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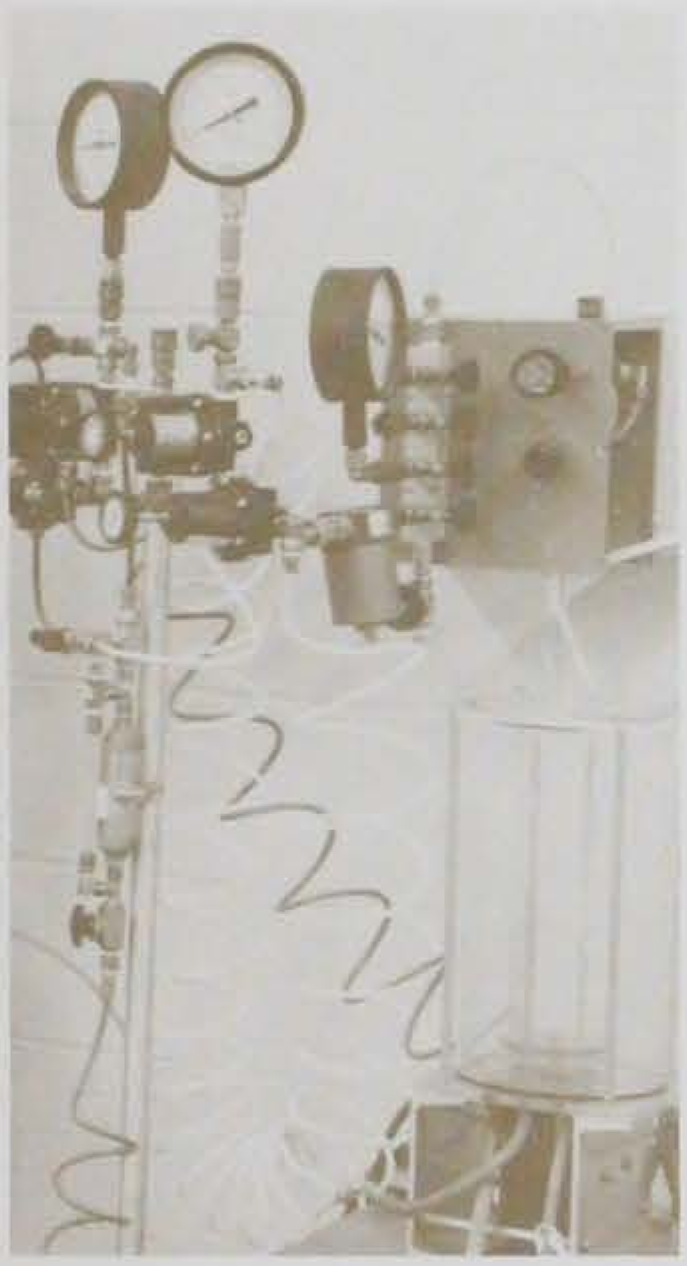

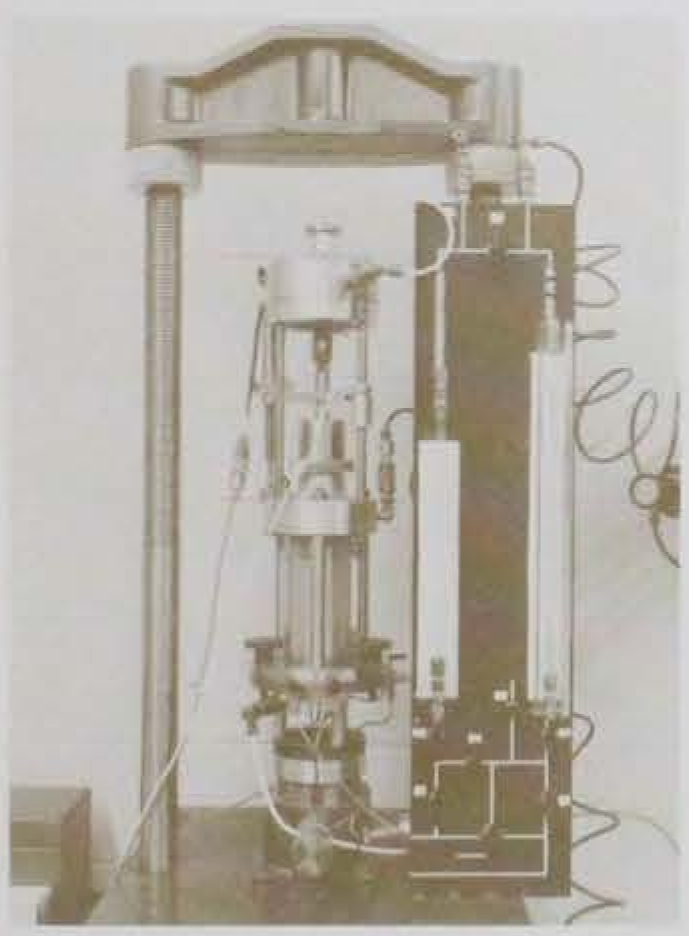

GEOTECHNICAL
LABORATORY

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MEASUREMENT OF HORIZONTAL AND VERTICAL SWELL PRESSURES FROM A TRIAXIAL LABORATORY TEST; A FEASIBILITY STUDY

by

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Horizontal and vertical swell pressures in cohesive soil influence the performance of permanent military facilities found on such soils. Horizontal pressures influence skin friction on deep foundations that may lead to uplift and heave of foundations in expansive soil or downdrag and settlement in consolidating or collapsible soil. Excessive horizontal pressures on basement and retaining walls may require uneconomical structural designs. Vertical swell pressures in foundation soils often lead to foundation heave and may cause structural distress.

The purpose of this study was to determine the feasibility of evaluating vertical and horizontal swell pressures using a triaxial test apparatus. This work developed a double chamber triaxial apparatus and test procedure to measure vertical and horizontal swell pressures caused by introducing water to a 1.4-in. diam by 3.5-in. high soil specimen subject to no volume change. This equipment and test procedure eliminate lateral skin friction normally

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present during one-dimensional consolidation testing and should provide improved results compared with tests performed in a one-dimensional consolidometer. The specimen may subsequently be consolidated and rebounded without lateral skin friction to evaluate consolidation parameters. The shear strength may also be determined on the same specimen following measurement of the swell pressures or consolidation parameters. Lateral confining pressure on the specimen is currently limited to 80 psi to accomplish the purpose of this study, but the pressure may be increased up to 200 psi after further calibration tests. Applied horizontal pressures cannot exceed vertical applied pressures; this apparatus will measure lateral expansion if horizontal swell pressures exceed the horizontal applied pressure.

Results of three series of tests performed on two different expansive soils trimmed from undisturbed boring samples indicated no difference in swell pressure between vertical and horizontal orientations of the specimen. Optical analysis of two thin sections of intact soil prepared from one of the soil samples indicated birefringence or anisotropy. Consolidation and strength parameters determined using the double chamber triaxial apparatus are also consistent with those performed on similar specimens using other test apparatus. An exception is that the elastic modulus evaluated for soil specimens tested in the double triaxial chamber provides an upper bound limit up to two times (four times for soft soils) of that evaluated from standard triaxial tests. This is attributed partly to friction from an O-ring required to pass the vertical loading ram through the outer chamber into the inner chamber and use of a solid piece of geotextile filter fabric to promote flow of water in and out of the specimen.

Additional work should be performed to expand the lateral range of confining pressures that may be applied by the apparatus. A variety of filter fabrics should be tested to further reduce the calibration correction and improve evaluation of the elastic modulus. A variety of undisturbed clays and clay shales should be tested to confirm the observation that swell pressures are isotropic under no volume conditions. This study has shown that measurement of vertical and horizontal swell pressures prior to consolidation or strength tests is feasible.

PREFACE

This study was performed during the period October 1985 to September 1987 at the US Army Engineer Waterways Experiment Station (WES), for the Assistant Secretary of the Army (R&D) as an In-House Laboratory Independent Research (ILIR) Program under Project No. 4A161101A91D, Task 02.

Dr. L. D. Johnson, Research Group, Soil Mechanics Division (SMD), Geotechnical Laboratory (GL) conceived the project and accomplished the work. The double chamber triaxial cell was designed and fabricated by Mr. B. N. MacIver in 1970 while an employee of WES. Mr. D. A. Leavell, Soil Research Facility, SMD, designed and fabricated the pore pressure system of the apparatus. Mr. S. Bell, Instrumentation Services Division, assembled and calibrated the electronic equipment. Mr. J. Burkes, Petrography Unit, Materials and Concrete Analysis Group, Structures Laboratory, performed optical analysis of the particle orientation. Personnel of the Soils Testing Facility, SMD, completed the standard classification, consolidation, and strength tests.

Drs. P. F. Hadala, Assistant Chief, GL, J. F. Peters, Soil Research Facility, SMD, and Mr. C. L. McAnear, Chief, SMD, reviewed the report and provided many helpful comments. The work was performed under the direct supervision of Mr. McAnear, Chief, SMD, and the general supervision of Dr. W. F. Marcuson III, Chief, GL. The report was edited by Ms. Odell F. Allen, Information Products Division, Information Technology Laboratory.

COL Dewayne G. Lee, CE, was the Commander and Director of WES during the conduct of the study and preparation of this report. Dr. Robert W. Whalin was Technical Director.

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC)
UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
degrees (angle)	0.01745329	radians
feet	0.3048	metres
inches	2.54	centimetres
pounds (force)	4.448222	newtons
pounds (force) per square inch	6.894757	kilopascals
square inches	6.4516	square centimetres
tons (mass) per square foot	9,764.856	kilograms per square metre

MEASUREMENT OF HORIZONTAL AND VERTICAL SWELL PRESSURES FROM A TRIAXIAL LABORATORY TEST; A FEASIBILITY STUDY

PART I. INTRODUCTION

Background

1. Horizontal and vertical swell pressures in cohesive soil influence the performance of many military and civilian structures. Horizontal pressures influence the magnitude of skin friction on deep foundations that may lead to uplift thrust and heave of the foundation in expansive soil or downdrag and settlement in consolidating soil. Horizontal pressures cause a lateral thrust on basement and retaining walls that may be large in expansive soil and require uneconomical structural designs. Vertical swell pressures in foundation soils often lead to heave of foundations and may cause structural distress. These horizontal and vertical swell pressures should be evaluated to determine optimal design and construction techniques. Expansive soils, which are widely distributed throughout the world, are frequently encountered in practice.

Description of swell pressure

2. Definition. Swell pressure σ_s can develop in clay soils on contact with water and can lead to extensive damages to overlying structures and pavements from the swell that accompanies relief of the swell pressure. Swell pressures exceeding 70 psi or even more have been observed (Komornik and David 1969) and can be expected depending on the nature of the soil. Swell pressure has been described by at least the four different definitions given in Table 1. The magnitude of swell pressure depends on the degree of confinement and usually decreases in the order of method A > B > C > D. Table 1 compares some differences between these methods.

3. Mechanism. Swell pressure develops from the hydration of clay mineral platelets and exchangeable cations. Clay platelets of the Montmorillonite or Smectics Group are most susceptible to expansion on hydration, particularly sodium bentonites. The extent of hydration leading to the

Table 1

Description of Swell Pressure

Method: Johnson and Stroman (1976)	Method: ASTM D 4546	Definition	Remarks
A	A	Pressure required to bring soil back to the original volume after the soil is allowed to swell completely without surcharge (except for an initial small seating pressure).	May lead to larger swell pressures because this method incorporates hysteresis that tends to overcome sample disturbance.
B		Pressure applied to the soil so that neither swell nor compression takes place on inundation. A specimen may be confined and pressure inferred from deflection of the confining vessel.	A null test in which meassured swell pressures are influenced by apparatus stiffness. Apparatus of higher stiffness leads to less expansion on swelling. Large swell pressures can be relieved with small specimen expansion; therefore, stiffer apparatus can provide improved control over one-dimensional changes and can lead to improved measurements of swell pressure.
C	C	Pressure necessary to permit no change in volume upon inundation when initially under applied pressure equal to the total overburden pressure. Various loads are applied to the soil after inundation to maintain no volume change.	Test must be corrected for sample disturbance. A suitable procedure for one-dimensional consolidometer swell tests is described in ASTM D 4546. One-dimensional consolidometer tests are also influenced by lateral skin friction, especially tests conducted on stiff clays or shales.
D		Pressure required for preventing volume expansion in soil in contact with water. Various loads are applied to the soil after inundation to maintain no volume change.	This requires correction of swell pressure similar to Method C above, but a standard correction procedure is not available.

development of swell pressure depends on the factors described in Table 2. Other literature (Komornik and David 1969, Snethen et al. 1975, O'Neill and Poormoayed 1980) shows that swell pressure is a function of void ratio, dry density, initial water content, and Atterberg limits; these soil parameters are scalar quantities. The swell pressure may also approximate the soil suction without confining pressure (negative pore water or capillary pressure) for some clays when the degree of saturation is one (Johnson and Snethen 1978, Johnson 1984). The soil suction may exceed the swell pressure when the degree of saturation is less than one where voids contain air as well as water. All of these studies refer to swell pressure as a scalar quantity essentially independent of the orientation of the clay minerals in the soil. Swell pressure measured under a no volume change condition may be isotropic because the swell pressure essentially originates from the pressure in water being sorbed into the soil; liquid water exerts or transmits isotropic pressure.

4. Skempton (1961) indicated that the capillary pressure (or suction in the soil subject only to atmospheric air pressure) is a function of the vertical effective stress

$$\sigma_k = \sigma'_v \left[K_o - A_s(K_o - 1)\right] \tag{1a}$$

where

σ_k = capillary pressure, psi

σ'_v = vertical effective stress, psi

K_o = coefficient of earth pressure at rest

A_s = pore pressure parameter on change in pore pressure during sampling

The values of A_s for many swelling clays which retain high degrees of saturation for suctions exceeding 1,000 psi varied from 0.25 to 0.7 (Skempton and Bjerrum 1957, Blight 1967). If $A_s \approx 1/3$, Equation 1a reduces to

$$\sigma_k = \sigma'_v \left(\frac{2K_o + 1}{3}\right) = \sigma'_m \tag{1b}$$

Table 2

Factors Influencing Swell Pressure

(After Johnson and Stroman 1976)

Factor	Effect
Ion concentration in soil solution	Swell pressure decreases with larger ionic concentration.
Valency of adsorbed cation	Swell pressure decreases with larger valency.
Temperature	Swell pressure increases with higher temperature.
Surface charge density of clay mineral	Swell pressure decreases with larger surface charge density.
Void ratio or dry density	Swell pressure increases with decreasing void ratio or increasing density. Preloading increases swell pressure because of increased density.
Surface tension or suction	Swell pressure increases with larger suction. Suction is a negative pore or capillary pressure in the soil water.
Structure	Flocculated structure (compacted dry of optimum water content) exhibits larger swell pressure than dispersed structure (compacted wet of optimum water content). Cementation or bonds found in undisturbed soil tends to reduce swell pressure.

where σ'_m is the mean effective stress. The capillary pressure or suction is essentially a mean effective stress. The in situ suction h of such swelling clays is approximately (after Richards 1986)

$$h = \sigma_k - [\sigma_3 + A_s(\sigma_1 - \sigma_3)] \approx \sigma_k - \sigma_m \tag{1c}$$

where

σ_3 = total minor stress, psi

σ_1 = total major stress, psi

$A_s \approx 0.4$

σ_m = total mean stress, psi

The above equations were confirmed for similar swelling soils (Chandler and Gutierrez 1986, Johnson 1980). Other literature also relates soil suction to effective stress (Johnson and Snethen 1978).

5. The capillary pressure may also be determined from the soil shear strength (Skempton 1961):

$$\sigma_k = \sigma'_3 + A_f(2Cu) \tag{2}$$

where

σ'_3 = minor principal effective stress at failure, psi

A_f = pore pressure coefficient at failure in a drained test

C_u = undrained shear strength, psi

Methodology is also available to evaluate lateral active and passive earth pressures which requires details on the effective friction angle of the soil, angle of shearing resistance with respect to changes in soil suction, and in situ pore water pressures (Pufahl, Fredlund, and Rahardjo 1983; Schulz and Khera 1986).

Measurement of swell pressure

6. Most procedures for measuring swell pressures require a one-dimensional consolidometer device. Development of swell pressure on inundation with water is time dependent, perhaps extending over a period of 4 to 7 days or longer because of the slow rate of water sorption, low hydraulic conductivity, readjustment of particles, and specimen size and thickness.

Swell pressure may decrease with time after reaching a maximum because of rearrangement of particles along the direction of water flow or because of interparticle collapse.

7. Vertical swell pressure. Vertical swell pressures σ_{sv} are commonly measured by one-dimensional consolidometer swell tests such as those described in American Society for Testing and Materials (ASTM) D 4546 (ASTM 1986b). This standard describes procedures for evaluation of swell pressure by Methods A and C described in Table 1. A basic disadvantage of the one-dimensional consolidometer test is sidewall friction that may influence the swell pressure measured in the vertical direction. Schindler (1968) estimated the lateral friction loss assuming that slippage occurs at the soil-sidewall interface in accordance with the Mohr-Coulomb law and the normal stress between the soil and the sidewall at any depth in the specimen is directly proportional to the average vertical stress at that depth. Schindler calculated a friction loss of about 9 percent for a consolidometer with a diameter to height ratio of 4 and a 4 percent loss for a diameter to height ratio of 10. These estimates are qualitative because actual friction loss is more complex than assumed (e.g., sidewall friction loss is also a function of specimen stiffness). Method C of ASTM D 4546 describes an empirical procedure for correcting vertical swell pressures measured under no vertical movement in a one-dimensional consolidometer.

8. Horizontal swell pressure. Standard test methods are not yet available for measurement of horizontal swell pressures σ_{sh} . Several methods for measuring horizontal swell pressures are summarized in Table 3. These methods are similar to the null procedure of Method B, Table 1. All of these methods, except the Snethen and Haliburton (1973) triaxial cell method, are variations of the one-dimensional consolidometer test in which the specimen ring is instrumented with strain gages or pressure transducers to measure lateral swell pressure. These methods can be adapted to include the measurement of vertical swell pressure.

9. Single point measurements of lateral pressure such as the pressure transducer method of Abdelhamid and Krizek (1976) may provide misleading results because strains may not be uniform. The double wall method of Ranganatham and Pandian (1975) designed to eliminate sidewall friction in one-dimensional consolidometers appears promising, but results were not provided.

Table 3

Methods for Evaluating Horizontal Swell Pressure

Reference	Description
Komornik and Zeitlen 1965	Lateral pressure was measured in a fixed ring consolidometer. The specimen ring is a stainless steel thin wall 0.03 cm thick with three electrical resistance wire gages mounted around the outside circumference. The deflection of the ring was calibrated to evaluate change in lateral pressure per unit deflection from specimen wetting. Specimen diameter was 11.15 by 2.54 cm high. It also measures vertical swell pressure and swell.
Snethen and Haliburton 1973	Lateral pressure was measured in a single chamber lucite wall triaxial type cell. The chamber was filled with deaired distilled water. Lateral swelling of the wetted specimen caused the water in the chamber to increase in pressure which is measured by a pressure transducer. It also measures vertical swell pressure.
Ranganatham and Pandian 1975	Lateral pressure measured in a fixed ring consolidometer with a soil specimen 2.54 by 7.6 cm in diameter. A brass tube 2.54 cm high with wall thickness of 0.32 cm split into six equal sections is glued to a rubber membrane 8.25 cm in diameter. A lucite cylinder encloses the specimen and brass ring (tube) forming an annular space (chamber) between the membrane and lucite. This space is filled with water and back pressure applied to restrain lateral movement of a wetted specimen. No results were reported.
Abdelhamid and Krizek 1976	Lateral pressure was measured in a consolidometer device using two pressure transducers mounted on opposite sides of the specimen ring.

Limited studies of compacted clays by Komornik and Livneh (1967) using a consolidometer apparatus (diameter/height ratio of 4) for measuring lateral swell pressure (Komornik and Zeitlen 1965) and a Potential Volumetric Change (PVC) meter (Lambe 1960) indicated that swell pressure was not affected by particle anisotropy at zero swell. Komornik and Zeitlen (1970) later measured in the consolidometer device lateral swell pressures that usually exceeded vertical swell pressures when vertical swell was permitted in the specimen. Differences between lateral and vertical swell pressures decreased when the percent vertical swell decreased. Lateral skin friction may account for the difference between measured lateral and vertical swell pressures at zero volume change. Vertical pressures exceeded measured lateral pressures at relatively high vertical pressures.

10. The triaxial cell method of Snethen and Haliburton (1973) does not have the disadvantage of sidewall friction, but deflection of the lucite chamber can be substantial at large swell pressures leading to relatively large corrections. Snethen and Haliburton (1973) measured no difference between lateral and vertical swell pressures for two compacted Oklahoma cohesive soils when compacted on the dry side of optimum water content. The lateral to vertical swell pressure ratio was between 0.5 to 0.65 at water contents above optimum. Methods in Table 3 were not adapted to determining the shear strength of the soil, a parameter needed for design. These equipment and methods were primarily research tools and not directed toward routine applications.

