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A NEW APPARATUS FOR MEASURING THE PRINCIPAL STRAINS IN ANISOTROPIC CLAYS

ANALYZED

by C.M.K. Yuen, K.Y. Lo, J.H.L. Palmer and G.A. Leonards

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SOMMAIRE

L'article porte sur la mise au point d'un appareil et d'un dispositif expérimental destinés à la mesure précise de la déformation latérale dans les argiles tendres et sensibles au remaniement. L'appareil comporte des points de mesure légers et des transducteurs de déplacement en suspension dans un liquide, de manière que les contraintes internes puissent être mesurées directement sur l'échantillon avec un minimum de remaniement. Les données obtenues lors d'essais sur une argile tendre et sensible indiquent que l'appareil mis au point démontre la précision et la stabilité convenant à l'étude de la déformation des argiles.

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A New Apparatus for Measuring the Principal Strains in Anisotropic Clays

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ABSTRACT: An apparatus and an experimental arrangement were developed to provide an accurate measurement of the lateral deformation of soft sensitive clays. The apparatus contained light gage points and displacement transducers floated in a cell fluid in such a way that internal strains could be measured directly on the soil specimen with the least amount of disturbance. The performance data obtained from the testing of a soft sensitive clay indicated that the apparatus developed possessed adequate precision and stability for the study of the deformation behavior of clays.

KEY WORDS: clays, anisotropy, deformation gages, principal strains, displacement transducers, flotation.

Analyses of soil behavior are generally based on the assumption that the properties of soils are isotropic. However, if the mode of deposition and the stress metamorphosis subsequent to deposition are considered, it is conceivable that most natural deposits would be macroscopically anisotropic to some degree [1]. It is therefore possible that soils may possess some directional properties in terms of both strength and deformation characteristics.

While the strength of anisotropy of soft clays in terms of effective stresses has been studied in a few cases [2-4], the anisotropic deformation behavior has, so far, received relatively little attention. Although the theoretical treatment of an anisotropic material has been well established in the theory of elasticity [5-7], its application to soil mechanics has only been recently exemplified. Pickering [8] considered the theoretical bounding values of the relevant elastic parameters of soil as a cross-anisotropic elastic material. Gibson [9] studied the effects of anisotropy on the settlement of London clay. Barden [10] also suggested that a cross-anisotropic elastic half space, which included isotropy as a special case, was an improved model in representing the elastic behavior of a natural soil deposit. However, the intrinsic behavior of clay in loading and unloading has not been taken into account in any of the anisotropic soil models. In

addition, experimental determination of the anisotropic elastic parameters, particularly for soft clays, is seldom performed. Consequently, the five independent cross-anisotropic elastic parameters have not been measured for any particular clay deposit.

Determination of the anisotropic elastic parameters requires the measurement of the three principal strains in a soil specimen. While the strength properties of soil can be obtained with reasonable accuracy, deformation measurement cannot be made with adequate precision by conventional laboratory methods. Since most soft clays fail at strains as low as 1%, the degree of accuracy required for deformation measurements would be in the order of $2.54 \mu\text{m}$ (10^{-4} in.). Despite previous attempts to measure the deformation of a soil specimen in triaxial cells, by means of optical as well as transducerized electronic instrumentations [11-14], no systematic data were reported on the performance of the apparatus or the deformation behaviors, especially in the lateral directions, of undisturbed soft clays. It also appears that the difficulty of measuring small deformations of anisotropic clays in triaxial tests has not been successfully resolved.

In this paper, the design and development of an apparatus for the simultaneous measurement of three orthogonal strains are described in detail. Test data for the performance of the experimental arrangement are given. With this apparatus, the complete set of ten anisotropic elastic deformation parameters has been determined for a soft sensitive clay.

