in excess of line pressure. Since the area ratio used was 6:1, an air pressure of 100 psi can generate water pressures of 600 psi. The displacement valve in the cell-water system can be used to make external adjustments to correct for the compliance of the system, if desired.

The pore water drainage system which is made up of heavy wall 1/8 in. dia. Saran tubing and non-displacement valves has a specially formed

Saran spiral for the top drainage. The Saran has a very low compliance and essentially nil water absorption characteristics. The pore water system allows for drainage from both ends or drainage from the top with pore pressure measurements at the bottom of the sample along with back pressure provisions. The pore water drainage is measured by the differential pressure transducer which monitors the height of water in the pipette. The differential pressure transducer had a full scale output of 2 ft. of differential head at line pressures in excess of 100 psi.

Because of the very low compliance of not only the pore pressure measuring system but also the cell-water and constant rate of strain loading systems, it is necessary to have all equipment in a carefully controlled constant temperature environment. The present temperature control is considerably better than the recommended maximum variation of  $\pm 1^{\circ}\text{F}$  (Campanella and Mitchell 1968).

Measurement of all quantities, including volume changes, is done by means of electronic pressure transducers, load cells and differential transformers. The signals from these measuring devices are fed into a Vidar Digital Data System in which data is acquired on digital magnetic tape at preselected intervals. Data reduction is performed by a computer using the magnetic tape as the input file. Once the shear test is started no more attention is required until the end of the test.

## EXPERIMENTAL PROCEDURE

Installing samples.

Three water reservoirs and valves are temporarily attached to the tie down rods on the cell in order to facilitate saturation of the cell water, bottom drainage and top drainage lines during sample installation.

The soil sample is wrapped in two rubber membranes separated by silicon grease and independently sealed to the bottom pedestal and top cap by means of O-rings. This part of the procedure is similar to that in conventional triaxial testing. The rod A of the loading ram (Fig. 1) is then screwed into the top cap for  $K_0$ -consolidation. If isotropic consolidation is desired, a different sample cap and loading rod are used in which the rod is not screwed to the cap but sits with its rounded end seated in the cap.

The remaining assembly procedures are performed under water in order to prevent any air from getting trapped in the cell-water system. When under water, the stainless steel cylinder is first positioned around the sample. After all the air has been removed from the loop of the Bellofram seal, the head is carefully slipped around rod A until the top plate sits on the cylinder. For  $K_0$  tests the sample cap is clamped to the loading ram by tightening nut B (Fig. 1), while holding rod A against rotation by using a hex socket seat at the end of rod A in order to avoid twisting the sample and Bellofram. Finally, the head, cylinder and the

base are sealed together by tightening the nuts on the upright rods and removing the assembly from the water bath. After positioning the apparatus on the loading platform, a small seating hydrostatic stress is applied to the sample while undrained before cell and pore pressure connections are made. After all connections are made and the sample pore water drainage lines are closed, the cell pressure and axial stress are increased to 100 psi and left overnight. This method effectively dissolves any small volumes of entrapped air in either the cell-water or pore water system. Before shear testing, the saturation is checked by measuring the system response. For example, simultaneously increasing the lateral (cell pressure) and axial pressure by the same amount, and measuring the change in the undrained pore water pressure allows one to calculate the B-value.

#### Consolidation.

Consolidation can be performed in one or several load increments or under strain controlled loading. For  $K_0$ -consolidation in one increment, the sample is first loaded undrained with the same vertical and lateral stress which are equal to the consolidation vertical effective stress plus back pressure. Pore water drainage is then permitted against the back pressure while the cell-water system is maintained at constant volume. For  $K_0$ -consolidation under strain controlled loading, a vertical and lateral stress equal to the desired back pressure is applied to the undrained sample. Strain controlled loading is then commenced while the volume of water in the cell is held constant, and pore water drainage is

permitted only from the top of the sample. Excess pore pressure, if any, is measured at the bottom. Strain rates employed should be slow so as not to generate high excess pore pressures at the base. The loading is continued until the desired vertical consolidation stress is reached.

Isotropic consolidation in a single increment is performed as in a conventional triaxial cell. Isotropic consolidation under strain controlled loading is achieved by forcing water at a constant rate into the cell. The sample is drained at one end and pore pressures are measured at the other end. Just as in the case of  $K_0$ -consolidation, strain rates should be slow so that large excess pore pressures are not generated at the undrained end.

#### Shear Testing.

Following  $K_0$ -consolidation, shearing of samples can be achieved under a variety of stress paths. The following stress paths may be easily followed in the apparatus:

1. Passive compression - the conventional compression test in which the axial stress is increased while the cell pressure or lateral stress is maintained constant.

2. Active compression - compression test in which the cell pressure is decreased while the axial stress is maintained constant.
3. Passive Extension - extension test in which the cell pressure is increased while the axial stress is maintained constant.
4. Active Extension - extension test in which the axial stress is decreased while the cell pressure is maintained constant.

Both stress and strain controlled loadings can be simulated to perform compression and extension tests. In stress controlled tests, stresses are increased or decreased in discrete steps by regulating either the cell pressure or pressure in the loading piston until failure occurs under the selected loading path. Strain controlled tests are performed by forcing water at a constant rate into the axial loading piston or into or out of the cell chamber.