Purpose and Scope

11. The purpose of this work is to determine the feasibility of evaluating vertical and horizontal swell pressures from triaxial apparatus that is capable of consolidating the specimen and determining the shear strength. The intent is to develop an economical testing procedure to permit practical measurement of vertical and horizontal swell pressures prior to consolidation or measurement of the undrained shear strength in cohesive soil. This test will also provide data on the relationship between swell pressures in vertical and horizontal directions of anisotropic undisturbed clay.

12. The test adopted to accomplish the purpose of this study is a variation of the null Method B (Table 1) using a triaxial cell. The triaxial cell eliminates error in swell pressure measured relative to sidewall friction. A double triaxial chamber is applied to minimize corrections and to increase accuracy of the swell pressure measurements. The apparatus also includes a vertical loading ram for measurement of soil shear parameters. Procedures were developed for calibrating the apparatus and for performing soil tests. Several tests using undisturbed cohesive CH clay soil of different stiffnesses and which have the potential for expansion were performed in the apparatus to measure horizontal and vertical swell pressures, consolidation parameters, and the undrained shear strength of the soils. A petrographic examination was conducted to confirm the anisotropy of some of the soils. Soil parameters evaluated from the double chamber apparatus were compared with swell pressures, consolidation parameters, and shear strength parameters measured using conventional equipment to assist evaluation of the feasibility of the adopted test procedures.

PART II. EQUIPMENT AND TEST PROCEDURES

Equipment and Setup

13. Equipment consists of a double chamber triaxial cell, pore pressure system with a 10 cc specimen burette and 25 cc inner chamber burette, and monitoring devices as shown in Figure 1. All valves used in the apparatus are 1/8-in. ball-type valves. A porous stainless steel disk 1.4 in. diam by 1/8-in. thick, filter fabric 1.4 in. diam, and specimen 1.4 in. diam by 3.5 in. high is mounted on the central pedestal inside the inner chamber. Another filter, porous stainless steel disk and top loading cap are mounted on top of the specimen. Task A of Table 4 gives details on setup of the apparatus.

14. The 1.4-in.-diam filter fabric disks placed between the porous steel disks and top and bottom of the specimen and a piece of filter fabric 4.5 in. square wrapped around the perimeter of the specimen are made of a Typar geotextile. This fabric was selected because it has high permeability and low compressibility (Peters and Leavell 1986), which will promote drainage to the specimen and minimize correction of the specimen and chamber burette readings. One or two latex membranes are subsequently placed around the filter fabric and specimen.

15. Electronic devices were used to monitor the load applied to the 500 lb load cell, vertical dimensional changes of the specimen, and pressure of the fluid in the inner and outer chambers. The load cell is a transducer Model WML2-51-500-P with a range of 500 lb and sensitivity of 2 mv/volt. The maximum vertical pressure that can be applied to a 1.4-in.-diam specimen can approach 300 psi. The vertical deformation is monitored by a linear variable differential transformer with a range of $\pm$ 1.0 in. with sensitivity of 0.001 in./0.001 v. The chamber pressure is monitored by a BLH Endevco pressure transducer of 200 psi range with sensitivity of 0.1 psi/0.001 v. A photograph of the apparatus is shown in Figure 2.

Test Procedure

16. The sequence of operation is to perform the swell pressure test first. When no further tendency to swell or consolidate exists, the specimen

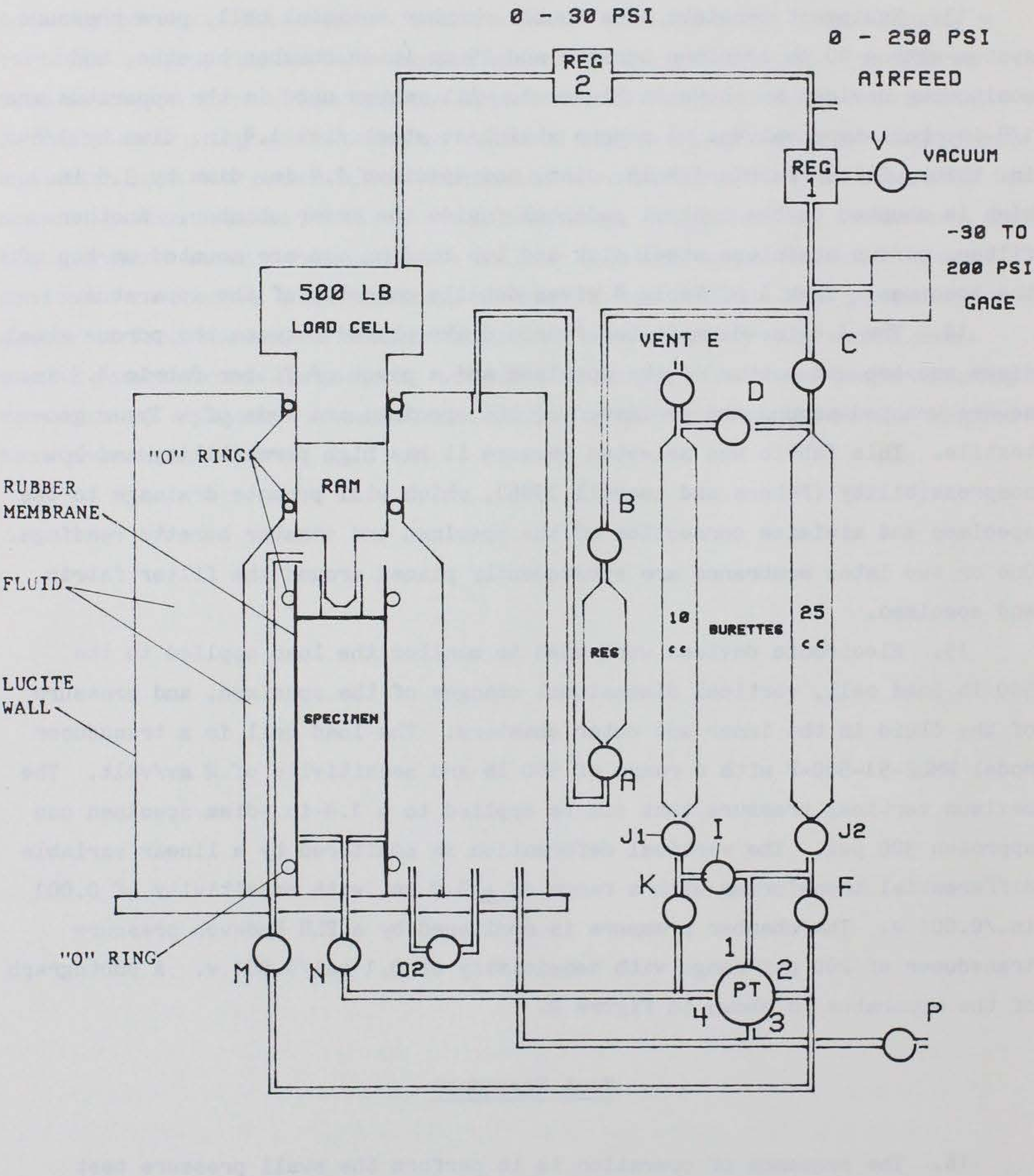


Figure 1. Schematic diagram of apparatus

Table 4

Soil Test Procedure

Task	Step
A. Setup	1. Clear specimen line and burettes.
	2. Trim specimen to 1.4 in. diam by 3.5 in. high; measure and record dimensions and weight.
	3. Mount specimen using two latex membranes; use silicone grease and O-rings to seal membranes.
	4. Assemble apparatus.
	5. Close all valves.
B. Dear system	1. Adjust AIRFEED to at least 25 psi.
	2. Open V and adjust REG 1 to apply vacuum.
	3. Open C, D, J1, K, N, J2, F, B, A, O2, M.
	4. Close D, J1, K, N, M; check I closed.
C. Fill double chamber with deaired distilled water	1. Connect distilled water to P; deair water to valve P.
	2. Check C, O2, F, J2, B, A open; vacuum should be on chambers.
	3. Check PT down in position 3.
	4. Open deaired water to air.
	5. Open P and fill at moderate rate (≈ 3 mm/sec).
	6. Close A when water at 1/2 level in RES 2; wait 1 min, then open M.
	7. Close J2 when water rises in 25 cc burette through J2 to about 6 cc level; close O2, P.
	8. Apply $\sigma_1 = \sigma_3 = 1$ psi isotropic pressure through REG 1 and read J2 (25 cc burette).
	9. Open A, J2, E, J1, K, N; take all readings except J1.
	10. Apply $\sigma_1 = \sigma_3 = \sigma_v$ soil overburden pressure through REG 1 and take readings (except J1) for approximately 24 hr; correct J2 burette readings from calibration curves when σ_v is applied.
D. Saturate specimen and prevent swell	1. Connect deaired distilled water to valve P; open deaired water to air.
	2. Switch PT up to position 1.
	3. Close J2, F, A, E, J1, K, N.
	4. Apply vacuum through valve C and open D, J1, K, N.
	5. Close K, N, and open I.
	6. Open P to fill 10 cc burette through J1 to 0.0 ml level; close P, I, J1, D.

(Continued)

Table 4 (Concluded)

Task	Step
	7. Reapply $\sigma_1 = \sigma_3 = \sigma_v$ through REG 1.
	8. Open J2, F, A.
	9. Open vent E, J1, K and measure water level in 10 cc burette.
	10. Open N and measure water level in J1 when it stabilizes after a few seconds; measure water level in J2.
	11. Adjust σ_3 through REG 1 to maintain no volume change in burette J2; correct burette reading J2 from calibration curves for changes in pressure.
	12. Adjust deviator stress $\sigma_1 - \sigma_3$ through REG 2 to maintain no change in vertical deformation.
	13. Repeat steps 11 and 12 until no further tendency to swell.
E. Consolidation and shear	1 Apply isotropic confining pressures of 10, 20, 40, and 80 psi through REG 1 to consolidate the specimen allowing 24 hr per pressure increment; record vertical dimension and burette level readings.
	2. Rebound isotropic confining pressure to 20 psi for 24 hr, then to the swell pressure for 24 hr; take readings for each pressure decrement.
	3. Close valve N to maintain undrained condition.
	4. Perform Q test at constant σ_3 applying deviator stress increments to fail specimen in approximately 30 min; take readings at each deviator stress increment.
F. Disassembly	1. Switch PT down to position 3; make sure N closed.
	2. Open O2.
	3. Open P to drain chambers.
	4. Disassemble apparatus.
	5. Remove specimen and weigh; determine final specimen water content.

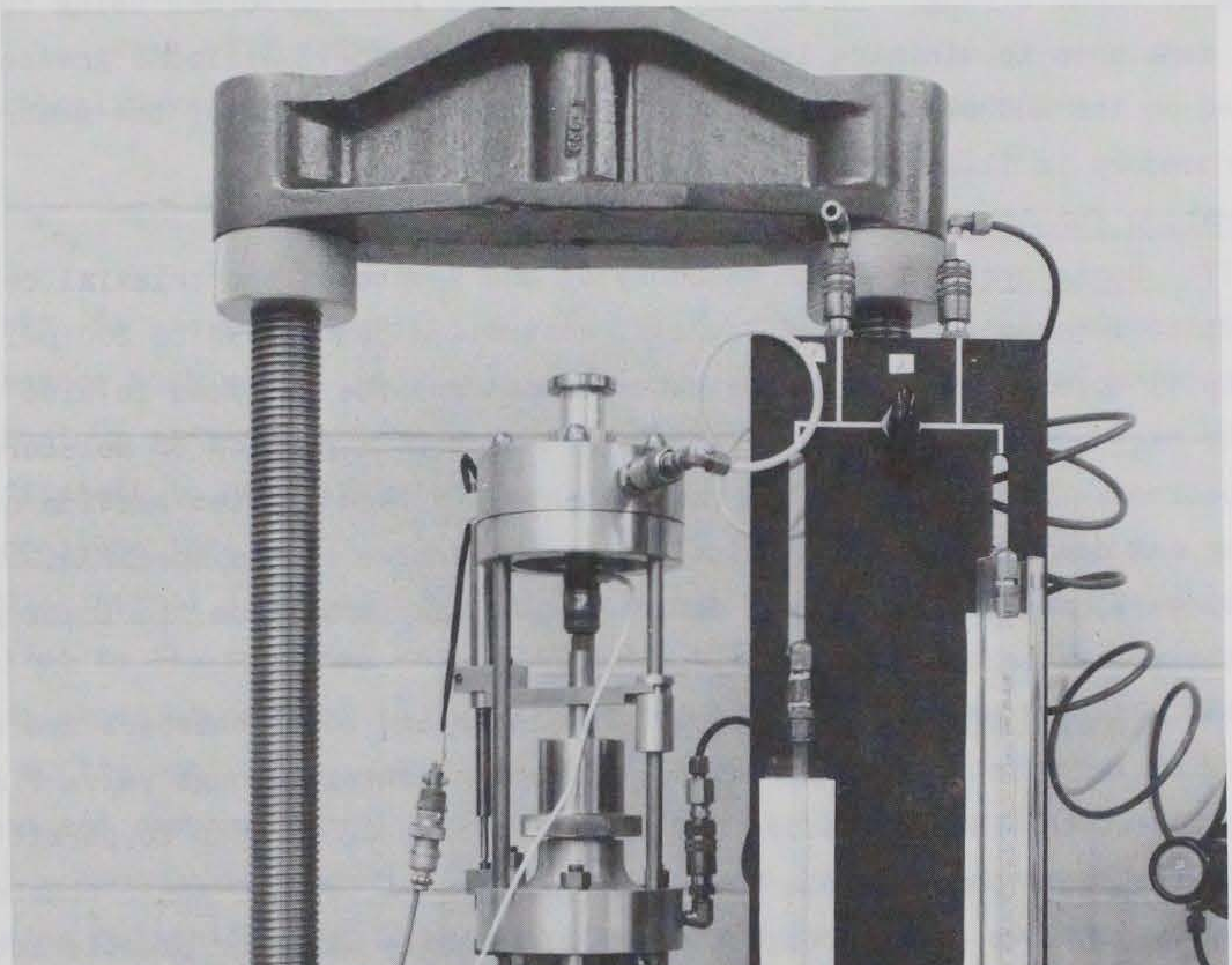


Figure 2. View of the apparatus

may be consolidated to determine consolidation parameters or a particular state of effective stress if desired. Then a shear test may be performed to determine shear strength parameters. Soil tests were performed using two latex membranes to minimize leaks through the membrane. Silicone grease was applied on the end platens to eliminate seepage at the ends of the membranes. The procedure is illustrated in Table 4.

Preparation for test

17. Deair system. After assembly of the apparatus the triaxial cell is subject to a vacuum, Task B of Table 4, controlled by the -30 to 200 psi gage (Figure 1) to deair the inner and outer chambers. The specimen is also subject to the vacuum to avoid air bubbles and promote migration of moisture into the specimen. The vacuum in the inner chamber in turn applies suction on the loading ram causing a small vertical seating pressure on the specimen. Some initial vertical compression may occur in soft specimens from the loading ram when the vacuum is applied in the inner chamber.

18. Filling of double chambers. The inner and outer chambers are subsequently filled with deaired and distilled water flowing through valve P and up the bottom of the outer chamber (Figure 1). Valve 02 is open to permit fluid to fill the inner chamber from the outer chamber. After the inner chamber is filled, water flows down through the 1/8-in. outside diameter plastic tubing that surrounds the specimen and out through valves M, F, and J2 into the 25 cc burette. This arrangement minimizes any air bubbles within the inner chamber. Fluid changes in the 25 cc burette are used to monitor lateral dimensional changes in the specimen.

19. Application of chamber pressure. Chamber pressure is applied through REG 1 shown in the schematic diagram to control the isotropic $\sigma_1 = \sigma_3$ pressure applied to the specimen. A vertical stress is applied by 0 to 30 psi air pressure controlled through REG 2 to the 500 lb load cell. A force F required in the load cell to balance the chamber pressure is given by

$$F = \sigma_3 A_o \tag{3}$$

where

F = force to balance chamber pressure, lb

σ_3 = chamber pressure, psi

A_o = area of specimen pedestal, 1.53 in.^{2}

The vertical deviator stress applied to the specimen is therefore

$$\sigma_1 - \sigma_3 = \frac{F^* - F}{A_o} \tag{4}$$

where F^* is the force applied by the 500 lb load cell. The maximum confining pressure that may be applied by this system is expected to be about 200 psi. Maximum pressure actually applied to the inner chamber was 80 psi, which was sufficient to determine feasibility of this test procedure.

Swell pressure test

20. Initial isotropic pressure. The above described isotropic pressure is applied to the specimen for approximately 24-hr prior to giving the specimen free access to water. A 24 hr initial compression time was selected to assure sufficient time to minimize any residual fluid level changes in the specimen and chamber burettes. The required corrections to the measured lateral volume changes of the specimen discussed below are reduced, thereby increasing reliability of the swell pressure measurements. Future studies should investigate the effect of reducing time for initial compression. The initial applied pressure in this study is the estimated in situ total vertical overburden pressure.

21. The pore pressure in the specimen is subject to atmospheric air through valves N, K, J1, 10 cc burette, and vent E (Figure 1). If a positive pore water pressure existed in the specimen when in situ, then some positive pore pressure developed following application of the isotropic pressure to the specimen may be relieved during the 24 hr initial compression time. This depends on the degree of soil disturbance and magnitude of the horizontal in situ earth pressure.

22. Access to free water. Distilled water is drawn into the 10 cc burette through valves P, I, and J1 after the initial compression. Distilled water was used in this study to provide a basis for comparison between swell pressure tests. Fluid changes in the 10 cc burette are used to monitor the amount of water sorbed into or expelled from the specimen. Fluid level

changes in the 10 cc and 25 cc burettes may be monitored to within 0.05 cc.

23. Adjustment of vertical and horizontal pressures. The specimen is initially subject to sufficient isotropic $\sigma_1 = \sigma_3$ pressure through REG 1 to prevent vertical and lateral swell. If the vertical swell pressure exceeds the horizontal swell pressure, then a deviator stress will also be required through REG 2 to prevent any dimensional changes.

24. The existing test equipment does not permit applied lateral pressures to exceed the vertical applied pressures because the loading ram is not attached to the top cap placed on the top porous disk; therefore, horizontal swell pressures exceeding vertical swell pressures cannot be measured with this arrangement. If the horizontal swell pressure in a soil should exceed the vertical swell pressure during a test, the specimen will expand laterally under an isotropic pressure equal to the vertical swell pressure. The chamber volume changes can be measured if lateral swell occurs under isotropic pressure suggesting that the horizontal swell pressure would have been greater than the vertical swell pressure under a no swell condition. The apparatus can be modified to secure the top cap on the loading ram if soil tests indicate that this is necessary.

25. Swell pressures evaluated in the triaxial double chamber apparatus were not corrected using any procedure as described for Method C of ASTM D 4546 for one-dimensional consolidometer tests. Such correction procedures are empirical and the consolidometer correction method may not be applicable to a triaxial test where lateral skin friction does not exist.

Consolidation test

26. A consolidation test may be performed following measurement of swell pressure. At the conclusion of the swell pressure test while confining pressures are still applied to the specimen, pore pressures in the specimen are assumed zero. Pore pressures were not measured during this study although this capability may be added later.

27. Isotropic consolidation. Some specimens were isotropically consolidated under 20, 40, and 80 psi pressure allowing 24 hr for each of these pressure increments. A time interval of 24 hr between pressure increments was selected based on ASTM D 2435 (ASTM 1986a) which recommends at least 24 hr for soils of low permeability. Longer consoliation time may be necessary if secondary compression must be evaluated.

28. Rebound. The specimens were rebounded with drainage to 20 psi isotropic confining pressure in one increment and held at this pressure for 24 hr, then rebounded to the swell pressure. If the swell pressure exceeded 20 psi, the specimens were simply rebounded to the swell pressure. Time-consolidation data may be obtained during the consolidation test.

Strength tests

29. The shear strength may be evaluated following conclusion of the swell pressure or consolidation tests. The undrained strength may be determined by closing valve N prior to this test (Figure 1). The vertical stress was increased in 1-min increments to cause failure of the specimen in approximately 20 to 30 min to be similar to the time rate for undrained Q tests described in EM 1110-2-1906 (Headquarters, Department of the Army 1970). Pore pressures were not measured in these specimens, but the apparatus may be adapted to the measurement of pore pressures and strain controlled shear parameters.

Calibration Tests

30. An important advantage of this equipment and its principle of operation is that the specimen is not subject to lateral skin friction as in a one-dimensional consolidometer test. Therefore, measured swell pressures should be more realistic, especially when testing stiff clays, than those swell pressures measured in a one-dimensional consolidometer. However, this equipment lacks stiffness in the lateral direction. Calibration tests are therefore required to determine the correction that must be made to the volume change readings in the specimen and chamber burettes.