Theoretical Background

The theory of elasticity for a cross-anisotropic material has been considered by Hearmon [6]. By taking into consideration the elastic symmetry in the material and the reciprocal relations of the elastic constants from energy considerations, the three principal strains can be expressed, on an incremental basis, in terms of five independent parameters: E_v , E_h , μ_{xx} ($= \mu_{xy} = \mu_{hh}$), μ_{zx} ($= \mu_{vh}$), and G_{zx} ($= G_{zx} = G_{hv}$). These relationships are

$$\left. \begin{aligned} \Delta\epsilon_x &= (\Delta\sigma_x/E_h) - [(\mu_{xx}/E_h)\Delta\sigma_y] - [(\mu_{zx}/E_v)\Delta\sigma_z] \\ \Delta\epsilon_y &= -[(\mu_{xx}/E_h)\Delta\sigma_x] + (\Delta\sigma_y/E_h) - [(\mu_{zx}/E_v)\Delta\sigma_z] \\ \Delta\epsilon_z &= -[(\mu_{zx}/E_v)\Delta\sigma_x] - [(\mu_{zx}/E_v)\Delta\sigma_y] + (\Delta\sigma_z/E_v) \end{aligned} \right\} \quad (1)$$

where

E = modulus of deformation,
 μ = Poisson's ratio,

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G = shear modulus,
 ϵ = strain,
 σ = stress,
 h = horizontal direction, and
 v = vertical direction.

In Eq 1, the vertical axis (z) is taken as the axis of symmetry and the horizontal plane (x - y plane) as the plane of isotropy.

Since deformation is controlled by the effective stress system, all the terms on the right-hand side of Eq 1 must be expressed in terms of effective stresses. In addition, it is well known that in an undrained triaxial test on a specimen with the minor principal stresses (cell pressure) constant, loading in the axial direction would produce unloading in terms of effective stresses in the lateral directions and vice versa. Since the "elastic" parameters for soil are generally different in loading and unloading, a total of ten independent parameters is required to define the deformation behavior completely. By using appropriate elastic parameters, the incremental stress-strain relationships of a cross-anisotropic soil, with the elastic parameters distinguished between loading and unloading, may be obtained from Eq 1. The details of the formulation have been described in Ref [7].

In principle, these elastic parameters may be determined from either drained tests or undrained tests with pore-pressure measurements if all the principal strains are accurately measured within the elastic range of the soil behavior. The experimental aspects of the adopted method are described in the following sections.

Requirements for Design of Apparatus

To achieve the necessary precision for the measurement of deformation, the following requirements must be met:

1. The axial strain distribution within a triaxial specimen is generally nonuniform, except for the middle half of the specimen. This difficulty is circumvented by employing gage points on the sample at appropriate gage lengths. The gage points should be light in weight and produce the minimum amount of disturbance in insertion and during deformation of the sample.

2. Under a system of applied principal stresses, a soil specimen deforms in all the three principal directions of strain. It follows that any reference gage point attached on the center line of the surface of the specimen would be undergoing displacements in the two principal directions simultaneously. It is therefore necessary that, when displacement measurement of the gage point in one of the principal directions is being undertaken, the displacements of the gage point in the other principal direction should concurrently be accommodated so that no force or moment should be induced.

3. At low-strain level, we envisaged that the magnitude of deformation in the specimen would be small [total deformation about 0.25 mm (0.01 in.) in lateral direction]. Therefore, instrument sensitivity should be at least 2.54 μ m (0.0001 in.), and stability over long periods of measurement (generally one week) would be essential.

To meet these requirements, a system of lightweight gage points and displacement transducers was adopted. The design of the components of this deformation measurement system is described in detail in the following sections.

Gage Points for Deformation Measurements

The gage points were constructed with commercially available sewing needles (Sharp 10) 0.51 mm (0.02 in.) in diameter,⁴ cut to about 8 mm (0.3 in.) long. The needle was pushed perpendicularly, through a thin bronze sheet, 6.35 mm (0.25 in.) square by 0.127 mm (0.005 in.) thick, with the sharp end protruding approximately 6.35 mm (0.25 in.), and then epoxied in position to ensure a rigid contact. A projection of about 1.27 mm (0.05 in.) was allowed at the back of the bronze sheet to facilitate positioning into the specimen. The average weight of a gage point was 0.09 g.

After the gage points were positioned, the membrane was placed over the specimen and pierced through at the gage points. The puncture was sealed with silicone sealant (room-temperature vulcanizing) to prevent any possible leakage.