It is necessary to point out here that during shear loading, any changes in the initial cross sectional area of the sample requires that a correction be calculated for the applied load in order to compute the axial stress. This arises from the fact that the initial area of the sample and loading piston were the same. Thus, the new axial load would be either the applied load plus the product of the change in the initial area and the current cell pressure for compression tests or the applied load minus the product of the change in area and the current cell pressure for extension tests.

## CHARACTERISTICS OF THE APPARATUS

A one dimensional Oedometer

In addition to performing triaxial shear tests, the apparatus has the important capability of being used as a frictionless, one dimensional Oedometer in which simultaneous measurements of  $K_0$  are obtained. For consolidation testing only, shorter samples can be accommodated by merely using a shorter chamber cell. The use of samples larger than 1.4 in. dia. necessitates a larger effective area Bellofram and a redesign of the entire apparatus. A 2 1/2 in. dia.  $K_0$  triaxial apparatus is presently being built primarily for consolidation testing.

Strain controlled consolidation is particularly attractive as it furnishes a continuous spectrum of  $K_0$ -values and other consolidation properties, like permeability and compressibility (Wissa et al 1971, Vaid and Campanella 1972, Byrne 1970, Smith and Wahls 1969). In addition, it is a simple matter to simulate loading and unloading cycles in order to study the variation of these properties with consolidation history.

When  $K_0$ -consolidating by either the incremental or strain controlled technique, the small but finite compliance of the lateral pressure system results in a slight departure from conditions of absolutely zero lateral strain. During strain controlled consolidation, the expansion of the cell due to continuously increasing pressure permits a very small extensional lateral strain. On the other hand, during  $K_0$ -

consolidation in one increment the cell pressure decreases from its initial value and consequent contraction of the cell results in a very small compressive lateral strain. It may therefore, be argued that lateral pressures measured may not be consistent with the pressures which would have been generated under truly one-dimensional strain. However, it can be shown that a small compliance of the cell-water system does not cause any significant error in the measured  $K_0$  value for most normally consolidated clays. The error involved in case of overconsolidated clays may be significant only if its compressibility gets very small. For example, assume a clay sample is in equilibrium under vertical, and horizontal effective stresses of  $\sigma'_V$  and  $K_0 \sigma'_V$  respectively. Let

$V$  = volume of sample in c.c.

$c$  = compliance of the cell-water system in c.c./kg/cm<sup>2</sup>

$m_v$  = compressibility of clay with respect to changes in mean normal effective stress,  $\sigma'_m$ , under essentially  $K_0$ -conditions.

$\Delta \sigma'_V$  = increment in vertical stress under fully drained conditions.

Then if  $c = 0$  i.e. for the case of an infinitely stiff lateral pressure system, the increase in horizontal stress

$$[1] \quad \Delta \sigma'_h = K_0 \Delta \sigma'_V$$

Since  $c \neq 0$ , the actual increase in horizontal stress will not

equal  $K_0 \Delta \sigma'_V$  but  $\Delta p'$ , where

$$\Delta p' < K_0 \Delta \sigma'_V$$

Change in volume of the sample then is

$$[2] \quad \Delta V_1 = m_v V \frac{1}{3} (\Delta \sigma'_V + 2\Delta p')$$

Expansion of the lateral pressure system is

$$[3] \quad \Delta V_2 = c \Delta p'$$

In comparison, the change in volume of a sample in the presence of a  $c = 0$  lateral pressure system is

$$[4] \quad \Delta V_3 = m_v V \frac{1}{3} (\Delta \sigma'_V + 2K_0 \Delta \sigma'_V)$$

Then, the deficiency in volume change,  $\Delta V_3 - \Delta V_1$ , equals the expansion of the cell-water system,  $\Delta V_2$ , i.e.

$$[5] \quad c \Delta p' = \frac{2}{3} m_v V (K_0 \Delta \sigma'_V - \Delta p')$$

which yields

$$[6] \quad \Delta p' = K_0 \Delta \sigma'_V \eta$$

where

$$[7] \quad \eta = \frac{1}{1 + \frac{1.5}{V} \frac{c}{m_v}}$$

The ratio of lateral to vertical effective stresses after the stress

increment  $\Delta\sigma'_V$  is

$$[8] \quad (K_0)_m = \frac{K_0 \sigma'_V + \Delta p'}{\sigma'_V + \Delta\sigma'_V} = K_0 \frac{\sigma'_V + \eta \Delta\sigma'_V}{\sigma'_V + \Delta\sigma'_V}$$

where  $(K_0)_m$  denotes the measured value of  $K_0$ . Eq.[8] shows that the error in measured  $K_0$ , for a given  $\Delta\sigma'_V$ , depends on the current value of vertical effective stress,  $\sigma'_V$ , and on  $\eta$  which is a function of the ratio of the compliance of the apparatus to the compressibility of the soil. The magnitude of  $\eta$  is less than unity when  $c \neq 0$ . During normal consolidation,  $\Delta\sigma'_V$  is positive, which results in  $(K_0)_m < K_0$ . However, during rebound  $\Delta\sigma'_V$  is negative and, therefore,  $(K_0)_m > K_0$ .