31. The double chamber allows the inner chamber to be sealed when valve 02 is closed (Figure 1). The inner chamber wall is subject to identical pressure on both sides eliminating any large correction required to fluid level changes in the 25 cc burette caused by deflection of the chamber walls. The correction for deflection that remains to be applied to fluid level changes in the 25 cc burette is caused by deflection of tubing, compressibility of water, and compression of the membranes covering the specimen when chamber pressure is applied.

32. Table 5 illustrates the procedure for calibration of the apparatus

to correct for specimen and chamber volume changes because of deflections in the apparatus. This procedure initially deairs the chambers of the triaxial cell to minimize compressibility of the chamber fluid and deairs any space within the membrane or membranes containing the stainless steel specimen. Variations of the calibration procedure in Table 5 were made as described below to optimize reliability of the test. It was determined during these calibration tests that the correction for vertical deformation was from less than 0.003 in. to 100 psi vertical pressure, and it was neglected. The filter cage used around the dummy specimen during calibration and during most of the soil tests was a 4.5-in. by 4.5-in. square of solid Typar geotextile fitted around the specimen perimeter.

Single membrane, M open

33. The calibration procedure is described in Table 5, except valve M was left open in Task B4 to allow the distilled and deaired chamber water to flow through M, F, and J2 into the 25 cc burette as soon as the fluid level in the inner chamber reached the top open end of the plastic tubing surrounding the specimen (Figure 1).

34. The fluid level changes in the specimen (10 cc) and inner chamber (25 cc) burettes for this calibration procedure using a single membrane are shown in Figure 3 for up to 80 psi isotropic chamber pressure. Figures 3a and 3b are the fluid level results of two independent calibrations, Test C1 and Test C2. Figure 3c shows the fluid level results of a repeat of Test C2, which was performed without any disassembly of the apparatus following Test C2. The results of repeating Test C2 show smaller fluid level changes than the earlier two calibration tests.

35. The fluid level changes shown for the chamber (25 cc) burette in Figure 3 are attributed to residual space between the membrane and specimen, compressibility of water, compression of the membrane and filter fabric, and deflections in tubing. The smaller fluid level changes shown in the specimen (10 cc) burette are caused by changes in the volume of water occupying space between the membrane and the specimen. This space is reduced with increasing confining pressure in the inner chamber that pushes water into the 10 cc burette while increasing the volume in the inner chamber and reducing the fluid level in the 25 cc burette. The slightly smaller specimen fluid level changes shown for the repeat of Test C2 (Figure 3c) compared with Figures 3a

Table 5

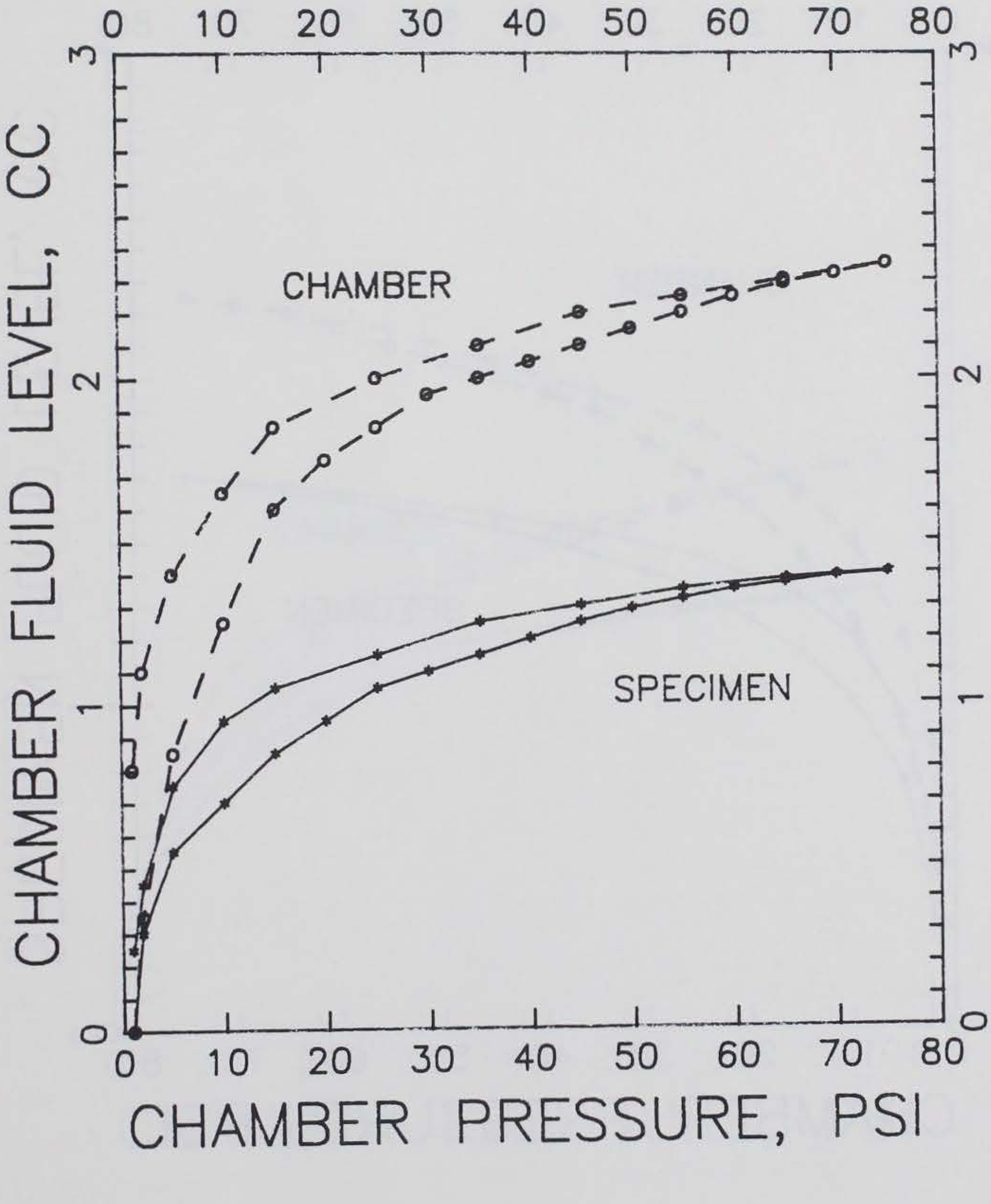
Calibration Test Procedure

Task	Step
A. Setup	1. Clear specimen line and burettes.
	2. Mount steel specimen with latex membranes; use silicone grease and O-rings to seal membranes.
	3. Assemble apparatus.
	4. Close all valves.
B. Deair system	1. Adjust AIRFEED to at least 25 psi.
	2. Open V and adjust REG 1 to apply vacuum.
	3. Open C, D, J1, K, N, J2, F, B, A, 02, M.
	4. Close D, J1, K, N, M; check I closed.
C. Fill double chamber with deaired distilled water	1. Connect distilled water to P; deair water to valve P.
	2. Check C, 02, F, J2, B, A open; vacuum should be on chambers.
	3. Check PT down in position 3.
	4. Open deaired water to air.
	5. Open P and fill at moderate rate (≈ 3 mm/sec).
	6. Close A when water at 1/2 level in REG 2; wait 1 min, then open M.
	7. Close J2 when water rises in 25 cc burette through J2 to about 6 cc level; close 02, P.
	8. Apply $\sigma_1 = \sigma_3 = 1$ psi isotropic pressure through REG 1 and read J2 (25 cc burette).
	9. Open A, J2, E, J1, K, N; take all readings except J1.
D. Saturate stainless steel specimen	1. Connect deaired distilled water to valve P; open deaired water to air.
	2. Switch PT up to position 1.
	3. Close J2, F, A, E, J1, K, N.
	4. Apply vacuum through valve C and open D, J1, K, N.
	5. Close K, N, and open I.
	6. Open P to fill 10 cc burette through J1 to 0.0 ml level; close P, I, J1, D.
	7. Reapply 1 psi to REG 1.
	8. Open J2, F, A.
	9. Open vent E, J1, K and measure water level in 10 cc burette.
	10. Open N and take all readings.

(Continued)

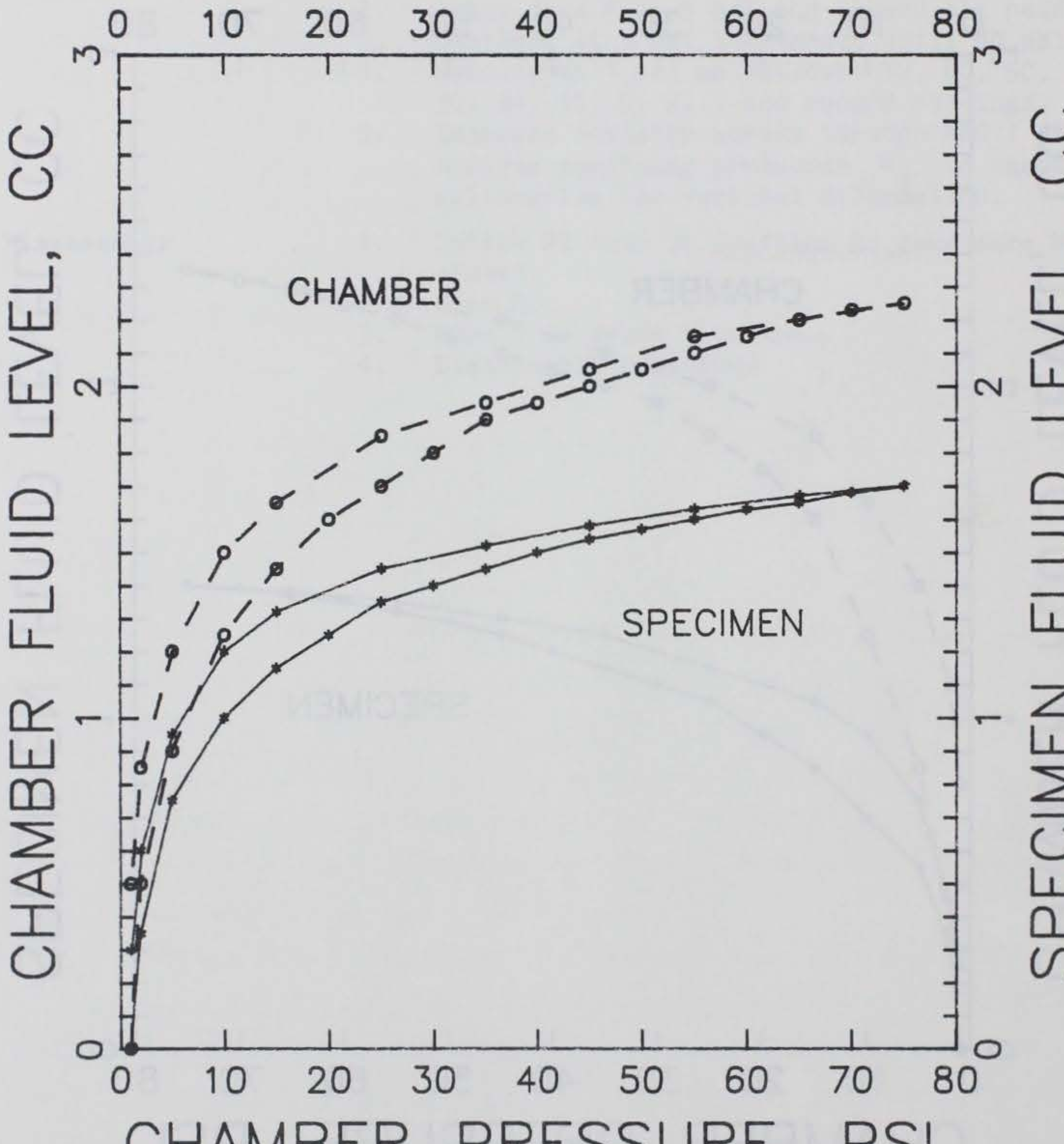
Table 5 (Concluded)

Task	Step
E. Calibration	1. Apply $\sigma_1 = \sigma_3 = 2$ psi through REG 1 and record all readings.
	2. Apply $\sigma_1 = \sigma_3 = 5$ psi and record all readings.
	3. Continue at 5 psi increments until 80 psi.
	4. Rebound to 1 psi as follows: 70, 60, 50, 40, 30, 20, 10, 5, 2, 1 and record readings.
	5. Increase deviator stress through REG 1 at various confining pressures σ_3 to check the calibration for vertical deformation.
F. Disassembly	1. Switch PT down to position 3; make sure N closed.
	2. Open 02.
	3. Open P to drain chambers.
	4. Disassemble apparatus.



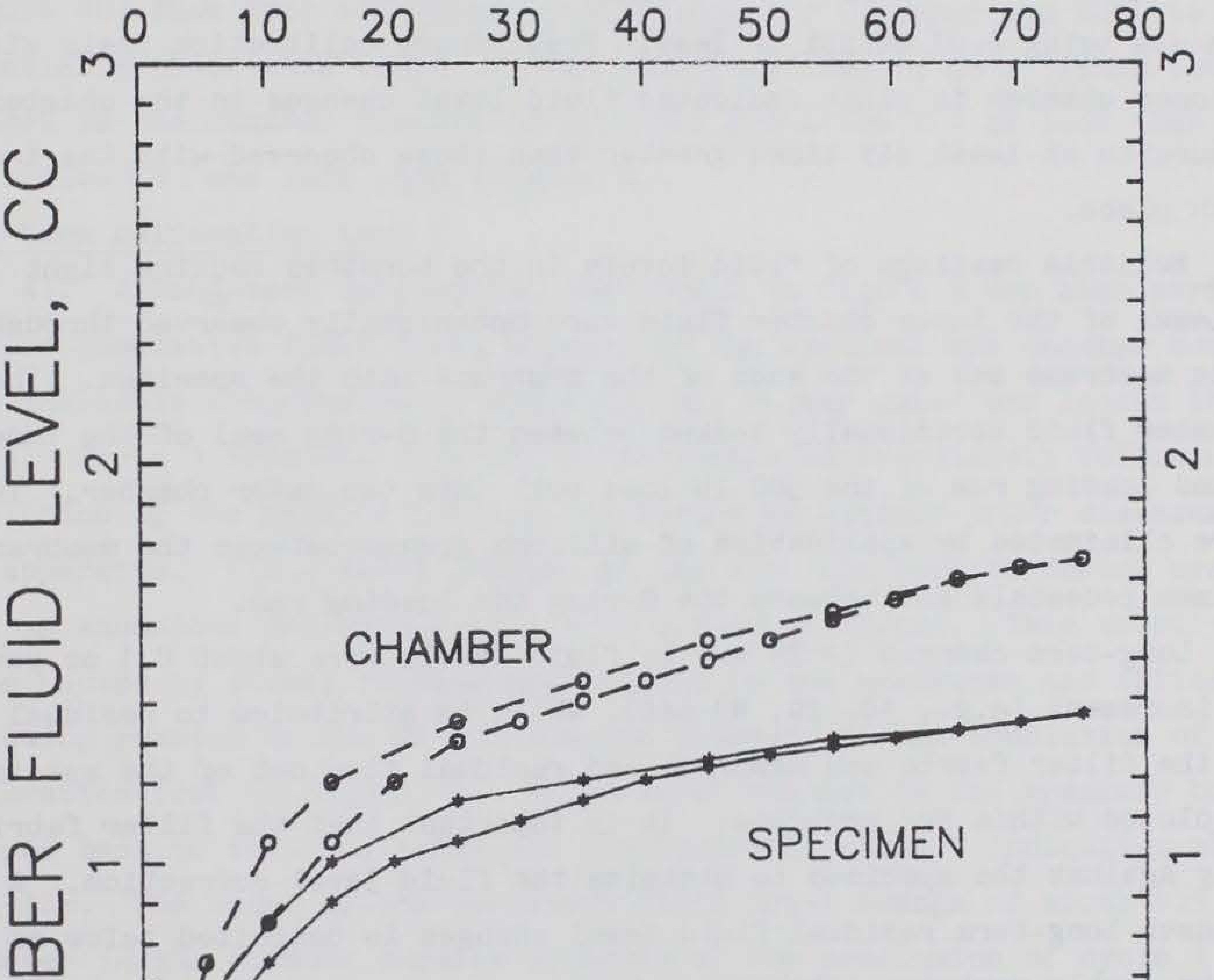
a. Test C1

Figure 3. Calibration curves for single membrane, Valve M open (Continued)



b. Test C2

Figure 3. (Continued)



c. Repeat Test C2

Figure 3. (Concluded)

and 3b are attributed to inelastic closure of some air spaces between the membrane and stainless steel specimen and inelastic compression of the membrane and Typar filter fabric.

36. Figure 3 shows that fluid level changes are relatively small and limited to about 2 cc. Fluid level changes above 30 psi confining pressure are minuscule being 0.01 cc/psi or less. Preliminary calibration tests without the inner chamber in place indicated fluid level changes in the chamber (25 cc) burette at least six times greater than those observed with the inner chamber in place.

37. Reliable readings of fluid levels in the burettes require tight seals. Leaks of the inner chamber fluid were occasionally observed through the single membrane and at the ends of the membrane into the specimen. The inner chamber fluid occasionally leaked between the O-ring seal of the inner chamber and loading ram of the 500 lb load cell into the outer chamber. These leaks were eliminated by application of silicone grease between the membrane and specimen pedestals and between the O-ring and loading ram.

38. Long-term changes ($>$ 24 hr) in fluid levels were about 0.1 cc per pressure increment (e.g., 10, 20, 40 psi), which is attributed to residual creep in the filter fabric and membrane and residual flow out of the specimen volume enclosed within the membrane. It is important that the filter fabric fit snugly against the specimen to minimize the fluid level correction. A test to check long-term residual fluid level changes is described below as part of the double membrane calibration tests.

Double membrane, valve M open

39. A calibration test using the procedure in Table 5 (except valve M was not closed during filling of the chambers) was also performed using a double membrane to minimize fluid leaks from the inner chamber into the specimen. A previously used and cleaned Typar filter was placed around the stainless steel specimen. The results of this calibration test (Figure 4a) indicate approximately 0.5 cc greater fluid level changes compared with the results in Figure 3c for the repeat of Test C2. Much of the additional fluid level changes is attributed to elastic and inelastic compression of the second membrane and air captured between the two membranes during assembly.

Double membrane, valve M closed

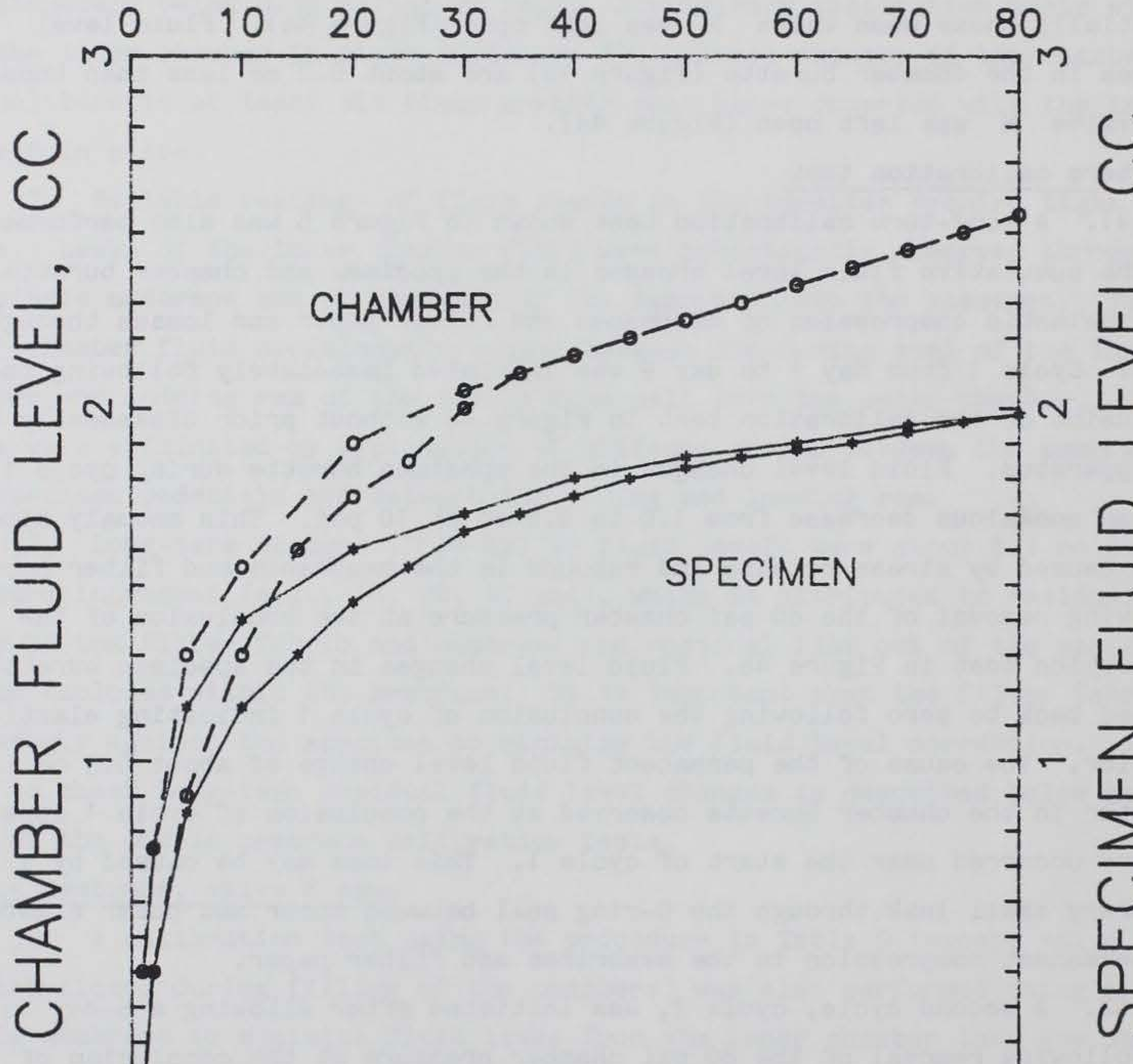
40. A final calibration test was performed using the procedure exactly

described in Table 5 where valve M was closed while the chambers were filled with deaired and distilled water. Valve M was opened 1 min after valve A was closed (Task C6, Table 5) to allow water to pass through the inner chamber into the 25 cc chamber burette through valve J2. The results of this test (Figure 4b) show that the fluid level changes in the specimen burette are essentially those when valve M was left open (Figure 4a). Fluid level changes in the chamber burette (Figure 4b) are about 0.2 cc less than those when valve M was left open (Figure 4a).