In conventional strain-controlled triaxial tests, the axial displacement in the soil specimen at any stage of loading or unloading is measured as the relative movement of the loading ram to the cell, and uniformity in axial deformation in the soil specimen is assumed. However, in view of the end restraint effects and the possibilities of local disturbance at the ends of the specimen because of trimming, the strains at the end of the specimen should be quite different from those at the central sections. A series of pilot tests (stress-controlled unconfined compression tests) were initially performed to investigate the uniformity of strains within a specimen. It was found that the middle half of the specimen yielded reasonably uniform axial strains. It appears therefore appropriate to use the middle half of the specimen as the gage length [35.6 mm (1.4 in.)] for axial strain measurement to eliminate the end restraint effects.

For the lateral strains it has been found that at low strain levels, such as those encountered in the present series of tests, the bulging is insignificant and the distribution is fairly uniform within the central section. Strains measured at the midsection of the specimen would be representative of the state of strain within the entire vertical gage length.

Accordingly, for vertical deformation measurement, the gage points were located at the quarter points of the specimen, whereas, for lateral deformation measurements, they were located at the center of the specimen on opposite faces of the square-section specimen.

Displacement Transducers for Deformation Measurements

The displacement transducers used in this study were of the linear variable differential transformer type with built-in 24-volt d-c-excited carrier-oscillator and phase-sensitive demodular systems (DCDT). Displacement of the core produces a voltage change in the output proportional to the displacement. The d-c output voltage is sufficient to drive a strip recorder.

The resolution capability of a DCDT is theoretically infinite, being limited usually by the capacity of the readout instrument. For the purpose of the tests reported here high sensitivity was required, which meant that the strip chart recorder had to be set in a sensitive range. Since the output of the DCDT was ± 5 V, the core of the DCDT had to be set very close to the electrical center, otherwise the initial output voltage exceeded the zero adjustment capacity of the recorder. Such a precise setting was

⁴The original experimental data were measured in English customary units.

impossible within the triaxial cell; therefore, an electronic unit was constructed which permitted adjustment of the output signal to zero, regardless of the core position.

Three 24DC-DT-100 displacement transducers, having a displacement range of ± 2.54 mm (± 0.10 in.), were employed for deformation measurements. A 24DC-DT-500 displacement transducer with a displacement range of ± 12.7 mm (± 0.50 in.) was used for the external measurement of axial strain for comparison. These transducers were supplied by Hewlett-Packard Co., complete with core assembly. Figure 1 shows the gage points and the extension rods adapted to the cores for axial and lateral deformation measurements. Subsequent attachment of the extension rods to the gage points was made by means of a rapid-setting adhesive (Aron® alpha No. 102).

Cell Fluid

As the experimental investigation involved measurements with delicate electronic instruments in the triaxial cell under pressure, the cell fluid had to be a nonconductor and had to be noncorrosive to any part of the displacement transducers. The normal cell fluid (water) was not suitable. A transformer oil, Esso Univolt N-36, was found to be satisfactory.

A separate inlet to the triaxial cell was provided for the transformer oil so that the cell pressure could be applied through the water-pressure system, as described by Bishop and Henkel [15]. The oil and water interface was indicated by a glass reservoir installed along the pressure line.

Membrane for Soil Specimen

Latex rubber membrane, which is commonly used, tends to expand and deteriorate in oil as a result of chemical interaction. A special order was placed to manufacture silicone rubber sheets 0.381 mm (0.015 in.) in thickness from a product under the trade name Silastic 1125U (134-11K), produced by Dow Corning Co. The sheets were then made into tubular forms using a compatible silicone sealant (room-temperature vulcanizing) as a glue and were cured for at least 24 h.

The membrane proved to be sufficiently oil-resistant and exhibited a fairly low degree of expansion within the duration of the triaxial tests (generally one week).

FIG. 1—Gage points and extension rods for displacement transducers in axial and lateral strain measurement.