As an example, the magnitude of error involved in measurements of  $K_0$  can be demonstrated by considering one dimensional virgin consolidation, during which  $K_0$  is known to be constant. If the clay is consolidated from a slurry (i.e. initial effective stresses are essentially zero) to a vertical effective stress of  $\sigma'_1$ , the magnitude of horizontal effective stress can be found by summation of Eq.[6], i.e.

$$[9] \quad p' = K_0 \int_0^{\sigma'_1} d\sigma'_V \eta$$

In the apparatus described  $c = 0.06 \text{ cc/kg/cm}^2$  and considering the case of a triaxial sample (1.4 in. dia. x 3.25 in. high,  $V = 80 \text{ c.c.}$ ) Eq.[7] gives

$$[10] \quad \eta = \frac{1}{1 + \frac{0.0011}{m_v}}$$

The compression index  $C_c$  for most normally consolidated clays is constant with pressure. Assuming the average void ratio of the soil equal to unity,

$$[11] \quad m_v = \frac{0.22 C_c}{\sigma'_m}$$

Inserting Eqs.[10] and [11] into Eq.[9] gives

$$[12] \quad p' = K_0 \int_0^{\sigma'_1} \frac{1}{1 + \frac{.0011}{0.22 C_c} \sigma'_m} d\sigma'_v$$

Consider, for example, a clay with true  $K_0 = 0.5$  and  $C_c = 0.2$ , consolidated to  $\sigma'_1 = 6 \text{ Kg/cm}^2$ . Then Eq.[12] yields

$$p' = 2.9 \text{ Kg/cm}^2, \text{ which gives}$$

$$(K_0)_m = 0.483$$

Thus, the error in measured  $K_0$  is only 3.5%. However,  $C_c$  for most clays is larger than 0.2, and therefore the error in measured  $K_0$  will be smaller for consolidation to the same vertical effective stress. Similarly, for consolidation to a lower vertical effective stress, the error is correspondingly smaller. The error in measured  $K_0$  could be reduced by decreasing the compliance of the cell. However, for the volume of cell water under consideration about half of the measured compliance of  $0.6 \text{ cc/Kg/cm}^2$  is due to the compressibility of water. Thus, stiffening the cell boundaries will gain little if the cell water volume cannot be reduced. Another way to reduce the error in measured  $K_0$  is to make first order adjustments for compliant volume changes by using the calibrated displacement valve connected to the cell chamber (see Fig.2). This method is useful for very stiff soils where errors in  $K_0$  measurements may be considerable.

### A universal triaxial apparatus.

The apparatus is suited to perform shear tests on isotropically or  $K_0$ -consolidated samples.  $K_0$  consolidation in one increment can be done in the same time duration as conventional isotropic consolidation, thus resulting in large savings in consolidation times required by existing methods. Stress paths to failure other than the conventional passive compression can be simulated with no additional difficulty. This is an important advantage in view of the fact that soil properties, particularly those of  $K_0$ -consolidated clays, are known to be very sensitive to stress changes leading to failure (Ladd 1965, Vaid 1971), and a proper assessment of this variation is a prerequisite for any rational field design (Lambe 1967).

### High pressure capacity.

The triaxial cell offers the possibility of performing high pressure consolidation and shear tests. With the present design, cell pressures as high as 42 Kg/cm<sup>2</sup> (600 psi) can be used. This pressure happens to be the maximum safe working pressure for the standard type of Bellofram seal used on the loading ram. However, it is possible to increase pressure rating to 85 Kg/cm<sup>2</sup> (1200 psi) if a specially fabricated Bellofram is employed.

The closed fluid system for applying the vertical load gives a very high axial loading capacity, even if a low capacity strain drive is used.

The loading capacity of the strain drive is magnified by a factor equal to the ratio of areas of the loading piston to the displacement plunger.

### TYPICAL RESULTS

Some of the results obtained in the new apparatus are described below. These results serve to demonstrate the characteristics of the apparatus outlined previously. A locally available undisturbed saturated sensitive marine clay (Haney clay) was used for the tests. The clay was obtained in block samples from open pits at the Brick and Tile Plant at Haney, B.C.

#### Consolidation Tests.

These consisted of a cyclic  $K_0$ -consolidation test and an isotropic consolidation test. In the  $K_0$ -test, two cycles of loading and rebound were performed. The sample was loaded to a maximum vertical effective stress of  $16.4 \text{ Kg/cm}^2$  (230 psi) during the second loading cycle. In the isotropic test, only one loading and unloading cycle was performed and the maximum consolidation pressure used was  $20.4 \text{ Kg/cm}^2$  (290 psi). Both tests were made under strain controlled loading.

Fig. 3 shows  $e$ - $\log \sigma'$  relationships for the two tests. For the  $K_0$ -test, both vertical and mean normal effective stresses are represented. A slight difference in the initial void ratio of the samples causes the initial portion of the isotropic relationship to fall slightly below that for the  $K_0$ -test. The loading relationships are typical of a sensitive clay and are essentially parallel in the normally consolidated range. As demonstrated by others, (Khera and Krizek 1966, Lewin and Burland 1970)  $K_0$ -consolidation results in lower void ratio of the normally consolidated clay when compared to that resulting under isotropic consolidation at the same  $\sigma'_m$ .