Long-term calibration test

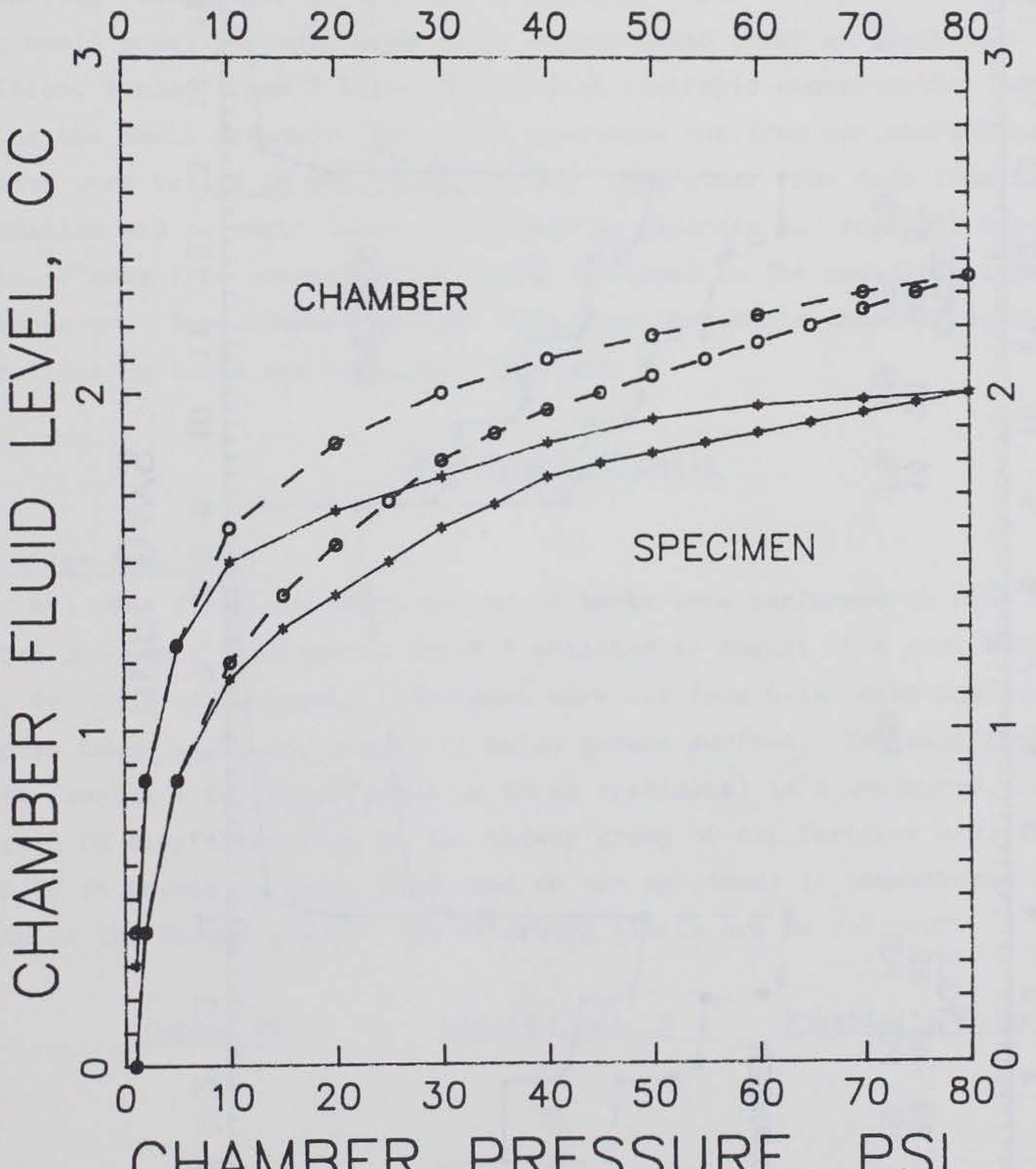
41. A long-term calibration test shown in Figure 5 was also performed to measure cumulative fluid level changes in the specimen and chamber burettes from inelastic compression of membranes and filter paper and losses through seals. Cycle 1 from day 1 to day 9 was initiated immediately following the conclusion of the calibration test in Figure 4b without prior disassembly of the apparatus. Fluid level changes in the specimen burette during cycle 1 show an anomalous decrease from 1.0 to 0.8 cc at 10 psi. This anomaly appears to be caused by stress release and rebound in the membranes and filter paper following removal of the 80 psi chamber pressure at the conclusion of the calibration test in Figure 4b. Fluid level changes in the specimen burette dropped back to zero following the conclusion of cycle 1 indicating elastic behavior. The cause of the permanent fluid level change of about 0.5 cc loss of water in the chamber burette observed at the conclusion of cycle 1 appears to have occurred near the start of cycle 1. This loss may be caused by a temporary small leak through the O-ring seal between inner and outer chambers and permanent compression in the membranes and filter paper.

42. A second cycle, cycle 2, was initiated after allowing a 5-day interval following removal of the 80 psi chamber pressure at the conclusion of cycle 1. The anomalous behavior observed in the specimen burette during cycle 1 at the 10 psi stress is not present during cycle 2. Fluid level changes were essentially reversible or dropped back to zero in both the specimen and chamber burettes.



a. Valve M open

Figure 4. Calibration curves for double membrane (Continued)



b. Valve M closed

Figure 4. (Concluded)

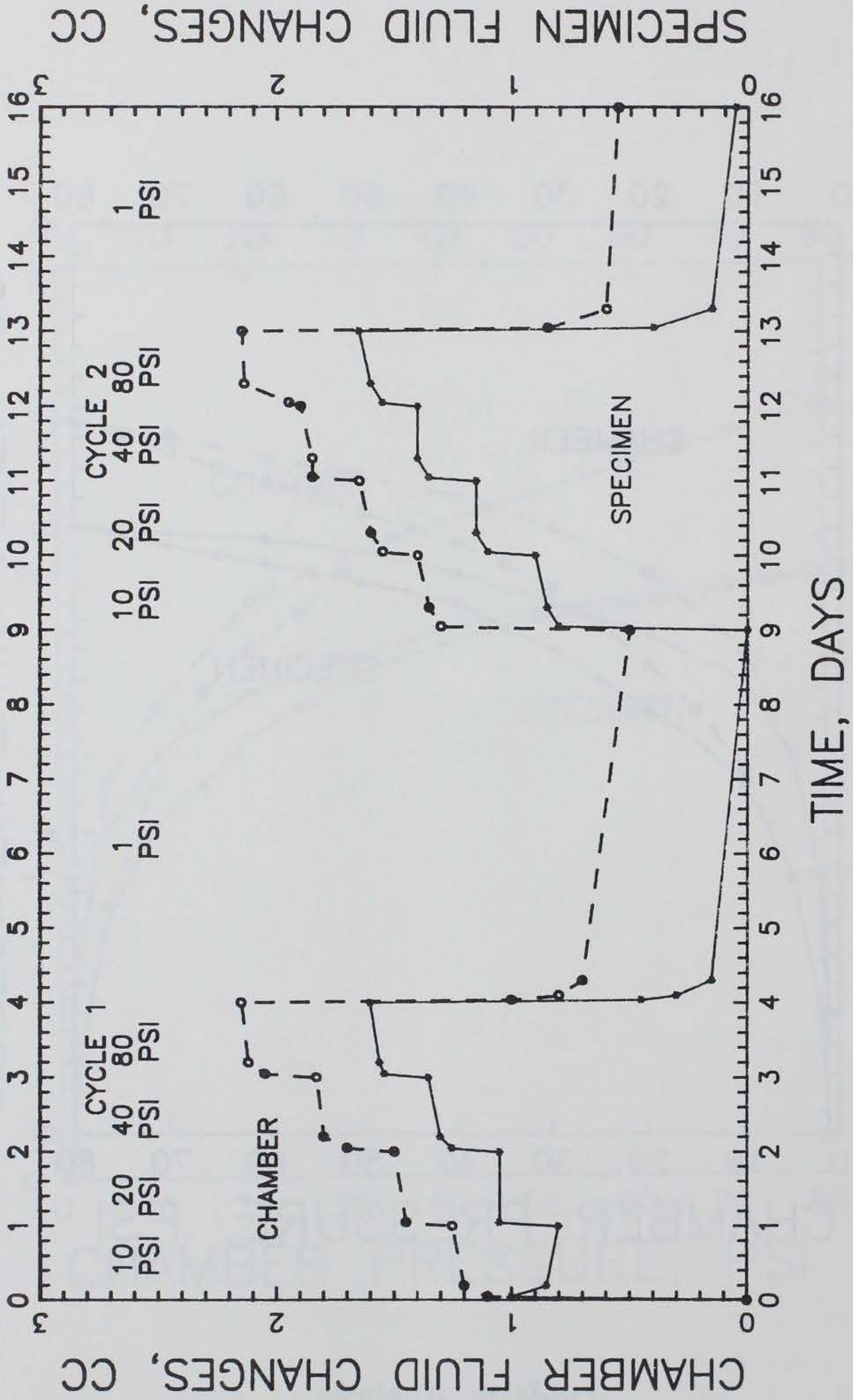


Figure 5. Long-term calibration test

PART III. ANALYSIS

43. Three series of tests were conducted on two different soils to determine performance of the double chamber apparatus and permit a conclusion concerning feasibility of the test procedure. Each series of tests consisted of a swell pressure test followed by an undrained shear strength test. In addition, series 1 and 2 tests included an isotropic consolidation test following the swell pressure test. Six specimens cut from undisturbed boring samples were tested in the double chamber apparatus. The data from the consolidation and strength tests are listed in Appendix A. Appendix B shows plots of data from consolidation tests performed in the one-dimensional consolidometer. The deformation-time data from the double chamber isotropic consolidation tests are plotted in Appendix C.

Description of Soils

Red River Army Depot

44. The first and third series of tests were performed on four undisturbed specimens from boring 6DC-419 obtained in August 1984 near Building 333, Red River Army Depot. Specimens were cut from 6-in. diam undisturbed samples taken at 8, 23, and 40 ft below ground surface. The soil from 8 and 23 ft (series 1 tests performed on three specimens) is a weathered, tan, plastic CH clay identified as the Midway group of the Tertiary age. The soil from 40 ft (series 3 tests performed on one specimen) is unweathered clay shale of the Midway group. The Atterberg limits are as follows:

Depth, ft	Liquid Limit, %	Plasticity Index, %
8	67	51
23	75	61
40	62	43

The strength and stiffness of this soil increases approximately linearly with increasing depth. The undrained strength varies from 10 to 25 psi, 8 ft below ground surface increasing to about 100 psi or more, and 40 ft below ground surface. The elastic modulus varies from 1,500 to 4,000 psi, 8 ft below ground surface increasing to 7,000 psi or more, and 40 ft below ground surface (Johnson 1986). Soil overburden pressure σ_v is about 7 psi at 8 ft depth, 19 psi at 23 ft depth, and 33 psi at 40 ft depth. A perched water table is present at this location with ground-water level 5 to 8 ft below ground surface. The effective vertical pressure σ'_v at 8, 23, and 40 ft below ground surface is about 7, 12, and 18 psi.

Incirlik Air Force Base

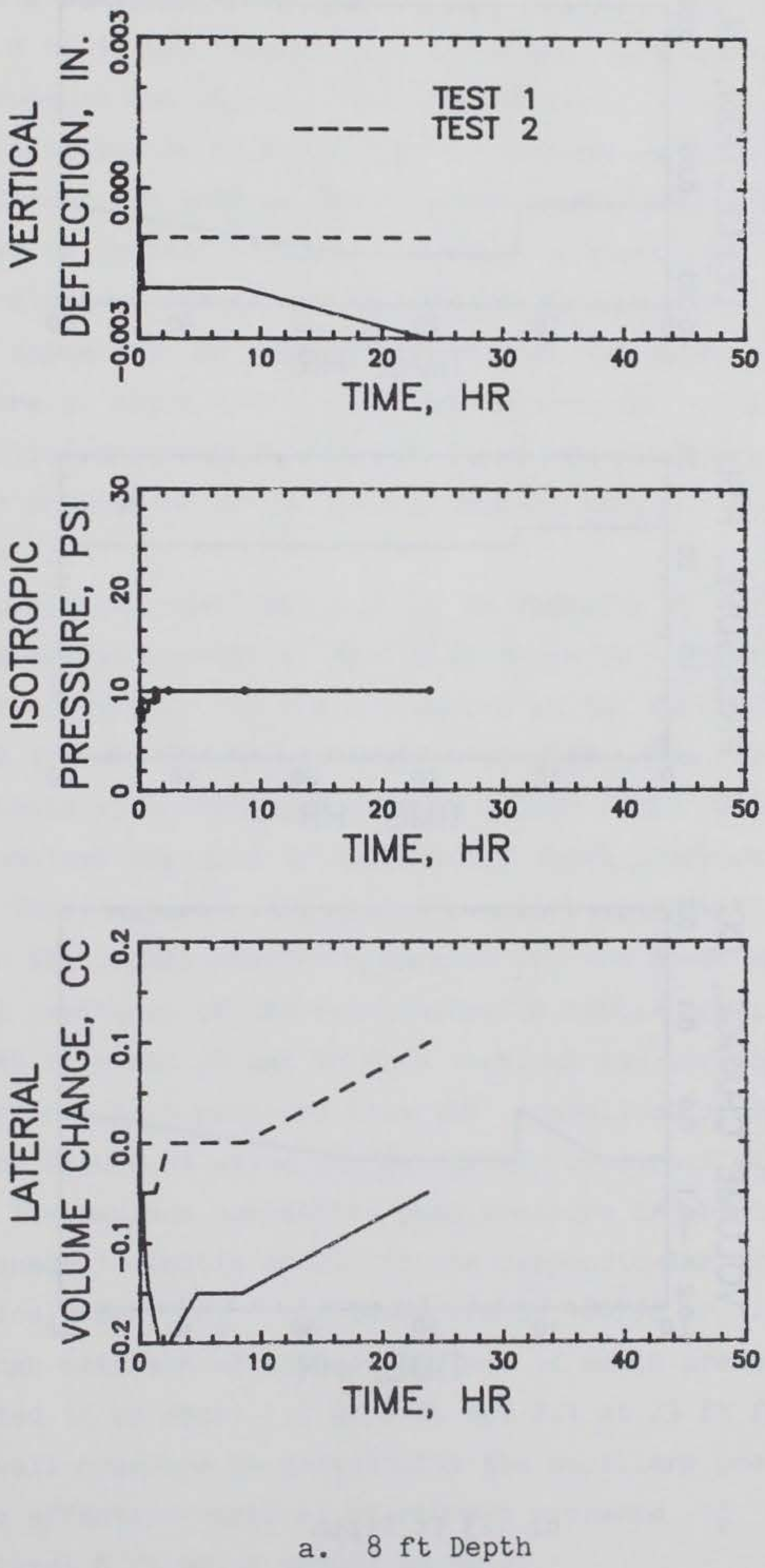
45. The second series of tests was performed on specimens from boring sample 2-2B obtained in January 1986 from Incirlik Air Force Base, Turkey. Two specimens were cut from 3-in. shelby tube samples taken approximately 5 ft below ground surface. This soil is a tan, plastic CH clay containing some small calcareous nodules or grains. These grains are dispersed nonuniformly and may influence the soil stiffness and compressibility. The liquid limit of this soil about 5 ft below ground surface is 67 and the plasticity index is 44. A water table may exist about 20 ft below ground surface. The total vertical overburden pressure σ_v , at 5 ft below ground surface is about 4.2 psi.

Series 1 Tests

46. These initial tests of series 1 were performed on specimens from boring sample 6DC-419 at 8 and 23 ft depth to check capabilities of the apparatus and to check the soil test procedure described in Table 4. Test 1 on soil from 8 ft depth was used to determine the swell pressure and the undrained shear strength. The specimen of Test 2 from 8 ft and Test 3 from 23 ft of depth were isotropically consolidated following evaluation of the swell pressure. The calibration curves used for all three series are given in Figure 4a. The specimen from 8 ft depth indicated a vertical prestrain of 0.03 in. or almost 1 percent following application of the vacuum during Task B, Table 4. All the remaining specimens did not indicate any vertical strain during Task B.

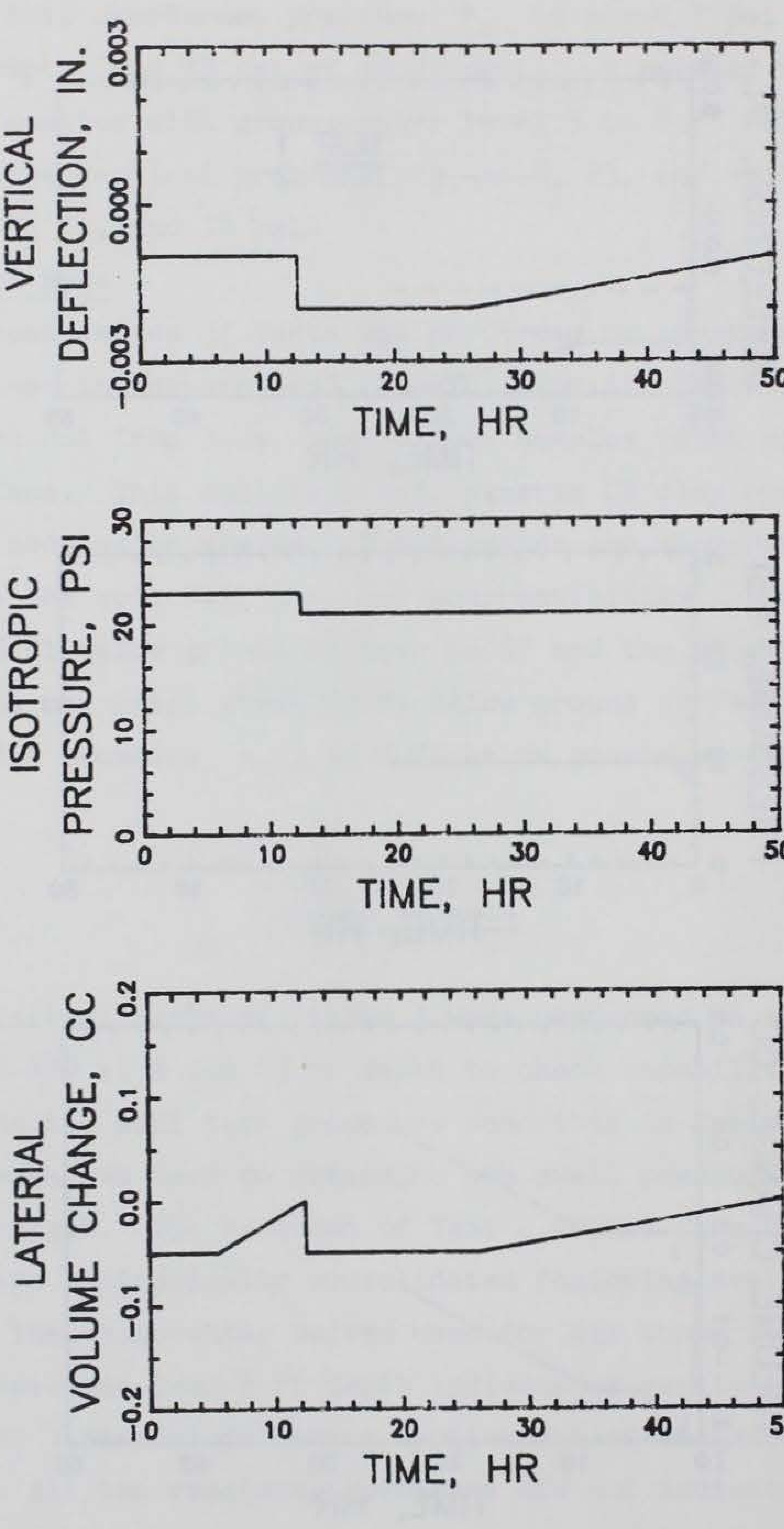
Swell pressure

47. The initial isotropic confining pressure at 8 ft was 6 psi and at 23 ft was 18 psi. Figure 6 shows the applied isotropic pressure, lateral volume change, and vertical deflection of these specimens as a function of time.



a. 8 ft Depth

Figure 6. Swell pressure measurements of specimens from boring 6DC-419 (Continued)



b. 23 ft Depth

Figure 6. (Concluded)

Negative volume and deflection readings indicate swell. The specimen at 8 ft depth exhibited a reversal in lateral volume change as the applied pressure increased from 8 to 10 psi (Figure 6a). Therefore, the lateral swell pressure is probably between 8 and 10 psi. The lateral swell pressure is approximately 21 psi for the specimen at 23 ft of depth. Changes in vertical deflection were not significant for both of these tests; therefore, vertical deformation is not sensitive to applied vertical pressure, and vertical swell pressure cannot be determined as accurately as lateral swell pressure. The vertical swell pressure appears to be the same as the lateral swell pressure. A small vertical pressure of about 1 to 3 psi must be applied on the ram in excess of the lateral applied pressure to overcome friction in the system. This friction presumably originates at the O-ring contact between the ram and inner chamber (Figure 1).