Calibration of Transducers

The displacement transducers were calibrated in air as well as in the transformer oil by means of a micrometer to an accuracy of $1.02 \mu\text{m}$ (4×10^{-5} in.). It was found that the relationship between the displacement of the core and the output voltage was essentially linear, and the performance of the transducer was practically unaltered when calibrated in the transformer oil. A calibration constant of $0.245 \mu\text{m/mV}$ (9.65×10^{-6} in./mV) was obtained in both cases. It was also observed that the transducers were stable under the cell pressures and that the effects of temperature variations on the output voltages were negligible under normal laboratory test conditions ($\pm 2^\circ\text{C}$).

The calibration of the displacement transducer used for the purpose of comparative external deformation measurements was performed in a similar manner in air, where a calibration constant of $1.02 \mu\text{m/mV}$ (4×10^{-5} in./mV) was attained. Both calibrations were performed with a constant 24-V d-c excitation voltage.

Support Systems for the Displacement Transducers

The usual procedure for the use of a displacement transducer is to provide a rigid mounting with the core aligned in the direction of displacement. However, if coupled displacements in the principal directions should occur, there is a tendency for the core to tilt. Since the output signal of the transducer is highly sensitive to the position of the core, tilting of the core will induce an error, the amount of which depends on the length of the extension rod and the magnitude of the accompanying displacements in the perpendicular directions. Figure 2 shows the relative error involved in the axial and lateral displacement measurements as a result of tilting of the core. It may be observed that:

1. With a long extension rod for the core and relatively small lateral displacements, the effect of tilting is insignificant.
2. With a short extension rod (limited by the space available in the triaxial cell) and relatively large accompanying axial displacements, the error imposed on the lateral displacement measurement would be substantial.
3. Apart from the effects on the displacements, excessive tilting of the core and the extension rod assembly would induce undesirable moments on the gage points, thus impairing the accuracy of the measurement.
4. The bore of the displacement transducer is only slightly oversized to allow for the axial movement of the core. Excessive tilting in the core would tend to increase the frictional forces which might inhibit the instantaneous response of the transducer.

It is therefore acceptable to use rigid supports (Fig. 3) for the transducers in the internal axial-deformation measurements; however, it is apparent that a rigid support system for the transducers would be unsuitable for measuring the lateral deformation.

A procedure was developed based on the principle of flotation by which the lateral displacement transducers were made buoyant in the cell fluid. In an essentially weightless state, the transducer units could follow the vertical displacement of the gage points while the cores were free to move laterally along the bores of the transducers, thus registering reliably the lateral displacements of the gage points with virtually no stress applied to the specimen as a consequence of the instrumentation.

The basic setup for the lateral displacement measurement (in one of the principal directions) is illustrated in Fig. 4, and the

$$L^2 = (L-y)^2 + x^2$$

$$y = L - \sqrt{L^2 - x^2}$$

	VERTICAL DISPLACEMENT MEASUREMENT	LATERAL DISPLACEMENT MEASUREMENT
L	1.5 in	1.75 in
Maximum strain envisaged in triaxial test	Lateral Strain = 0.06%	Axial Strain = 0.8%
Corresponding values of X	8.4×10^{-4} in	112×10^{-4} in
y	3×10^{-7} in	8.37×10^{-5} in
% Error = $\frac{y}{\text{max. axial displacement of core}}$	0.0027%	10%

FIG. 2—Relative error in displacement measurement due to tilting of core.

components are shown in Fig. 5. The displacement transducer was mounted on an aluminum bracket (Fig. 6), which was so proportioned that the center of gravity of the assembly was close to the center of the transducer. The design of the aluminum brackets permitted deformation measurements to be made in two orthogonal directions, as depicted in Fig. 7. The transducer end of the assembly was fitted into a Styrofoam® bracket, and small Styrofoam pieces were glued to the opposite end of the bracket to provide balanced flotation.

The Styrofoam used was a lightweight foam with a density of approximately 40.19 kg/m³ (2.51 lb/ft³). It was found that 2.8 g (0.1 oz) of Styrofoam was sufficient to float the unit (transducer with aluminum bracket) which weighed approximately 45.4 g (0.1 lb). Since there was a tendency for the foam to become saturated with oil under the cell pressure, the Styrofoam was "pre-pressurized" in oil under a pressure of 138 kPa (20 psi).