Fig. 4 shows the relationship between horizontal and vertical effective stresses during  $K_0$ -consolidation. The ratio  $\sigma'_h/\sigma'_v$  is the value of  $K_0$ , the coefficient of lateral stress at rest. Fig. 4 demonstrates the well known result that  $K_0$  for normally consolidated clay is independent of the magnitude of  $\sigma'_v$ . The significant feature to be noted is the constancy of  $K_0$ , even up to a vertical effective stress as high as  $16 \text{ Kg/cm}^2$  (230 psi).

The variation of  $K_0$  with overconsolidation ratio, O.C.R., is more clearly shown in Fig. 5.  $K_0$  is seen to be independent of the magnitude of maximum vertical effective stress from which the rebound cycle is initiated. However, for the same O.C.R.,  $K_0$  during reloading is smaller than during rebound.

$\sigma'_v$  = vertical effective stress  
 $\sigma'_m$  = mean normal effective stress

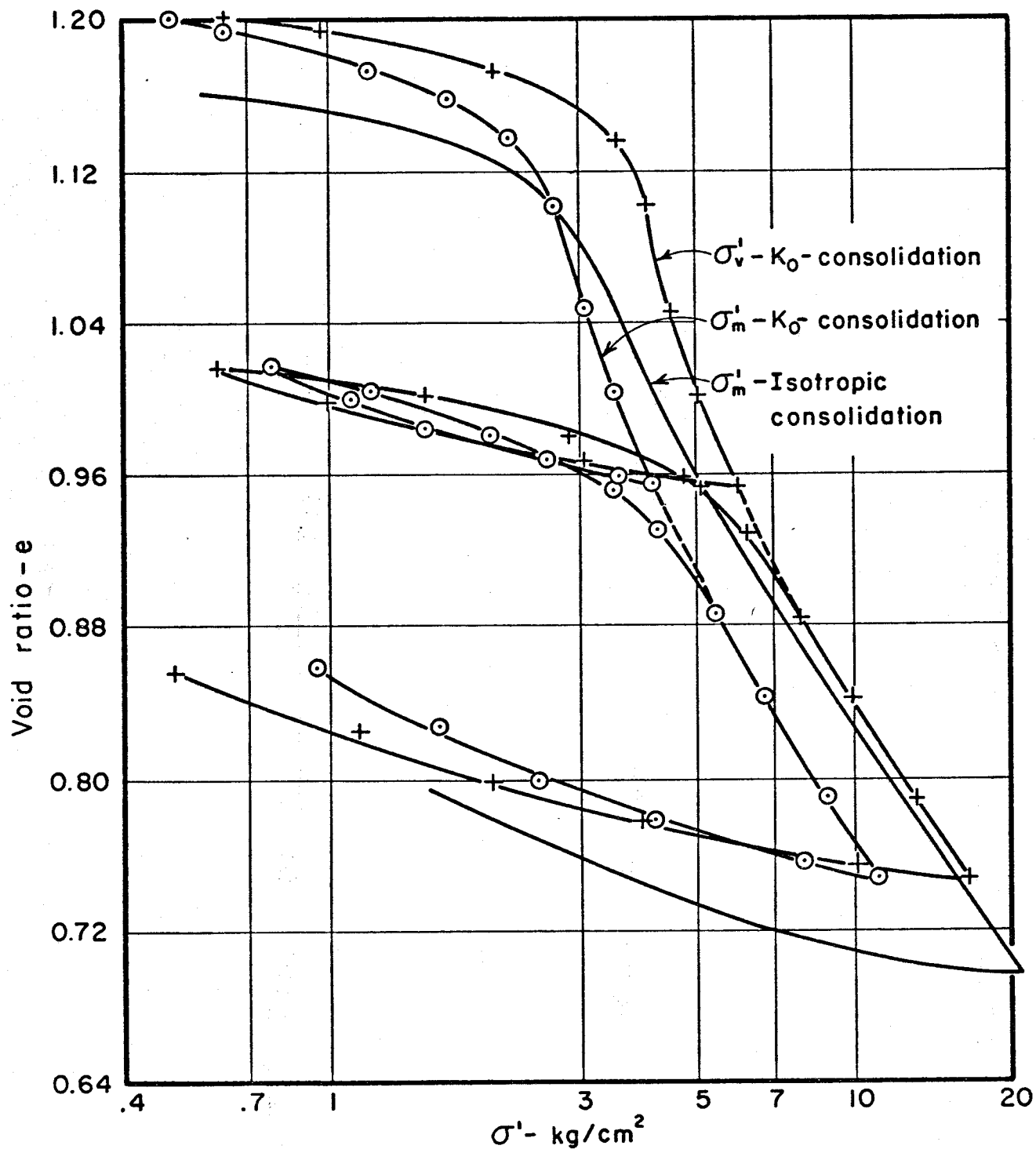


Fig.3.  $e$  vs.  $\log \sigma$  RELATIONSHIPS - UNDISTURBED HANEY CLAY

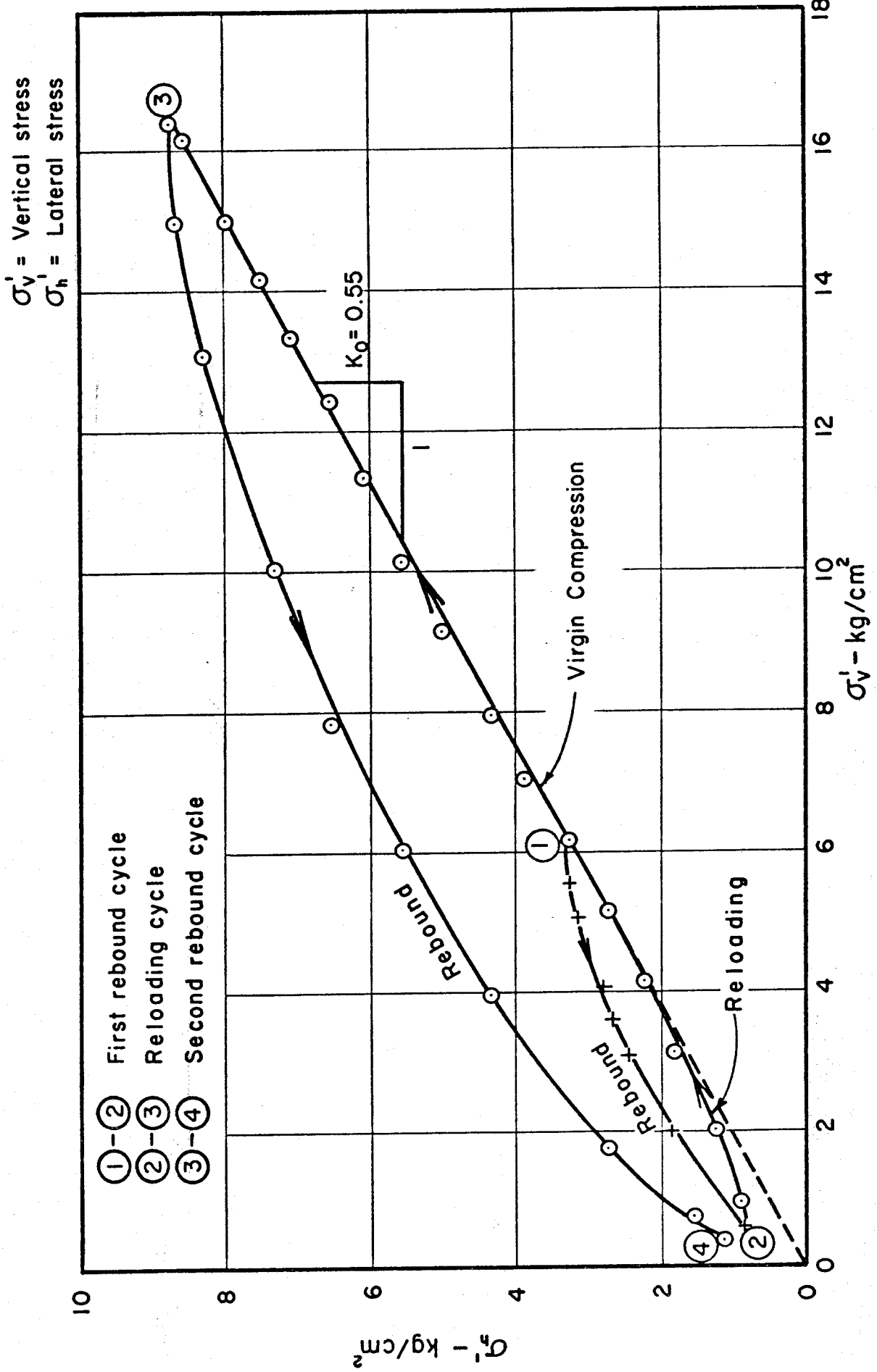


Fig. 4. RELATIONSHIP BETWEEN VERTICAL AND LATERAL EFFECTIVE STRESS DURING ONE DIMENSIONAL CONSOLIDATION - UNDISTURBED HANEY CLAY.