48. Two companion specimens 3.5 in. in diameter by 1.24 in. high were cut from boring sample 6DC-419 at the 23-ft depth at right angle orientations of each other to determine the swell pressure in the vertical and lateral directions from the one-dimensional consolidometer. The results of consolidometer swell tests after Method C of ASTM D 4546 (ASTM 1986b) (Figure B1) indicate an identical measured or uncorrected swell pressure of 24 psi in both orientations. This compares well with the uncorrected swell pressure of 21 psi measured in the double chamber apparatus for the 23-ft specimen. The corrected swell pressures of the conventionally tested specimens after Method C of ASTM D 4546 is about 30 psi in both vertical and horizontal orientations. The maximum vertical past pressure from the consolidation data in the vertical direction of Figure B1 using the Casagrande construction technique is about 90 psi. The maximum horizontal past pressure is about 160 psi assuming that possible unequal elastic moduli in the perpendicular axes have no influence on the calculation. K_o may therefore be 160/90 or 1.8 at 23 ft.

49. A rough estimate of the coefficient of earth pressure at rest K_o may be calculated to be about 1.4 at 8 ft and 2.1 at 23 ft from Equation 1b assuming the swell pressure is essentially the capillary pressure σ_k and calculating the effective vertical overburden pressure σ'_v on the basis of a perched water level 8 ft below ground surface.

Consolidation

50. The void ratio-logarithm pressure relationships of the isotropically consolidated specimens taken from boring 6DC-419 at 8 and 23 ft depth are shown in Figure 7. The consolidation-time plots of the specimen from 8 ft (Figure C1) show relatively large lateral volume change and little vertical deformation. The vertical prestrain in the specimen from 8 ft depth observed during Task B, Table 4, may have influenced these results. The specimen from 23 ft is much stiffer than the specimen from 8 ft, particularly in the lateral direction (Figure C2).

51. The relative compressibility m between vertical and horizontal directions of the drained isotropic consoliation tests may be used to evaluate Skempton's pore pressure parameter A (Leavell, Peters, and Townsend 1982)

$$A = \frac{m}{m + 2} \tag{5}$$

$$m = \frac{\Delta\epsilon_x}{\Delta\epsilon_y} \tag{6}$$

where

m = relative strain between vertical and horizontal directions

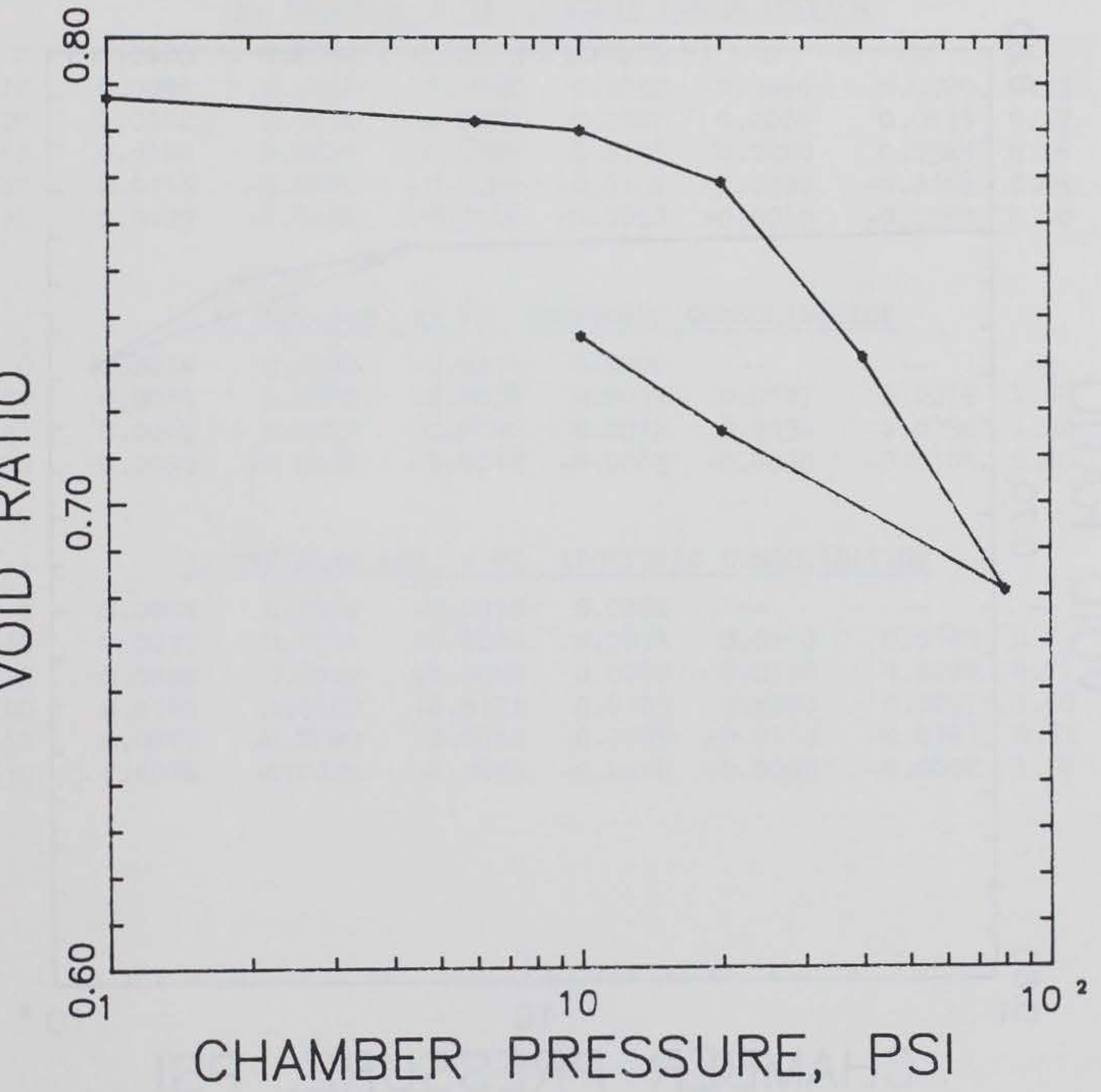
$\Delta\epsilon_x$ = change in vertical strain induced by change in effective isotropic stress $\Delta\sigma$, in./in.

$\Delta\epsilon_y$ = change in horizontal or lateral strain induced by change in effective isotropic stress $\Delta\sigma$, in./in.

Leavell, Peters, and Townsend (1982) concluded that A would be expected to fall within the limited range of 0.5 to 0.7 for an intact (unfractured) shale with significant anisotropy. The consolidation relationships for the isotropically consolidated specimens shown in Table 6_σ indicate that the specimen cut from boring 6DC-419 at 23 ft (Table 6b) may have significant anisotropy.

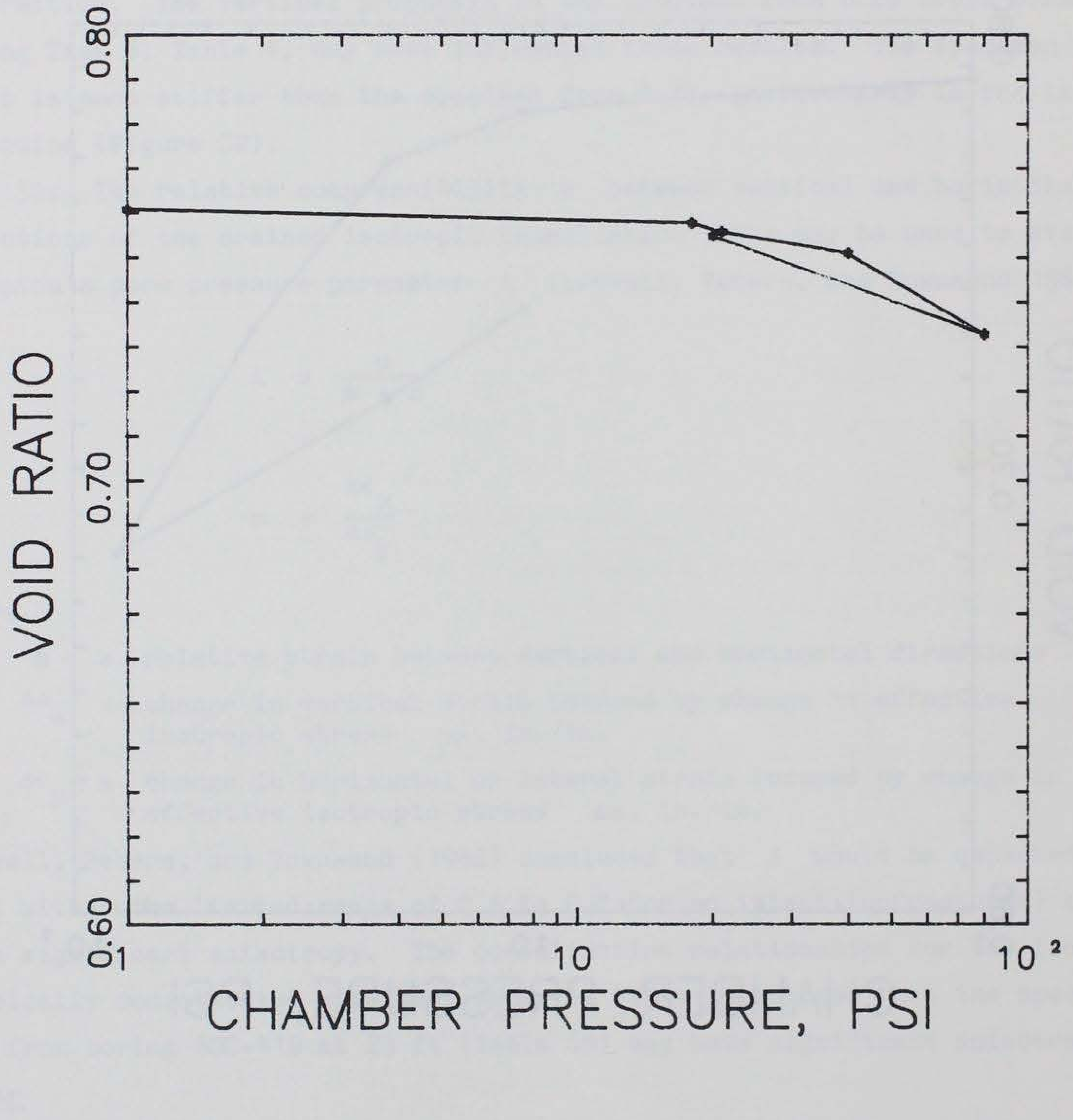
Shear

52. The maximum deviator stress of the unconsolidated specimen from boring 6DC-419 at 8 ft depth tested at a confining pressure equal to the swell pressure is 26.4 psi, while a similar specimen consolidated to 80 psi and



a. 8 ft Depth

Figure 7. Behavior of specimens from boring 6DC-419 isotropically consolidated in the triaxial double chamber (Continued)



b. 23 ft Depth

Figure 7. (Concluded)

Table 6

Consolidation Relationships

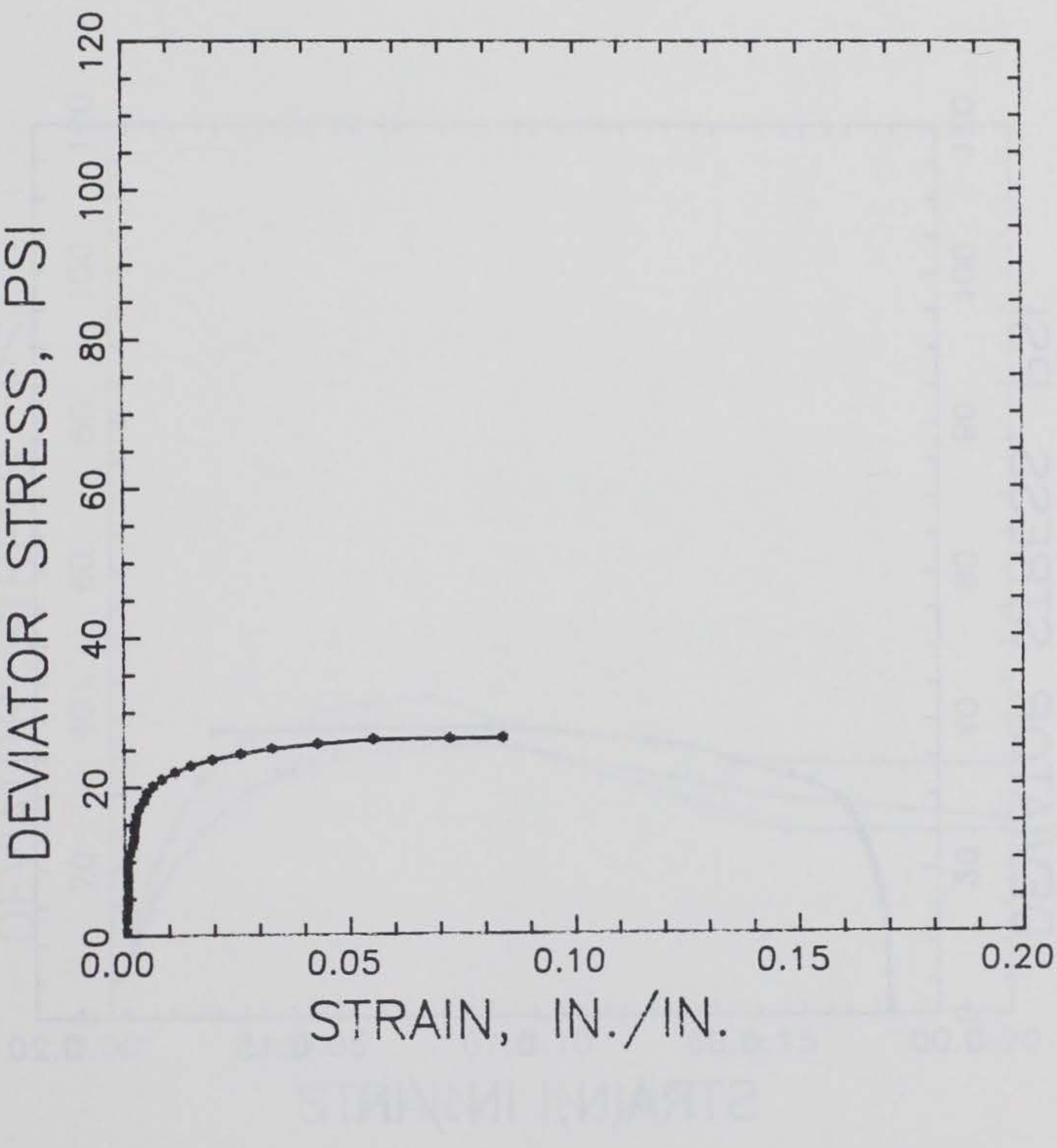
σ psi	$\Delta\sigma$ psi	ϵ_x in/in	$\Delta\epsilon_x$ in/in	ϵ_y in/in	$\Delta\epsilon_y$ in/in	$\frac{\Delta\epsilon_x, \%}{\Delta\sigma}$	$\frac{\Delta\epsilon_y, \%}{\Delta\sigma}$	m	A
				a. 6DC-419 8 FT SOTROPIC CONSOLIDATION					
10	0	0.0086	0.0000	-0.0020	0.0000	--	--	--	--
20	10	0.0095	0.0009	-0.0052	0.0032	0.0090	0.0320	0.33	0.14
40	20	0.0112	0.0017	-0.0159	0.0107	0.0085	0.0535	0.17	0.08
80	40	0.0120	0.0008	-0.0305	0.0146	0.0020	0.0365	0.06	0.03
20	60	0.0115	-0.0005	-0.0204	-0.0101	-0.0008	-0.0168	0.05	0.02
10	10	0.0109	-0.0006	-0.0146	-0.0058	-0.0060	-0.0580	0.10	0.05
				b. 6DC-419 23 FT ISOTROPIC CONSOLIDATION					
21	0	-0.0014	0.0000	-0.0014	0.0000	--	--	--	--
40	19	0.0014	0.0028	-0.0028	0.0014	0.0147	0.0075	2.00	0.50
80	40	0.0065	0.0051	-0.0080	0.0052	0.0130	0.0130	1.00	0.33
20	60	0.0059	-0.0006	-0.0017	-0.0063	-0.0010	-0.0105	0.10	0.05
				c. INCIRLIK AFB 5 FT ISOTROPIC CONSOLIDATION					
10	0	0.0000	0.0000	-0.0014	0.0000	--	--	--	--
20	10	0.0011	0.0011	-0.0028	0.0014	0.0110	0.0140	0.83	0.29
40	20	0.0040	0.0029	-0.0068	0.0040	0.0150	0.0200	0.77	0.28
80	40	0.0140	0.0100	-0.0171	0.0103	0.0250	0.0257	1.00	0.33
20	60	0.0071	-0.0069	-0.0086	-0.0085	-0.0115	-0.0141	0.83	0.29
10	10	0.0046	-0.0025	-0.0046	-0.0040	-0.0002	-0.0002	1.00	0.33

rebounded to 10 psi is 39.1 psi (Figure 8). Specimens from the same boring sample tested by the conventional unconsolidated undrained test procedure described in EM 1110-2-1906 (Headquarters, Department of the Army 1970) and subject to a much larger confining pressure of 110 psi had deviator stresses between 36 and 43 psi (Figure 9). The larger confining pressure could contribute to a slightly greater apparent strength to the specimens. Subjecting the specimens to free water in the double chamber apparatus to determine the swell pressure may provide a more rational estimate of shear strength because the pore pressures should be zero at equilibrium when confined by an isotropic pressure equal to the swell pressure. Pore pressures were not measured during this study.

53. The maximum deviator stress of the specimen from boring 6DC-419 at 23 ft depth (Figure 10) is 115.4 psi just prior to an abrupt failure after 3 percent strain. One-half of this maximum deviator stress or undrained strength is consistent with those of similar specimens tested conventionally (Johnson 1986).