Trial flotation was conducted by using a dummy of the same size and weight as the actual displacement transducer unit. The Styrofoam bracket and the end pieces were trimmed as required so that the whole assembly was barely buoyant in a horizontal position.

Until the cell was filled with oil, the units had to be mechanically supported. Since the measuring system was inside the cell, access to it was very difficult; therefore, a self-collapsible temporary support was desirable. After some experimentation, it was found that latex rubber, as mentioned earlier, deteriorated in a matter of minutes when immersed in the transformer oil, which had been adopted as cell fluid. Accordingly, the temporary sup-

NOTES

- 1) GAUGE POINTS
A & C FOR VERTICAL DISPLACEMENT MEASUREMENT
B - FOR LATERAL DISPLACEMENT MEASUREMENT
- 2) DISPLACEMENT TRANSDUCER FOR GAUGE POINT C IS SIMILAR TO THAT FOR A.

FIG. 3—General arrangement of supports for vertical transducer units.

port for each lateral transducer unit was in the form of a thin latex-rubber membrane stretched horizontally across two cantilever rods attached to aluminum columns from the base plate of the cell (Fig. 4). Since the weight of the transducer unit was concentrated at the transducer end, only one strip of latex was necessary for each unit. By adjusting the position of the cantilever rods, the axis of the transducer unit could be aligned with the position of the gage points. When the lateral displacements in the two orthogonal directions were to be measured, an additional temporary support was provided for the adjacent transducer unit. The details of the support system are given in Fig. 8. The setup is shown in Fig. 9.

With the transducers supported temporarily (Fig. 10), the extension rods of the cores were attached to the gage points with rapid-setting adhesive. At the same time, the positions of the cores were adjusted so that their centers were close to the electrical zero. A very slight disturbance was inevitable when the transducer units started to become buoyant and as the support collapsed under the action of the oil. Nevertheless, once equilibrium condition was reached, the output signals were stable and were adjusted electrically to provide a zero reading on the recorder. Figure 11 shows the lateral transducers floating in equilibrium in the triaxial cell.

When the transducers were active, the effectiveness of flotation was reflected in the output curves from the strip recorder. Previous experience had shown that any friction between the cores and the bores of the transducers produced discontinuous output signals. However, when the transducers were floating freely in the

FIG. 4—Setup for lateral displacement measurement.

FIG. 5—Assembly of equipment for lateral strain measurement.

cell fluid, any lateral deformation in the specimen produced a response in the form of a smooth and continuous curve on the recorder. With the transducer unit in an essentially weightless state, any accompanying vertical displacement of the gage point could easily be accommodated.

It must be noted that this method of deformation measurement demands a careful and delicate setup compared with other available techniques. However, the sensitivity of measurement offered by the displacement transducers is unsurpassed by any available measuring device so far used in the triaxial cell. We believe, therefore, that the instrumentation developed herein represents a step forward in the accurate measurement of small deformations, particularly for soft, sensitive clays.

Properties of Clay Tested

The clay tested was a Leda clay from Gloucester, near Ottawa, where a full-scale study on a test embankment was being con-

FIG. 6—Bracket for lateral displacement transducer.

Fig. 7—Layout of lateral displacement transducers.

ducted by the National Research Council of Canada [16]. Block samples, taken by excavating a test trench to a depth of 2.4 m (8 ft) below the ground surface, were waxed and preserved under 100% humidity. The properties of this clay at this particular location have been extensively investigated by Bozozuk and Leonards [16], Law [17], and Lo et al [18]. Typical properties of

FIG. 8—Support system for lateral transducers. RTV = room temperature vulcanizing.

FIG. 9—Temporary supports for transducer units in lateral strain measurement in the orthogonal directions.

the clay are liquid limit, 45%; plastic limit, 22%; and natural water content, 65%. The undrained shear strength is about 24.8 kPa (3.6 psi) with a sensitivity of 15 from field vane tests. The clay is slightly overconsolidated with a preconsolidation pressure of 55 kPa (8 psi).

Experimental Program

The objectives of the test program were (1) to obtain performance data for the apparatus developed and (2) to assess the anisotropic behavior for a particular clay. A summary of the types and the special features of the deformation measurements in each of the triaxial tests is given in Table 1. For purposes of comparison, the natural moisture contents and the volume changes during consolidation of the specimens are presented in the same table.