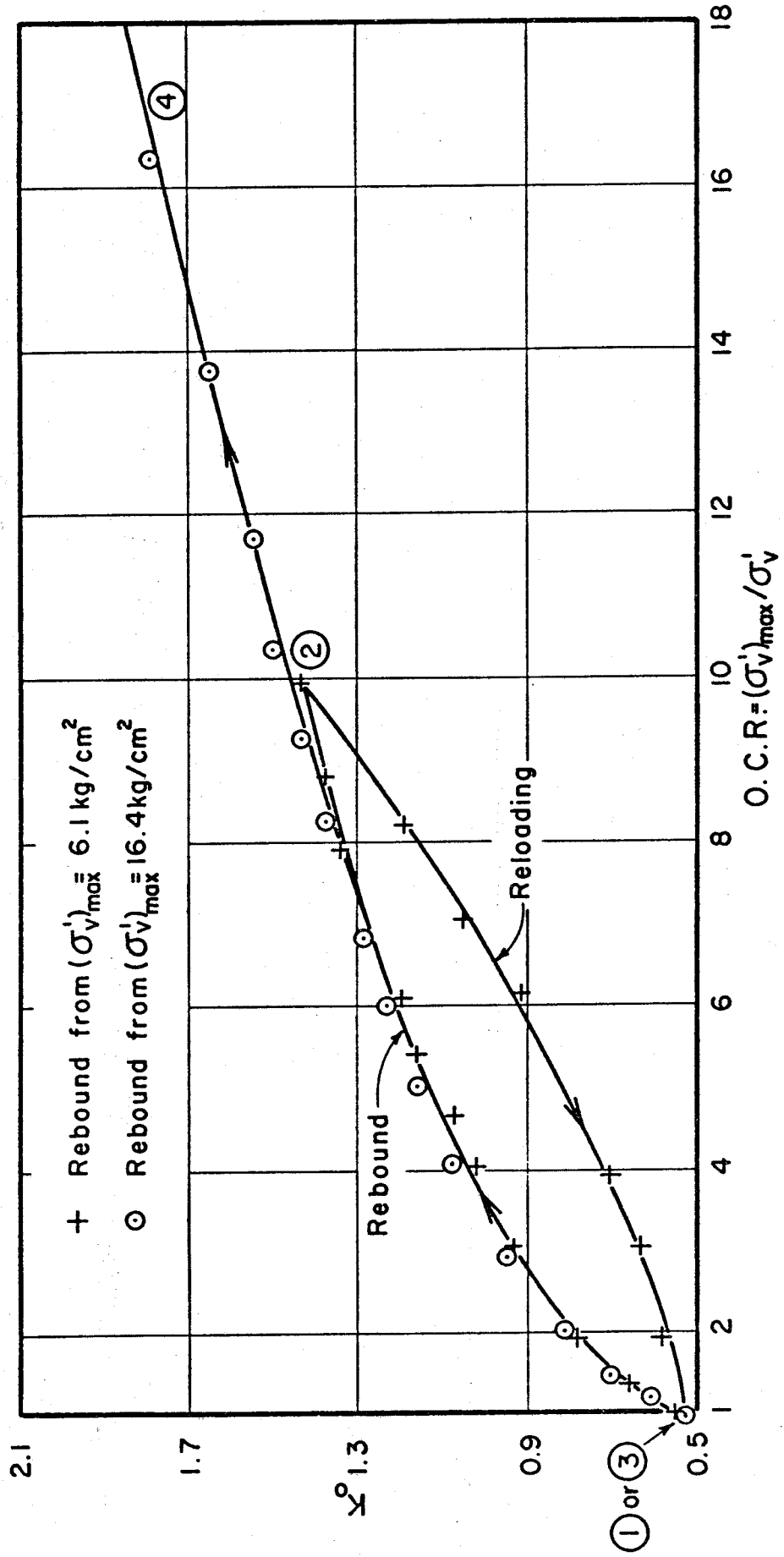


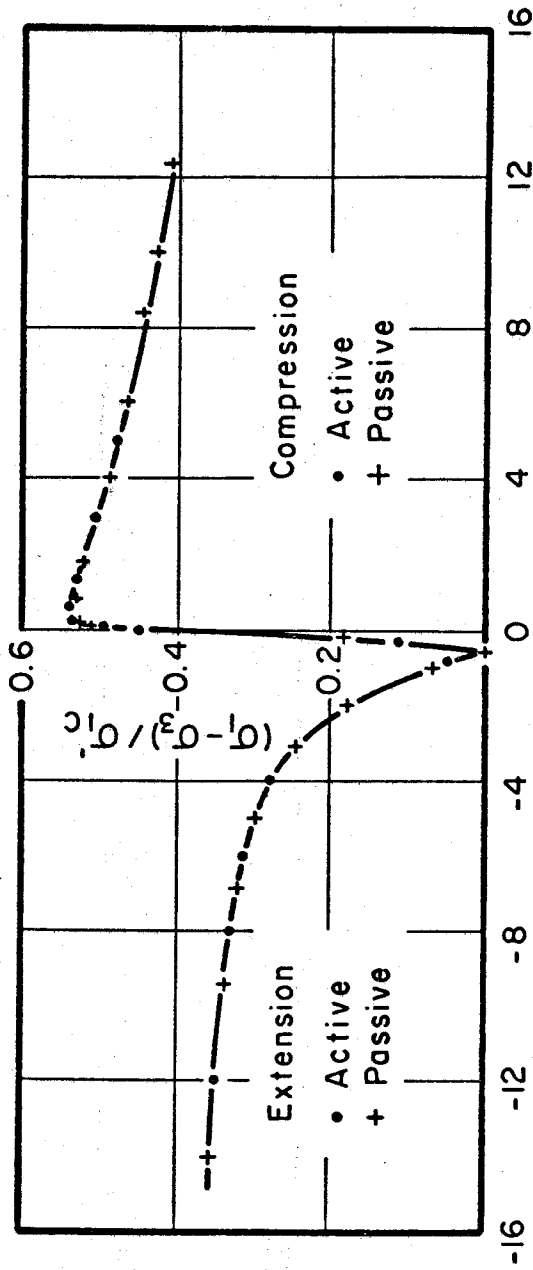
Fig. 5. VARIATION OF  $K_0$  WITH OVERCONSOLIDATION RATIO - UNDISTURBED HANEY CLAY.