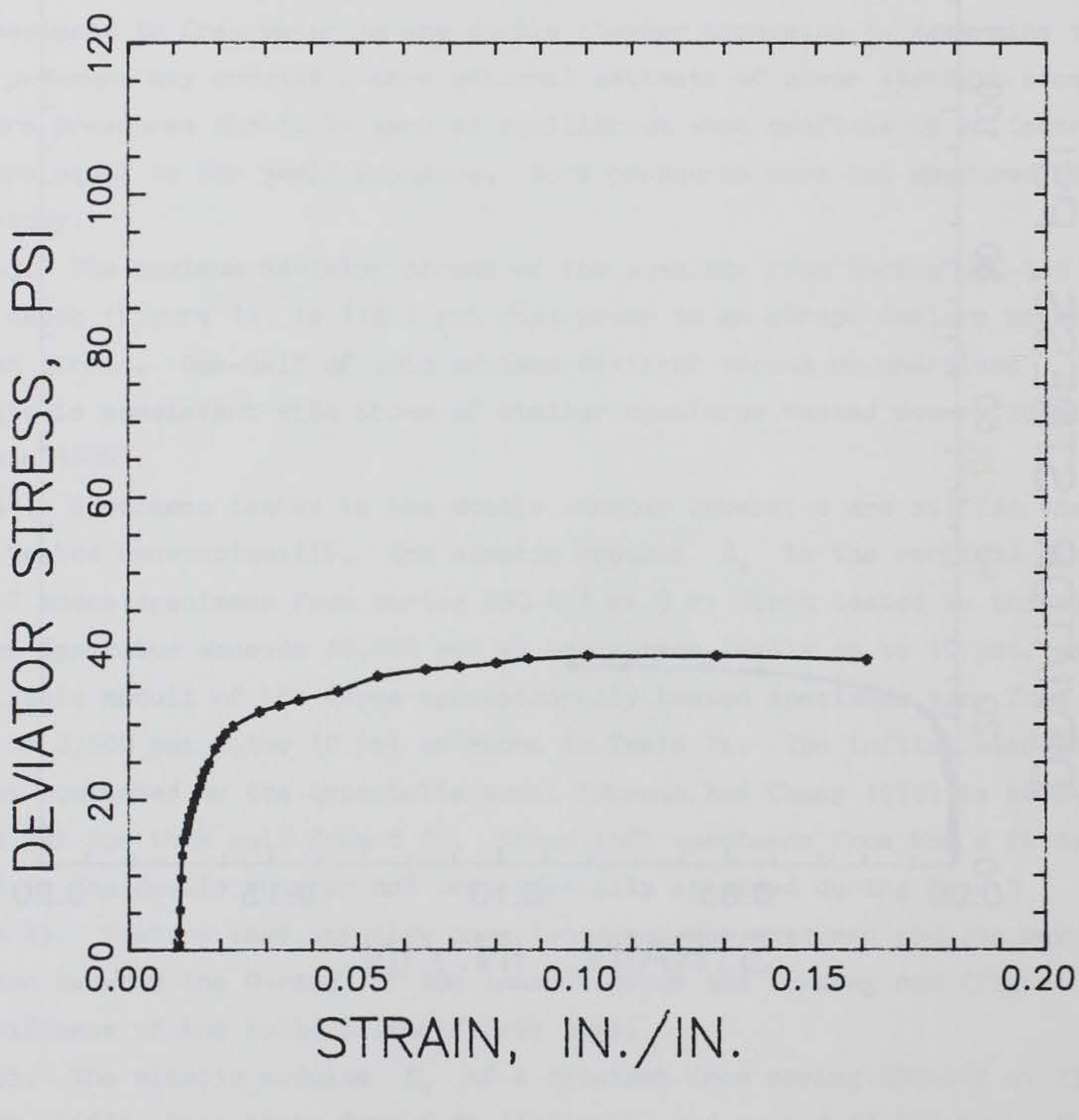
54. Specimens tested in the double chamber apparatus are stiffer than those tested conventionally. The elastic modulus E_x in the vertical direction of those specimens from boring 6DC-419 at 8 ft depth tested in the double chamber apparatus exceeds 10,000 psi at low stress levels up to 10 psi, and the elastic moduli of the three conventionally tested specimens vary from 1,670 to 2,500 psi below 10 psi as shown in Table 7a. The initial elastic modulus evaluated by the hyperbolic model (Duncan and Chang 1970) is about 14,000 psi for this soil from 8 ft. These soft specimens from the 8 ft depth tested in the double chamber had been initially strained during Task B (Table 4). Factors that may also have increased the measured modulus may be friction between the O-ring of the inner chamber and loading ram (Figure 1) and stiffness of the solid filter fabric cage.

55. The elastic modulus E_x of a specimen from boring 6DC-419 at 23 ft is much stiffer than those from 8 ft (Table 7b) and exceed 10,000 psi. The initial elastic modulus from the hyperbolic model is about 21,000 psi. These values of E_x are in the upper range of values observed in the literature (Johnson 1986).



a. Unconsolidated

Figure 8. Shear behavior of boring 6DC-419 of 8 ft depth in double chamber apparatus when drained (valve N open) (Continued)



b. Consolidated

Figure 8. (Concluded)

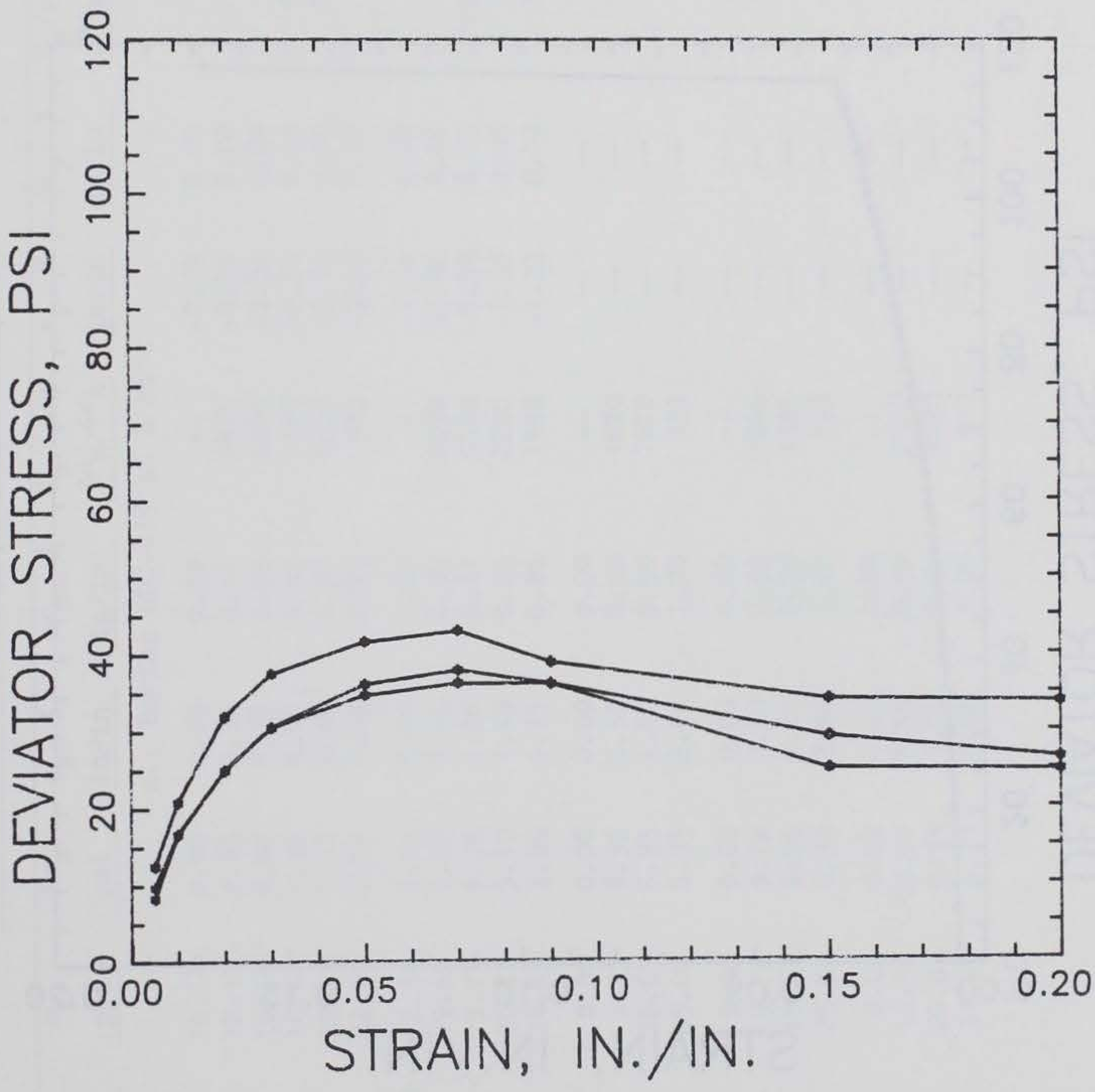


Figure 9. Shear behavior of specimens from boring 6DC-419 at 8 ft when tested conventionally

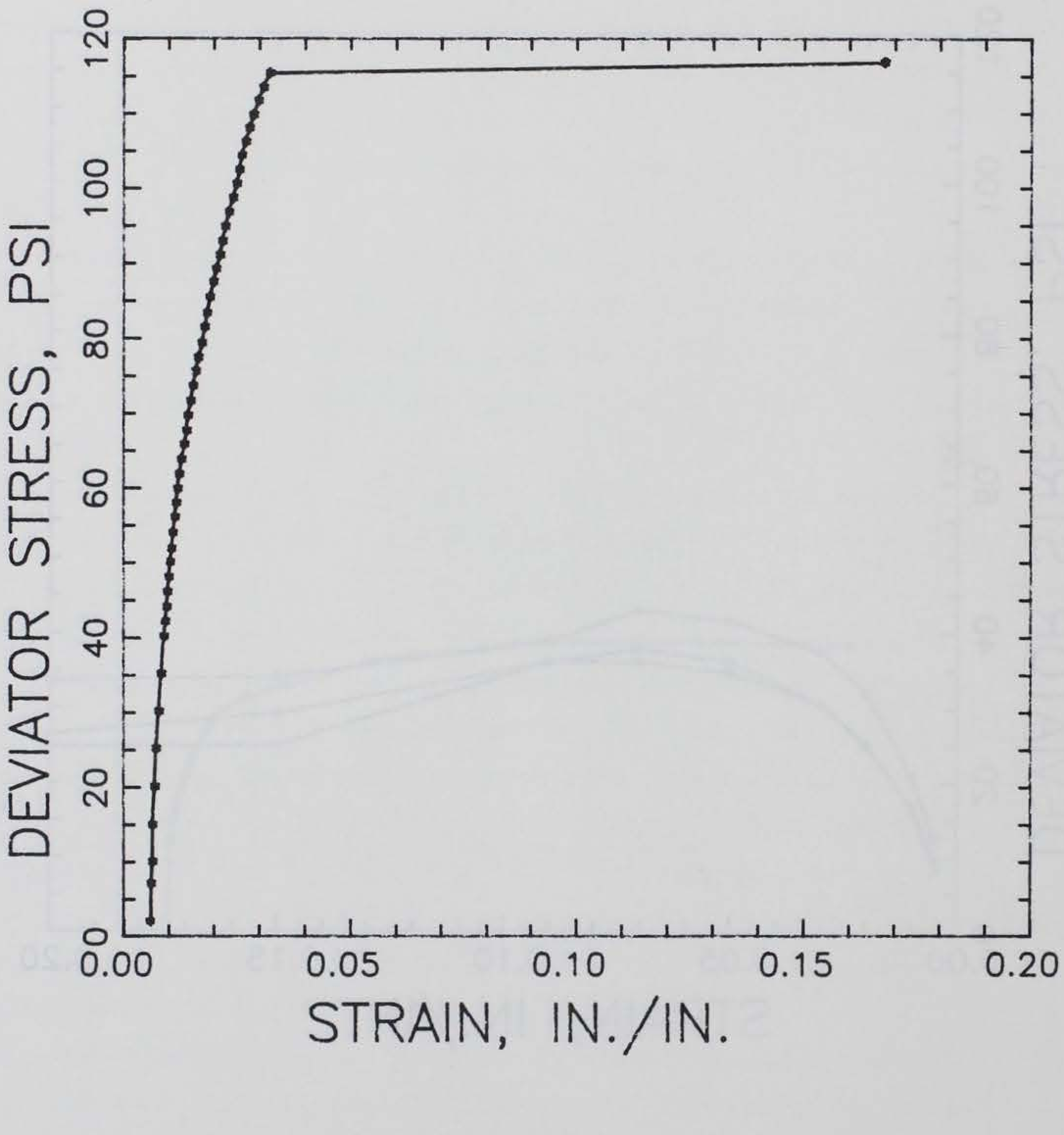


Figure 10. Shear behavior of specimen from boring 6DC-419 of 23 ft depth in double chamber apparatus

Table 7
Elastic Modulus of Soil Specimens By Stress

Specimen	σ_x, psi	$\Delta\sigma_x$, psi	ϵ_x, % in/in	$\Delta\epsilon_x$, % in/in	E_x, psi $\Delta\sigma_x/\Delta\epsilon_x$	ϵ_y, % in/in	$\Delta\epsilon_y$, % in/in	E_x/μ_y, psi $\Delta\sigma_x/\Delta\epsilon_y$	μ_y
				a. Boring 6DC-419 at 8 Ft					
Unconsolidated	10.14	0.00	0.09	0.00	--	-0.34	0.00	--	--
Double Chamber,	12.17	2.03	0.20	0.11	1815	-0.34	0.00	--	--
Figure 8a	16.16	4.00	0.28	0.08	5000	-0.34	0.00	--	--
	18.14	1.98	0.45	0.17	1160	-0.26	0.08	2470	0.47
	20.11	1.97	0.65	0.20	1000	-0.17	0.09	2190	0.46
	22.85	2.74	1.48	0.83	340	-0.28	0.40	685	0.50
Consolidated/Rebound	2.38	0.00	1.09	0.00	--	-1.46	0.00	--	--
to Swell Pressure	9.60	7.22	1.15	0.06	12000	-1.46	0.00	--	--
Double Chamber,	15.74	6.14	1.26	0.11	5580	-1.43	0.03	20500	0.27
Figure 8b	20.84	5.10	1.49	0.23	2220	-1.35	0.07	7280	0.31
	24.83	3.99	1.75	0.26	1538	-1.23	0.12	3330	0.46
Conventional Tri-	0.00	0.00	0.00	0.00	--	--	--	--	--
axial, Figure 9	8.33	8.33	0.50	0.50	1670	--	--	--	--
	16.67	8.33	1.00	0.50	1670	--	--	--	--
	25.00	8.33	2.00	1.00	833	--	--	--	--
	0.00	0.00	0.00	0.00	--	--	--	--	--
	9.72	9.72	0.50	0.50	1945	--	--	--	--
	16.67	6.95	1.00	0.50	1387	--	--	--	--
	25.00	8.33	2.00	1.00	833	--	--	--	--
	0.00	0.00	0.00	0.00	--	--	--	--	--
	12.50	12.50	0.50	0.50	2500	--	--	--	--
	20.84	8.34	1.00	0.50	1670	--	--	--	--
	31.95	9.11	2.00	1.00	911	--	--	--	--

(Continued)

Table 7 (Concluded)

Specimen	σ_x, psi	$\Delta\sigma_x$, psi	ϵ_x, % in/in	$\Delta\epsilon_x$, % in/in	E_x, psi $\Delta\sigma_x/\Delta\epsilon_x$	ϵ_y, % in/in	$\Delta\epsilon_y$, % in/in	E_x/μ_y, psi $\Delta\sigma_x/\Delta\epsilon_y$	μ_y
b. Boring 6DC-419 at 23 Ft									
Consolidated/Rebound	2.10	0.00	0.59	0.00	--	-0.17	0.00	--	--
to Swell Pressure	10.11	8.01	0.65	0.06	13350	-0.17	0.00	--	--
Double Chamber,	20.15	10.04	0.70	0.05	20000	-0.17	0.00	--	--
Figure 10	30.19	10.04	0.79	0.09	11100	-0.17	0.00	--	--
	40.16	9.97	0.90	0.11	9050	-0.17	0.00	--	--
	50.12	9.96	1.04	0.14	7120	-0.11	0.06	16600	0.43
	61.85	11.73	1.24	0.20	5880	0.00	0.11	10680	0.55
	71.65	9.80	1.49	0.25	3930	0.11	0.11	8900	0.44
c. Boring 6DC-419 at 40 Ft									
Unconsolidated	20.04	0.00	0.48	0.00	--	-0.06	0.00	--	--
Double Chamber,	40.02	19.98	0.60	0.12	16650	-0.03	0.03	66600	0.25
Figure 15a	59.92	19.90	0.71	0.11	18090	0.00	0.03	66333	0.27
	79.80	19.88	0.88	0.17	11694	0.06	0.06	33133	0.35
	99.56	19.76	1.05	0.17	11624	0.14	0.08	24700	0.47
	119.28	19.72	1.22	0.17	11600	0.20	0.06	32867	0.35
	138.83	19.54	1.42	0.20	9770	0.31	0.11	17764	0.55
	158.27	19.45	1.67	0.25	7780	0.43	0.12	16208	0.48
	177.50	19.23	1.96	0.29	6631	0.57	0.14	13736	0.48
	191.76	14.26	2.24	0.28	5093	0.69	0.12	11883	0.43
d. Incirlik AFB at 5 Ft									
Unconsolidated	8.08	0.00	0.00	0.00	--	-0.18	--	--	--
Double Chamber,	14.07	5.99	0.06	0.06	10000	-0.16	0.02	30000	0.33
Figure 13a	20.04	5.97	0.14	0.08	7470	-0.13	0.03	19900	0.37
	25.99	5.95	0.42	0.28	2130	0.01	0.14	4230	0.50
Consolidated/Rebound	2.06	0.00	0.46	0.00	--	-0.46	0.00	--	--
to Swell Pressure	8.16	6.10	0.49	0.03	16670	-0.46	0.00	--	--
Double Chamber,	18.30	10.14	0.57	0.08	12700	-0.42	0.04	25400	0.50
Figure 13b	26.24	7.94	0.71	0.14	5660	-0.35	0.07	11340	0.50

56. Elastic parameters based on effective stresses for a transverse isotropic specimen tested in a triaxial apparatus may be estimated (Leavell, Peters, and Townsend 1982) by the equation

$$\Delta\epsilon_x = C_x \Delta\sigma_x + 2C_{xy} \Delta\sigma_y \quad (7a)$$

$$\Delta\epsilon_y = C_{xy} \Delta\sigma_x + C_y \Delta\sigma_y \quad (7b)$$

where

$\Delta\epsilon_x$ = change in vertical strain, in./in.

$\Delta\sigma_x$ = change in vertical pressure, psi

$\Delta\epsilon_y$ = change in horizontal strain, in./in.

$\Delta\sigma_y$ = change in horizontal pressure, psi

Parameters C_x , C_{xy} , and C_y are three independent elastic constants. The solution of Equation 7(a and b) for a constant confining pressure $\Delta\sigma_y = 0$ is

$$C_{xy} = \frac{\Delta\epsilon_y}{\Delta\sigma_x} = \frac{\mu_y}{E_x} \quad (8)$$

where

E_x = Young's elastic modulus in the vertical direction, psi

μ_y = Lateral Poisson's ratio

The lateral Poisson's ratio for the specimens from boring 6DC-419 at 8 and 23 ft appears to approach the maximum possible value of 0.5, Table 7(a and b) with increasing deviator stress; therefore, these strength tests are undrained as intended.

Series 2 Tests

57. This series of tests was performed on a different soil to check the observation from the first series that swell pressures appeared isotropic on soil wetting under a no volume change condition. In situ pore water pressures had not been determined.

Swell pressure

58. The results of the swell pressure tests on two specimens cut from boring sample 2-2B at Incirlik Air Force Base (Figure 11) indicate an

isotropic swell pressure of about 10 to 12 psi. The lateral volume changes and vertical deflections of Figure 11 are almost negligible. The consolidation in Figure C3A at an applied isotropic pressure of 20 psi shows that the swell pressure in both horizontal and vertical orientations is less than 20 psi.

59. The one-dimensional consolidation behavior of a similar specimen cut from the same boring sample as 2-2B is given in Figure B2. The uncorrected swell pressure in the vertical direction slightly exceeds 10 psi, which is consistent with the swell pressure of a similar specimen observed in the double chamber. The vertical swell pressure corrected after Method C of ASTM D 4546 (ASTM 1986b) is less than 20 psi. Swell pressure results in the horizontal direction are not available.

Consolidation

60. The void ratio-logarithm pressure curve of the isotropically consolidated specimen from Incirlik Air Force Base is shown in Figure 12. The A parameter (Table 6c) of about 0.33 indicates an isotropic soil. Figure C3 shows the consolidation-time relationships.

Shear

61. The maximum deviator stress of the unconsolidated specimen tested at a confining pressure equal to the swell pressure $\sigma_s = 12$ psi is 32.7 psi (Table A5) and a similar specimen consolidated to 80 psi and rebounded to the swell pressure $\sigma_s = 10$ psi is 41.3 psi (Table A6). The stress-strain behavior of these specimens is shown in Figure 13. The process of consolidation and rebound appears to increase the soil strength similar to that observed for specimens from boring 6DC-419.

62. The elastic modulus E_x of these specimens from Incirlik Air Force Base exceeds 10,000 psi below $\sigma_x = 14$ psi (Table 7d). The lateral Poisson's ratio μ_y approaches 0.5, which indicates an undrained strength test.