All triaxial tests were performed on square-sectioned specimens 35.6 mm (1.4 in.) square by 71.1 mm (2.8 in.) high trimmed from block samples. the use of parallel-sided specimens avoided the ambiguity of the direction of principal stresses found in a cylindrical specimen and at the same time facilitated the use of instrumentation for measuring lateral deformations.

In all the tests performed, the consolidation pressure was 21 kPa (3 psi) and the back pressure was 69 kPa (10 psi). All the triaxial tests were strain-controlled with strain rates of 0.08%/h [16.9 nm/s (0.00004 in./min)] and 0.5%/h [101.6 nm/s (0.00024 in./min)] for the drained and undrained tests, respectively. The outputs from the pressure transducers and displacement trans-

FIG. 10—Transducer units supported temporarily in lateral strain measurement in the orthogonal directions.

ducers were displayed on a strip recorder, which enabled a simultaneous and continuous monitoring of the test results.

Results of Tests

The analysis and interpretation of the test results have been discussed in detail by Lo et al [1]. In this paper, some aspects of the experimental data relating to the performance of the apparatus and the significance of the deformation measurements will be examined.

Homogeneity of the Samples

It may be observed from Table 1 that the specimens have natural moisture contents ranging from 65 to 69% for isotropically consolidated undrained (CIU) tests and from 68 to 70% for isotropically consolidated drained (CID) tests. These small variations in the natural moisture content give an indication that the block sample used for the triaxial tests in this study was fairly homogeneous for a natural deposit. A further check on the homogeneity of the sample may be made by comparing the total volume changes in the specimens during the consolidation stages, in which all the specimens were subjected to the same hydrostatic state of stress. With the exception of the inclined specimen,⁵ the

⁵The large volume of change is due to induced internal shear stress in an anisotropy body.

FIG. 11—Transducer units floating in equilibrium in lateral strain measurement within the triaxial cell.

volume changes in each of the vertical ($i = 0$ deg) and horizontal ($i = 90$ deg) specimens are in close agreement (where i is the angle between the axis of symmetry of the soil deposit and the long axis of the test specimen).

In addition to these observations, it has also been found that the pore-pressure-axial-strain relationships of all the vertical specimens tested in the undrained condition were practically identical. Similar trends were noted for the horizontal specimens.

These experimental results show that the test specimens were sufficiently homogeneous to be used for comparison purposes. On this basis, test results obtained from different triaxial tests may be combined to give additional data for assessing the performance of the apparatus developed.

Axial Strains

A comparison of the axial strains, measured internally [gage length = 35.6 mm (1.4 in.)] and externally outside the triaxial cell for a CIU test on a horizontal specimen (H_1), is shown in Fig. 12a. It may be observed that the internal axial strain is consistently lower than the external axial strain. The same observations have been made in a vertical specimen (V_1). Since it has been noted that the specimens were fairly homogeneous, similar patterns of axial deformation would be expected in other specimens tested in the undrained condition. It follows that appropriate corrections could be applied to the external strains in order to

TABLE 1—Summary of tests performed on a Leda clay.

Specimen No.	Type of Test	Orientation of Specimen, deg	Natural Moisture Content, %	Volume Change in Consolidation Stage, %	Special Test Feature
V ₁	CIU ^a	$i = 0^c$	67	1.54	internal axial deformation measured
V ₂	CIU	$i = 0$	65	1.42	orthogonal lateral deformations measured at mid-height
V ₃	CIU	$i = 0$	66	1.5	lateral deformations measured at quarter points in one direction
H ₁	CIU	$i = 90$	65	1.68	internal axial deformation measured
H ₂	CIU	$i = 90$	66	1.7	orthogonal lateral deformations measured at mid-height
V ₄	CID ^b	$i = 0$	68	1.65	orthogonal lateral deformations measured
V ₅	CID	$i = 0$	69	1.78	internal axial deformation measured
H ₃	CID	$i = 90$	70	1.7	orthogonal lateral deformations measured
I ₁	CID	$i = 45$	70	2.4	...