### Shear tests.

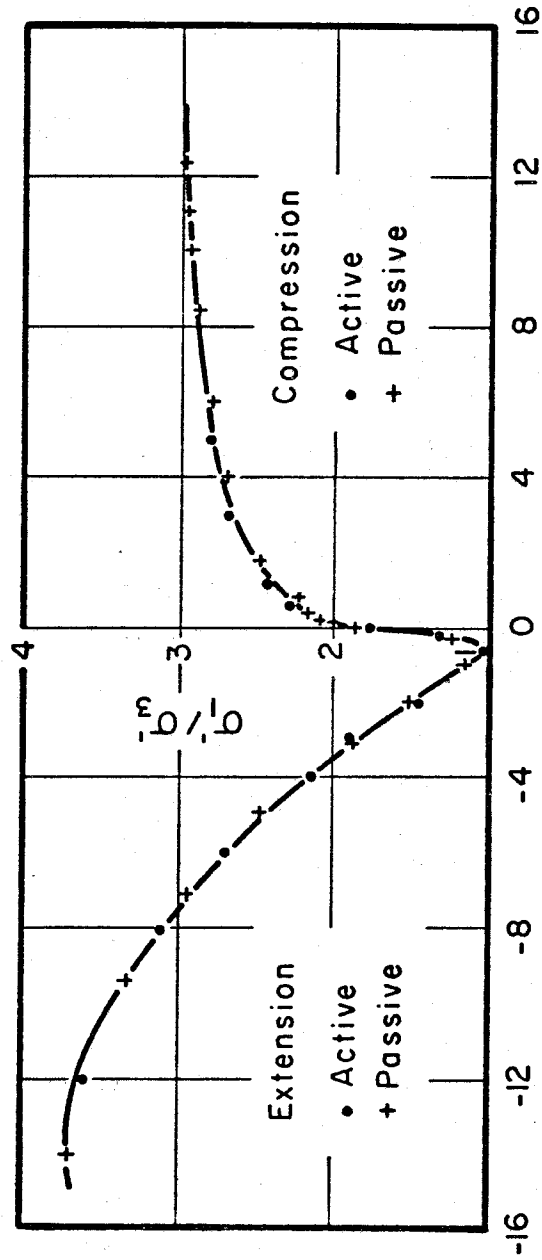
Some of the types of tests performed in the apparatus along with the conventional types are described in this section. In all the tests, samples were  $K_0$ -consolidated in one increment to a vertical effective stress of about  $6 \text{ Kg/cm}^2$ . The average value of  $K_0$  was 0.55. Consolidation time allowed was 48 hours prior to commencement of shear.

#### (a) Undrained compression tests.

Fig. 6a shows deviator stress-strain curve from a conventional load increasing (passive) undrained compression test performed under strain controlled loading. Also shown in the same figure are the results from a strain controlled unloading (active) compression test, which involved monotonic decrease of lateral pressure while the axial stress was maintained constant. It has often been shown (Bishop and Henkel 1962, Henkel 1960, Parry 1960) that the undrained compression behaviour of a saturated clay is independent of the applied total stress path to failure. This fact is clearly demonstrated in the results of the two types of compression tests presented in Fig. 6. As is often observed for sensitive natural clay, peak deviator stress occurs at small strains after initial  $K_0$  consolidation, while peak effective stress ratio occurs at comparatively large strains (Fig. 6b). For a clay possessing an unstable deviator stress-strain curve, such as shown in Fig. 6a, post peak active compression behaviour can only be obtained by strain controlled loading, which is often not possible in a conventional triaxial cell.



a) Normalised Deviator Stress vs. Axial Strain.



b) Principal Effective Stress Ratio vs. Axial Strain.

Fig.6. STRESS-STRAIN RELATIONS DURING UNDRAINED SHEAR - UNDISTURBED HANEY CLAY.

(b) Undrained extension tests.

Stress changes in many field problems do not always correspond to conventional passive compression. Under the centre line of a circular excavation, for example, the applied stress path corresponds to axial extension. Fig. 6 shows the extent of the difference in behaviour of identical samples sheared in compression and extension. It is seen in this figure that the undrained strength in extension was about 65% of the peak strength in compression. The value of  $\phi'$  at maximum effective stress ratio, however, was approximately 5 degrees larger in extension than in compression. Thus, the use of the undrained strength from compression tests for a short term undrained stability analysis may lead to an estimate on the unsafe side, whereas the use of the compression  $\phi'$  in a long term stability analysis may result in a conservative estimate. These results emphasize the need to determine soil behaviour under stress paths anticipated in a given field problem (Lambe 1967).

(c) Drained compression and extension tests.

Fig. 7 shows the behaviour of Haney Clay under drained conditions for both active and passive, compression and extension loading paths. All tests were performed under strain controlled loading. The results show that for both types of compressional loading the same peak value of  $\sigma_1'/\sigma_3'$  was approached. However, for extensional loading, the passive loading path resulted in a lower peak value of  $\sigma_1'/\sigma_3'$  when compared to the active loading path. The reason for this deviation was the widely