Series 3 Tests

63. A final series of tests was performed on a highly consolidated clay shale from boring sample 6DC-419 at 40 ft depth to check the measurement of vertical and horizontal swell pressure of an anisotropic material. Two thin sections of this soil were prepared to evaluate particle orientation. A

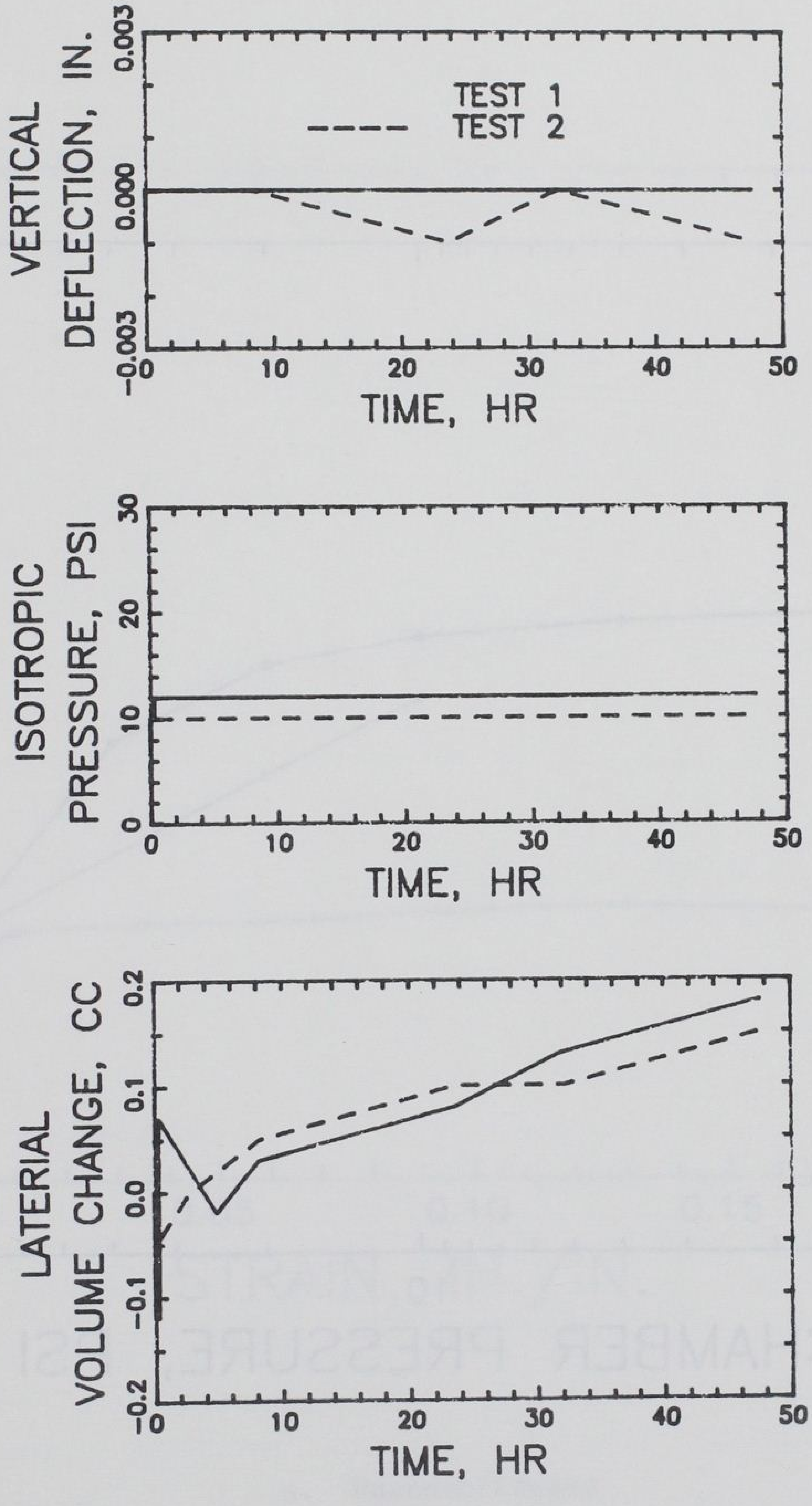


Figure 11. Swell pressure measurements of specimens from Boring 2-2B, Incirlik Air Force Base

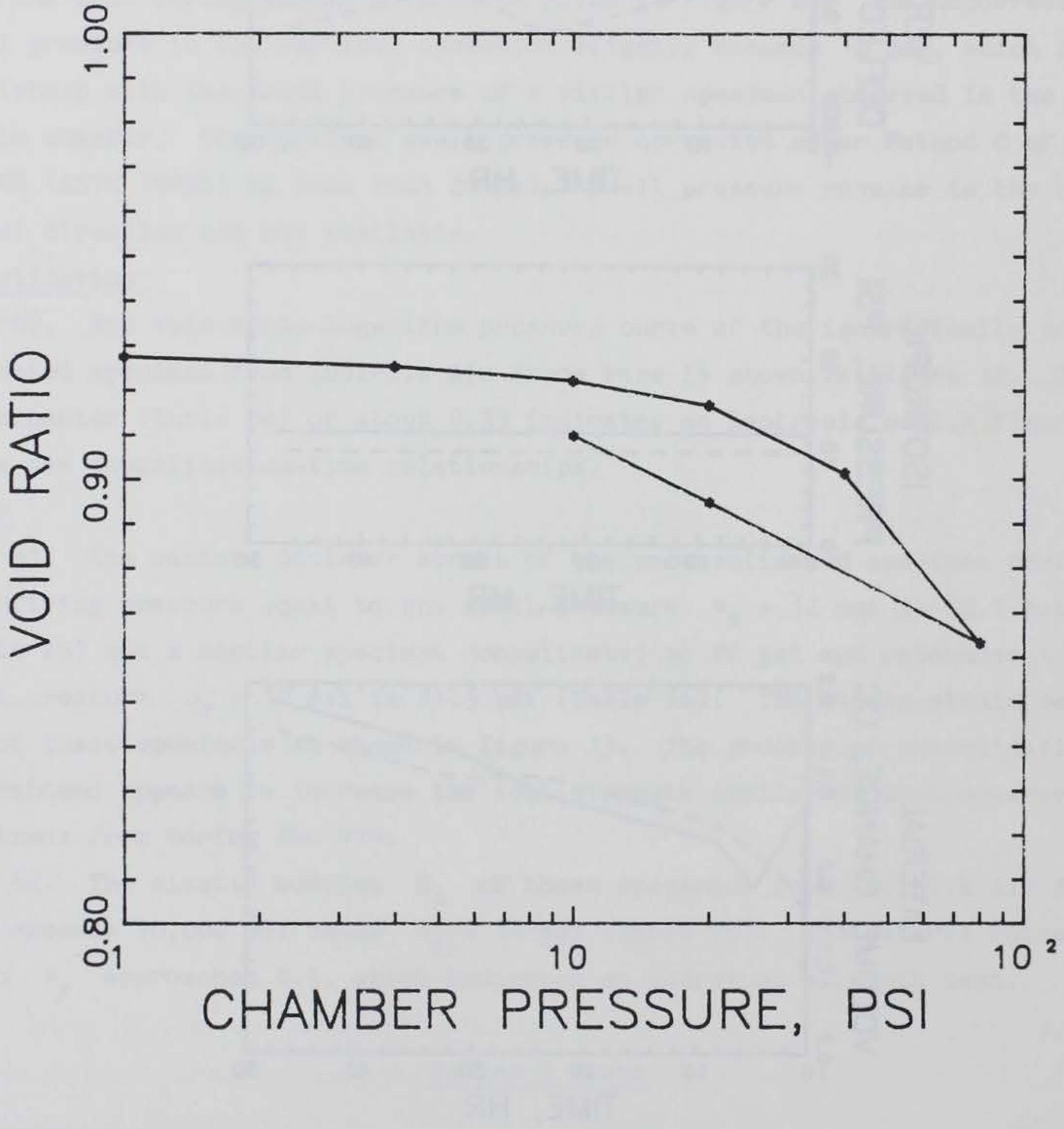
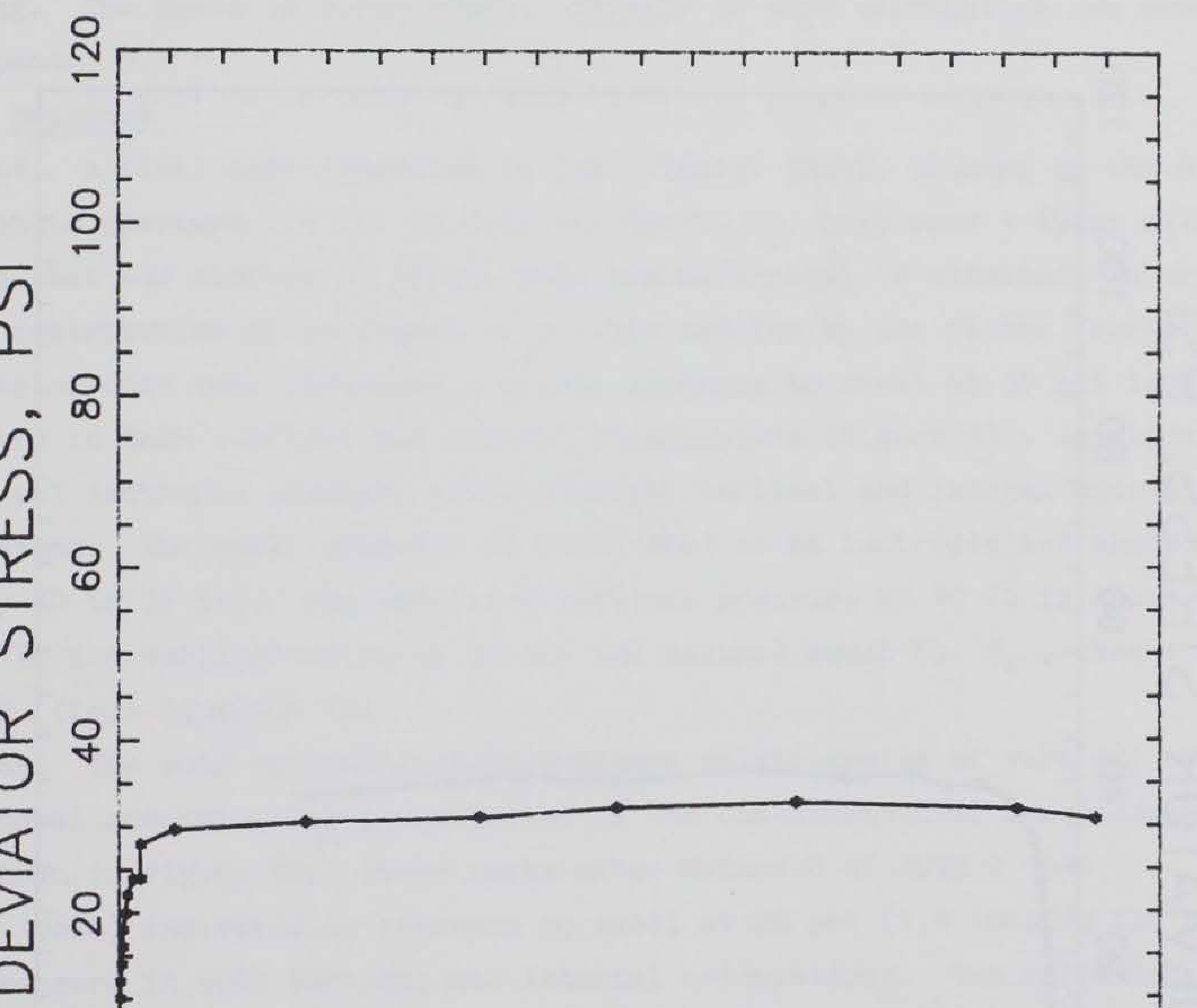
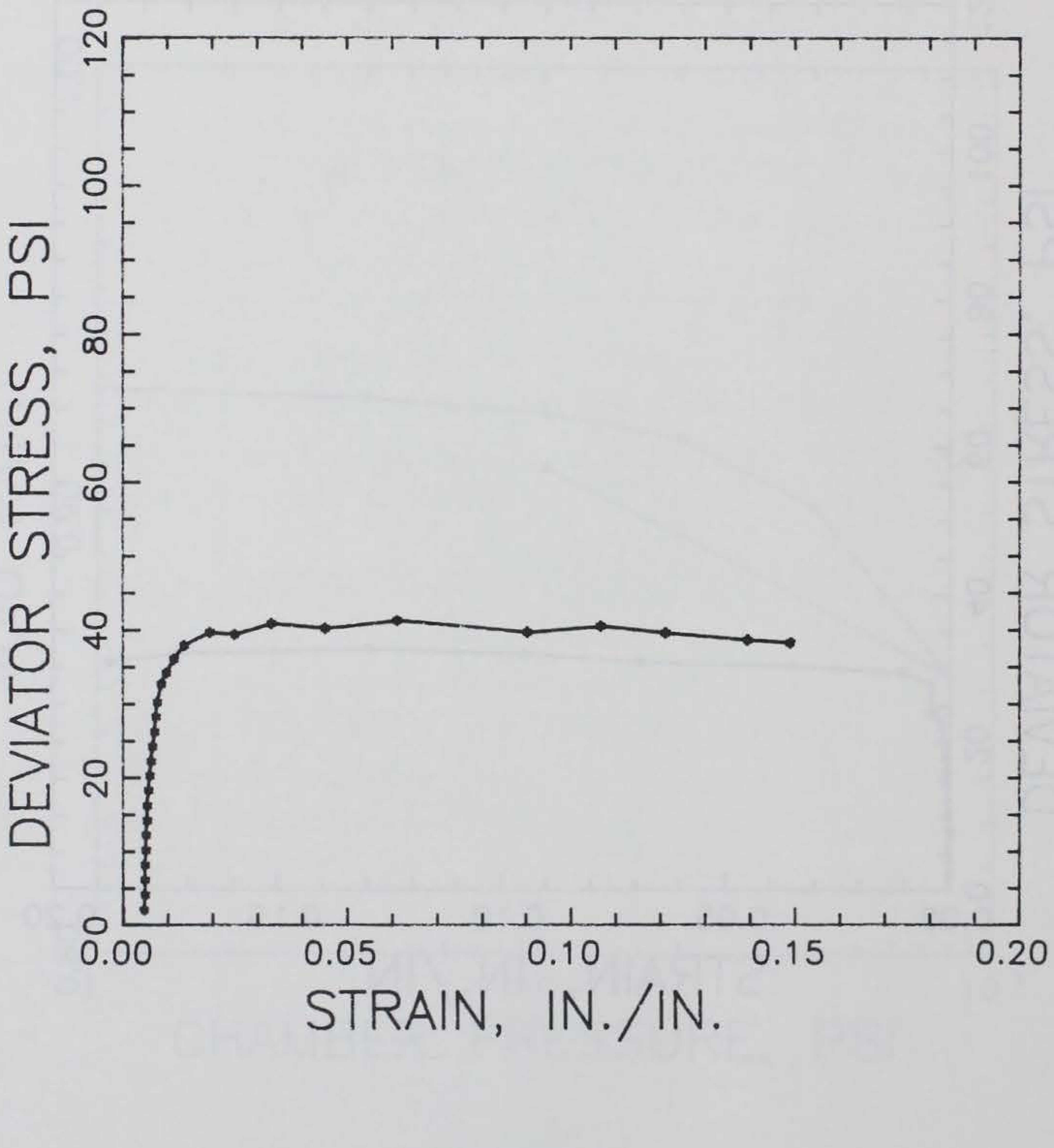


Figure 12. Behavior of specimen from Boring 2-2B, Incirlik Air Force Base isotropically consolidated in the triaxial double chamber



a. Unconsolidated

Figure 13. Undrained shear behavior of specimens from boring 2-2B of 5 ft depth from Incirlik Air Force Base tested in the double chamber (Continued)



b. Consolidated

Figure 13. (Concluded)

petrographic examination of these thin sections with a polarizing microscope showed that birefringence and extinction of material in the clay lamina occurred simultaneously; that is, the several lamina of clay material in the thin sections consisted of clay particles oriented with their C axes normal to bedding. The shale is anisotropic. Details of this examination are provided in Appendix D.

Swell pressure

64. A final test conducted in the triaxial double chamber on the stiff clay shale specimen 1.4 in. in diameter by 3.5 in. high used a Typar filter fabric that was slotted at 60 deg from the horizontal to eliminate an erroneous contribution of stiffness or elastic modulus by the filter fabric. The results of this test indicated a slight tendency to swell at 30 psi isotropic pressure in both vertical and lateral orientations (Figure 14). Application of 35 psi isotropic pressure induced slight vertical and lateral decreases in dimensions. The swell pressure is considered to be isotropic and approximately 30 to 32 psi. The effective vertical pressure at 40 ft is about 18 psi. If the swell pressure is 30 psi and assumed equal to σ_k, then $K_o = 2$ (from Equation 1b).

65. The void ratio-logarithm pressure relationships of vertical and horizontal companion specimens tested in the one-dimensional consolidometer are shown in Figure B3. These tests after Method C of ASTM D 4546 (ASTM 1986b) indicated no tendency to swell at 20 psi (1.4 tons/sq ft) confining pressure in both vertical and laterial orientations. The corrected swell pressures were not evaluated. The swell pressure correction procedure is not easily applied to these tests because the slopes of the curves at pressures less than the maximum past pressure and rebound curves are relatively flat.

66. The maximum vertical past pressure is about 220 psi estimated from the vertical consolidation test (Figure B3). The maximum horizontal past pressure is about 480 psi assuming that unequal elastic moduli in the perpendicular axes have no influence on the calculation. Therefore, K_o appears to be about 480/220 or 2.2. Lateral skin friction was probably substantial during the one-dimensional consolidometer test on this stiff clay shale because the specimens were 2.5-in. diam by 1.0-in. high for a diameter to height ratio of only 2.5.

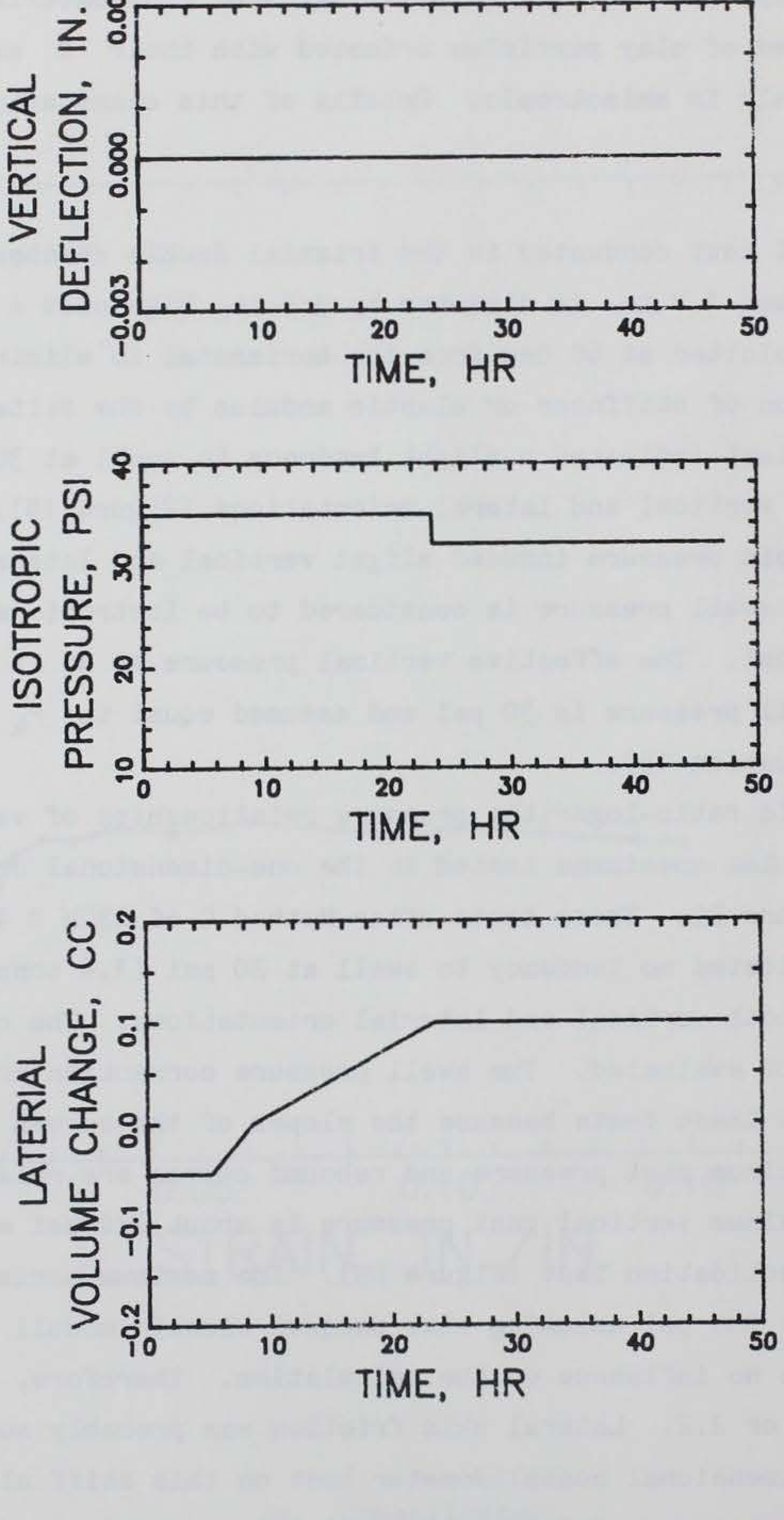
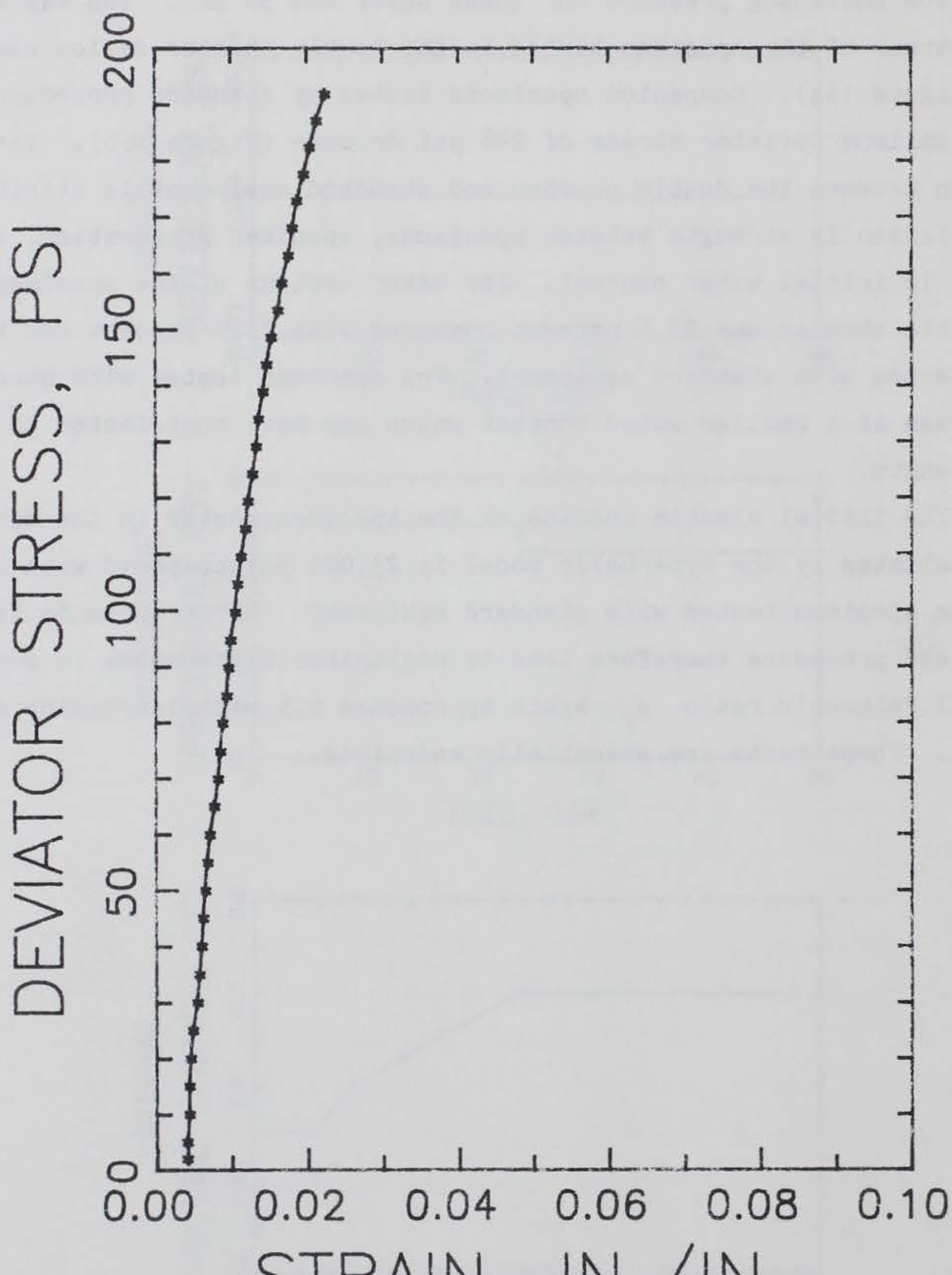