^a CIU = isotropically consolidated undrained.^b CID = isotropically consolidated drained.^c i = angle between the axis of symmetry of the soil deposit and the long axis of the test specimen.

FIG. 12—Relationships between the principal strains in CIU and CID tests.

obtain the true internal axial strains in the CIU tests. In the CID tests, however, the difference between the external and internal axial strains is very small; no such corrections are therefore necessary.

Lateral Strains

The uniformity of lateral strain within the middle half of the specimen was investigated by measuring the lateral deformations at quarter points of a vertical specimen (V₃) across two opposite faces. The results given in Fig. 13 show that the lateral strains independently measured at the quarter points are almost identical for both loading and unloading, indicating that the lateral strain distribution within the middle half of the specimen is essentially uniform.

The lateral strains in orthogonal directions in the x - y plane are given in Fig. 12b for a CIU test on a vertical specimen (V₂). It can be seen that the two lateral strains ϵ_x and ϵ_y were almost identical for both loading and unloading. This phenomenon suggests that the deformation behavior of the soil is isotropic in the x - y plane. Figure 12c shows the results of a CID test on a vertical specimen (V₄), and similar observations may be made.

Sum of Principal Strains

By combining the axial strains in Specimen V₁ and the lateral strains in two orthogonal directions in Specimen V₂, the sum of the principal strains ($\epsilon_{xv} + \epsilon_{yv} + \epsilon_{zv}$) at any stage of loading and unloading may be studied. The results are plotted in Fig. 14 in such a form that the dotted 45-deg line which passes through the origin represents the condition for an incompressible material ($\epsilon_{xv} + \epsilon_{yv} + \epsilon_{zv} = 0$). It may be noted that there seems to be a lag in the response of the lateral strains at the initial stages of loading and unloading. The behavior is reflected in the initial nonlinearities in the curves plotted. However, if incremental strain components are considered along the linearized portions of the curves, the incremental strain behavior is very close to that of an incompressible material ($\Delta\epsilon_{xv} + \Delta\epsilon_{yv} + \Delta\epsilon_{zv} = 0$).

One possible explanation for this initial behavior is that even though the transducer assembly is essentially weightless in the cell fluid, it is likely that a small amount of friction may occur between the core and the bore of the displacement transducer. A small amount of deformation would be absorbed before the movement in the core is initiated. The effect of this initial discrepancy is nevertheless very small since the incremental stress-strain theory was employed in the analysis of the test results [1].

FIG. 13—Relationship between lateral strains at quarter points in vertical Specimen V_3 in CIU test.

FIG. 14—Relationship between axial strain and the sum of lateral strains in vertical Specimen V_2 in CIU test.

On the basis of the performance data described above, we have concluded that the apparatus developed yielded adequate accuracy and stability in measuring the deformations of a soft sensitive clay. With all the principal strains accurately measured in both the drained and undrained triaxial tests, it is possible to

evaluate the cross-anisotropic elastic parameters of this clay deposit using the incremental stress-strain theory described by Lo et al [1]. A set of the elastic anisotropic parameters determined from consolidated-drained tests is shown in Table 2. It is clear that the clay tested was significantly anisotropic.

TABLE 2—Anisotropic elastic parameters for a Leda clay determined from CID tests.

Parameter	Loading	Unloading
E_v , psi ^a	680	1400
E_h , psi	370	940
G_{vh} , psi	290	510
μ_{hh}	0.10	0.29
μ_{vh}	0.08	0.30

^a1 psi = 6.8948 kPa.

Concluding Remarks

While the strength behavior of anisotropic clays has been investigated in terms of both total and effective stresses, the study of anisotropic deformation behavior has been rarely performed, probably because of the inadequacy of conventional test apparatus for accurate measurements of small lateral deformation.

This paper describes an apparatus and an experimental arrangement that appear to fulfill this purpose. The system employs light gage points and displacement transducers floated in a cell fluid so that internal strains may be measured directly on the specimen with the least amount of disturbance. Using specimens trimmed from a block sample of a soft sensitive clay, performance data have been obtained to indicate that the apparatus developed possesses adequate precision and stability for the study of deformation behavior of clays.

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