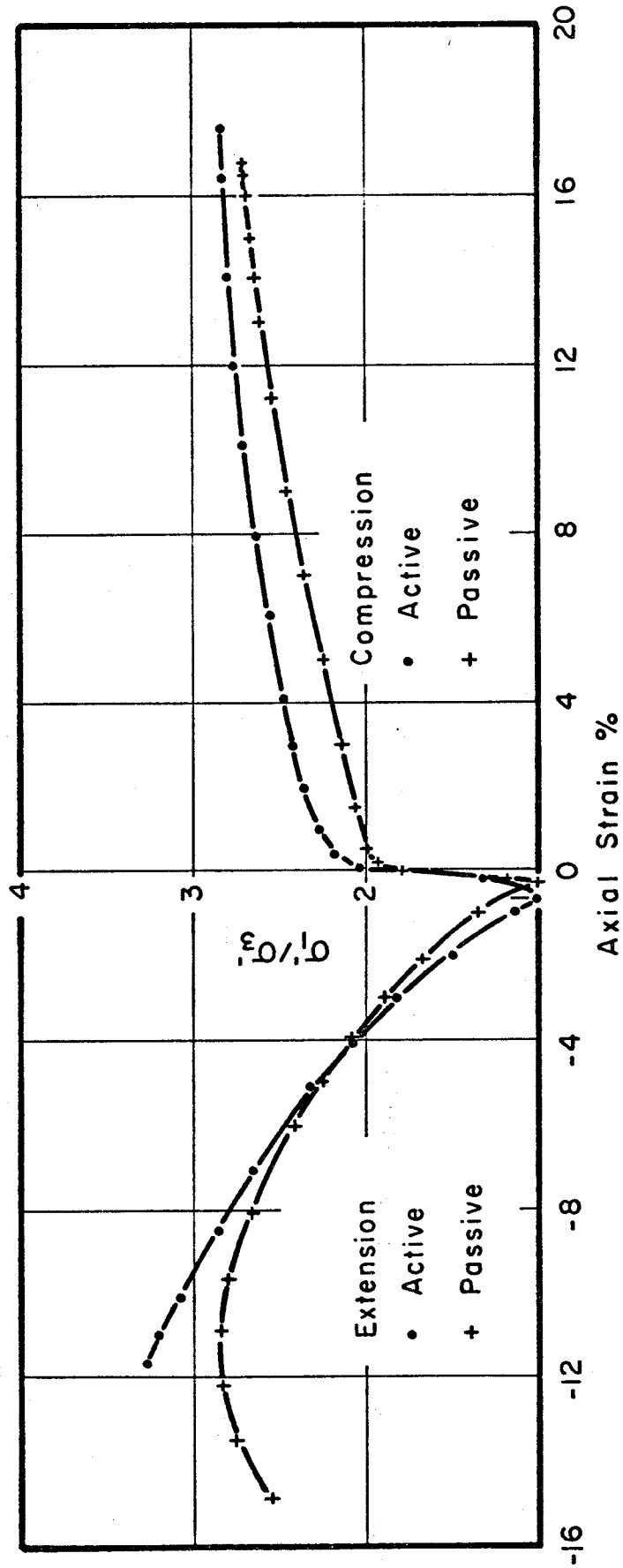


Fig.7. PRINCIPAL EFFECTIVE STRESS RATIO - STRAIN RELATIONS DURING DRAINED SHEAR - UNDISTURBED HANEY CLAY.

different rates of dilatancy in these two types of extension tests. (Unfortunately, the active extensional loading test was terminated before the peak stress ratio was reached.)

It should be mentioned here that in general the shear behaviour for the clay tested was found to be essentially the same, irrespective of whether  $K_0$ -consolidation was obtained by a single load increment, several small load increments or by strain control. The time allowed for one increment consolidation was 48 hours, whereas for consolidation to the same vertical effective stress under strain controlled conditions, approximately 5 to 6 days were required. Thus the savings in time was considerable for one increment  $K_0$ -consolidation which is a unique feature of the apparatus.

#### SUMMARY AND CONCLUSIONS

A new  $K_0$ -triaxial apparatus has been described. The simplifying features include ease of sample preparation and test procedure. No adjustments of any kind are needed during  $K_0$ -consolidation.

The apparatus is especially suited to consolidate cylindrical specimens under  $K_0$ -stresses in one load increment, several load increments or by strain controlled methods. The apparatus is equipped with a frictionless seal on the axial loading ram. Thus, it has the special feature of being used as a frictionless oedometer with measurements of

lateral stress. Isotropic consolidation is also possible.

Along with the above features it is also necessary to recall that the sample must be saturated to realize  $K_0$  conditions, and the finite compliance of the cell-water system together with the compressibility of the soil dictate the accuracy of the  $K_0$  measurements.

The hydraulic loading system described permits a variety of stress paths during shear (either active or passive, compression or extension, under drained or undrained conditions). A unique feature of the loading system is the fact that all of the above stress paths can be applied under strain controlled conditions. Constant lateral strain rates are possible only because of the relatively low compliance of the cell-water system. Stress controlled loading is also possible.

Typical data obtained from tests on an undisturbed saturated clay is presented which shows the consistency of  $K_0$  measurements and the need to reproduce in the laboratory the same stress path as that in the field if strength and stress-strain data is to be meaningful.

#### ACKNOWLEDGEMENTS

The authors wish to acknowledge the support from the Canadian National Research Council (Grant A.3401) and the expert assistance provided by the Civil Engineering Machine Shop at the University of British Columbia in the design and manufacture of the  $K_0$ -triaxial apparatus.

## NOTATION

$K_0$	Coefficient of lateral earth pressure at rest
$\sigma_{1,3}$	Major and minor principal effective stresses
$\sigma'_v, \sigma'_h$	Vertical and horizontal effective stresses
$\sigma'_m$	Mean normal effective stress
$p'$	Increment of pressure in cell-water system
$V$	Volume of sample
$c$	Compliance of cell
$m_v$	Compressibility of soil
$C_c$	Compression index
$n$	Compliance factor
$\phi'$	Angle of shear resistance

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