Figure 14. Swell pressure measurements from a specimen 40 ft depth, boring 6DC-419

Shear

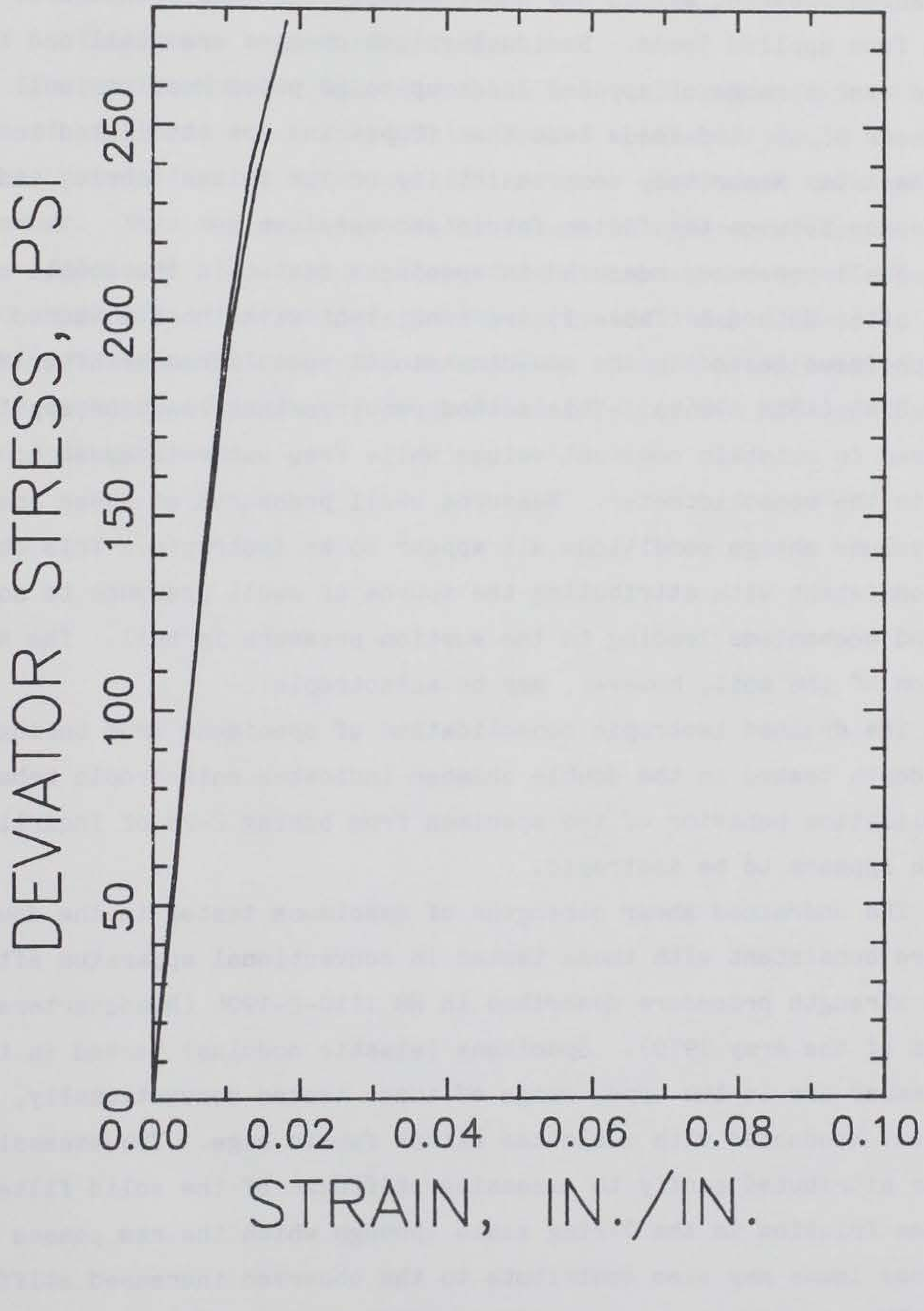
67. The confining pressure for these tests was 30 psi. The maximum deviator stress of the specimen tested in the double chamber device was 195 psi (Figure 15a). Companion specimens tested by standard procedures indicated maximum deviator stress of 248 psi or more (Figure 15b). Variation in strength between the double chamber and standard equipment is attributed to normal variation in strength between specimens, specimen preparation, and difference in initial water content. The water content of the specimen tested in the double chamber was 25.4 percent compared with 23.5 percent for the specimen tested with standard equipment. The specimen tested with standard equipment was at a smaller water content which may have contributed to its higher strength.

68. The initial elastic modulus of the specimen tested in the double chamber evaluated by the hyperbolic model is 23,000 psi compared with 22,000 psi for the specimen tested with standard equipment. Differences in test equipment and procedure therefore lead to negligible differences in moduli. The lateral Poisson's ratio μ_y again approaches 0.5 with increasing strain (Table 7c). These tests are essentially undrained.



a. Double Chamber

Figure 15. Shear behavior of specimens from boring 6DC-419 at 40 ft depth (Continued)



b. Standard Procedure

Figure 15. (Concluded)

PART IV. CONCLUSIONS AND RECOMMENDATIONS

69. The use of both an outer and inner chamber substantially limits volume changes observed within the inner chamber caused by flexure of the apparatus from applied loads. Residual volume changes are small and less than about 2 cc over a range of applied loads up to 80 psi. Most residual volume changes occur at applied loads less than 10 psi and are attributed to deformation in the latex membranes, compressibility of the filter fabric, and closing residual space between the filter fabric and specimen.

70. Swell pressures measured in specimens tested in the double chamber apparatus after Method B (Table 1) are consistent with those measured in similar specimens tested in the one-dimensional consolidometer after Method C of ASTM D 4546 (ASTM 1986b). This method requires that loads be applied to the specimen to maintain constant volume while free water is added to the specimen in the consolidometer. Measured swell pressures of these specimens under no volume change conditions all appear to be isotropic. This observation is consistent with attributing the source of swell pressure to soil suction and mechanisms leading to the suction pressure in soil. The elastic deformation of the soil, however, may be anisotropic.

71. The drained isotropic consolidation of specimens from boring 6DC-419 at 23 ft depth tested in the double chamber indicates anisotropic behavior. The consolidation behavior of the specimen from boring 2-2B of Incirlik Air Force Base appears to be isotropic.

72. The undrained shear strengths of specimens tested in the double chamber are consistent with those tested in conventional apparatus after the undrained strength procedure described in EM 1110-2-1906 (Headquarters, Department of the Army 1970). Specimens (elastic modulus) tested in the double chamber are in the upper range of those tested conventionally, except for the test conducted with a slotted filter fabric cage. The excessive modulus is attributed partly to excessive stiffness of the solid filter fabric cage. Some friction in the O-ring seals through which the ram passes to apply the vertical loads may also contribute to the observed increased stiffness.

73. The results of these tests show that measurement of swell pressure and consolidation or shear strength parameters are feasible with a single soil specimen.

74. Additional calibration tests should be performed with a variety of filters to determine if the volume corrections can be further reduced. The filter fabric should be precompressed to minimize the lateral volume correction and slotted similar to that applied in the Series 3 test to minimize stiffness in the fabric cage during shear.

75. The double chamber apparatus should be calibrated for confining pressures of up to 200 psi. The double chamber apparatus should also be modified to permit flow of water out of the inner chamber at the top of the inner chamber. This may also reduce the volume change correction.

76. Additional tests should be performed with a variety of expansive clays and anisotropic clay shales, particularly soft clay shales, to confirm that swell pressures are isotropic when volume changes are prevented in the soil. The test procedure should be modified to eliminate the vertical prestrain in soft specimens.

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APPENDIX A

TEST DATA FROM TRIAXIAL DOUBLE CHAMBER APPARATUS

Table A1

Nomenclature

Parameter	Definition
DATE	Day, Month, and Year of test
TIME	Standard 12 hr clock; i.e., 726 is 26 min after 7 o'clock
FORCE	Force applied by 500 lb load cell in the vertical direction, lb
LENGTH	Length of soil specimen, in.
DELTAJ2	Change in the chamber burette reading, cc
VOID RATIO	Specimen void ratio calculated from (VVO + DELTAJ2)*EO/VVO where VVO is the initial volume in cc and EO is the initial void ratio
A	Specimen cross-section area calculated from (DELTAJ2/($2.54^3 \cdot$ L) + *0.7^2 where 2.54 converts from centimeters to inches and 0.7 is the radius of the soil specimen in inches, $in.^2$
SIGMA1	Vertical applied stress σ_1 , psi
SIGMA3	Applied horizontal pressure σ_3 , psi
SIGMA	Deviator stress $\sigma_1 - \sigma_3$, psi
STRAIN1	Vertical strain ϵ_x , in./in.
STRAIN3	Lateral strain ϵ_y , in./in.
DELTAJ1	Change in specimen burette reading, cc

Table A2

Results Test 1 Boring 6DC-419 8 Ft Depth

INITIAL VOLUME = 88.71956
WET DENSITY = 1.855397
WATER CONTENT = .3024167
VOID RATIO = .8742364

"DATE	TIME	F	L	DELTAJ2	VOID	A	SIGMA1	SIGMA3	SIGMA	STRAIN1	STRAIN3	DELTAJ1"
"		LBS	IN.	CC	RATIO	IN.2	PSI	PSI	PSI	IN./IN.	IN./IN.	CC"
8/27/86	726	3.1000	3.5170	0.0000	0.8742	1.5394	2.0138	1.0000	1.0138	0.0000	-0.0000	0.0000
8/28/86	648	10.0000	3.5120	-0.7500	0.8584	1.5263	6.5516	6.0000	0.5516	0.0014	-0.0042	0.0000
8/29/86	659	16.2000	3.5150	-0.7000	0.8594	1.5272	10.6075	10.0000	0.6075	0.0006	-0.0040	1.2000
8/29/86	700	18.5000	3.5150	-0.7000	0.8594	1.5272	12.1135	10.0000	2.1135	0.0006	-0.0040	1.2000
8/29/86	701	20.0000	3.5150	-0.7000	0.8594	1.5272	13.0956	10.0000	3.0956	0.0006	-0.0040	1.2000
8/29/86	702	21.5000	3.5140	-0.6500	0.8605	1.5281	14.0698	10.0000	4.0698	0.0009	-0.0037	1.1500
8/29/86	703	23.1000	3.5140	-0.6500	0.8605	1.5281	15.1169	10.0000	5.1169	0.0009	-0.0037	1.1500
8/29/86	704	24.7000	3.5140	-0.6500	0.8605	1.5281	16.1639	10.0000	6.1639	0.0009	-0.0037	1.1500
8/29/86	705	26.2000	3.5140	-0.6500	0.8605	1.5281	17.1456	10.0000	7.1456	0.0009	-0.0037	1.1500
8/29/86	706	27.7000	3.5140	-0.6500	0.8605	1.5281	18.1272	10.0000	8.1272	0.0009	-0.0037	1.1500
8/29/86	707	29.3000	3.5140	-0.6000	0.8616	1.5290	19.1633	10.0000	9.1633	0.0009	-0.0034	1.1500
8/29/86	708	30.8000	3.5140	-0.6000	0.8616	1.5290	20.1444	10.0000	10.1444	0.0009	-0.0034	1.1500
8/29/86	709	32.3000	3.5120	-0.6000	0.8616	1.5290	21.1255	10.0000	11.1255	0.0014	-0.0034	1.1500
8/29/86	710	33.9000	3.5100	-0.6000	0.8616	1.5289	22.1721	10.0000	12.1721	0.0020	-0.0034	1.1500
8/29/86	711	35.4000	3.5090	-0.6000	0.8616	1.5289	23.1532	10.0000	13.1532	0.0023	-0.0034	1.1500
8/29/86	712	36.9000	3.5090	-0.6000	0.8616	1.5289	24.1343	10.0000	14.1343	0.0023	-0.0034	1.1500
8/29/86	713	38.5000	3.5080	-0.6000	0.8616	1.5289	25.1808	10.0000	15.1808	0.0026	-0.0034	1.1500
8/29/86	714	40.0000	3.5070	-0.6000	0.8616	1.5289	26.1619	10.0000	16.1619	0.0028	-0.0034	1.1500
8/29/86	715	41.6000	3.5050	-0.5500	0.8626	1.5298	27.1930	10.0000	17.1930	0.0034	-0.0031	1.1300
8/29/86	716	43.1000	3.5010	-0.4500	0.8647	1.5315	28.1417	10.0000	18.1417	0.0045	-0.0026	1.1200
8/29/86	717	44.7000	3.4990	-0.4000	0.8658	1.5324	29.1699	10.0000	19.1699	0.0051	-0.0023	1.1100
8/29/86	718	46.2000	3.4940	-0.3000	0.8679	1.5341	30.1146	10.0000	20.1146	0.0065	-0.0017	1.1000
8/29/86	719	47.7000	3.4870	-0.1500	0.8711	1.5368	31.0394	10.0000	21.0394	0.0085	-0.0009	1.1000
8/29/86	720	49.3000	3.4770	0.1500	0.8774	1.5420	31.9712	10.0000	21.9712	0.0114	0.0009	1.1000
8/29/86	721	50.8000	3.4650	0.4000	0.8827	1.5464	32.8500	10.0000	22.8500	0.0148	0.0023	1.0800
8/29/86	722	52.3000	3.4480	0.7500	0.8901	1.5527	33.6843	10.0000	23.6843	0.0196	0.0043	1.0700
8/29/86	723	53.8000	3.4260	1.3000	0.9017	1.5625	34.4312	10.0000	24.4312	0.0259	0.0075	1.0300
8/29/86	724	55.3000	3.4020	1.9900	0.9163	1.5751	35.1094	10.0000	25.1094	0.0327	0.0115	1.0200
8/29/86	725	56.9000	3.3660	2.8000	0.9334	1.5901	35.7830	10.0000	25.7830	0.0429	0.0164	1.0000
8/29/86	726	58.4000	3.3230	3.7000	0.9524	1.6073	36.3336	10.0000	26.3336	0.0552	0.0218	1.0000
8/29/86	727	60.0000	3.2630	5.9000	0.9989	1.6497	36.3698	10.0000	26.3698	0.0722	0.0352	0.9500
8/29/86	728	61.6000	3.2220	8.0000	1.0432	1.6909	36.4303	10.0000	26.4303	0.0839	0.0481	0.9200

Note: See Table A1 for definition of terms.

Table A3

Results Test 2 Boring 6DC-419 8 Ft Depth

INITIAL VOLUME = 88.03847
WET DENSITY = 1.921433
WATER CONTENT = .2858957
VOID RATIO = .7868653

"DATE	TIME	F	L	DELTAJ2	VOID	A	SIGMA1	SIGMA3	SIGMA	STRAIN1	STRAIN3	DELTAJ1"
"		LBS	IN.	CC	RATIO	IN.2	PSI	PSI	PSI	IN./IN.	IN./IN.	CC"
9/02/86	837	3.1000	3.4600	0.0000	0.7869	1.5394	2.0138	1.0000	1.0138	0.0086	-0.0000	0.0000
9/03/86	655	10.0000	3.4600	-0.2500	0.7818	1.5350	6.5148	6.0000	0.5148	0.0086	-0.0014	0.0000
9/04/86	650	15.9000	3.4600	-0.3500	0.7798	1.5332	10.3704	10.0000	0.3704	0.0086	-0.0020	0.8500
9/05/86	650	31.6000	3.4570	-0.9000	0.7686	1.5235	20.7418	20.0000	0.7418	0.0095	-0.0052	0.2800
9/08/86	645	62.2000	3.4510	-2.7500	0.7311	1.4908	41.7239	40.0000	1.7239	0.0112	-0.0159	-1.9500
9/09/86	649	128.1000	3.4480	-5.2200	0.6809	1.4470	88.5283	80.0000	8.5283	0.0120	-0.0305	-4.4500
9/10/86	650	31.5000	3.4500	-3.5200	0.7154	1.4771	21.3253	20.0000	1.3253	0.0115	-0.0204	-2.7000
9/11/86	652	16.2000	3.4520	-2.5200	0.7357	1.4948	10.8373	10.0000	0.8373	0.0109	-0.0146	-1.7000
9/11/86	700	18.5000	3.4520	-2.5200	0.7357	1.4948	12.3760	10.0000	2.3760	0.0109	-0.0146	-1.7000
9/11/86	703	23.1000	3.4510	-2.5200	0.7357	1.4948	15.4534	10.0000	5.4534	0.0112	-0.0146	-1.7000
9/11/86	707	29.3000	3.4500	-2.5200	0.7357	1.4948	19.6012	10.0000	9.6012	0.0115	-0.0146	-1.7500
9/11/86	710	33.9000	3.4490	-2.5200	0.7357	1.4948	22.6787	10.0000	12.6787	0.0117	-0.0146	-1.7800
9/11/86	712	36.9000	3.4480	-2.5200	0.7357	1.4948	24.6859	10.0000	14.6859	0.0120	-0.0146	-1.7800
9/11/86	713	38.5000	3.4460	-2.4700	0.7367	1.4956	25.7415	10.0000	15.7415	0.0126	-0.0143	-1.8000
9/11/86	714	40.0000	3.4450	-2.4700	0.7367	1.4956	26.7446	10.0000	16.7446	0.0129	-0.0143	-1.8000
9/11/86	715	41.6000	3.4440	-2.4500	0.7371	1.4960	27.8081	10.0000	17.8081	0.0132	-0.0142	-1.8000
9/11/86	716	43.1000	3.4420	-2.4200	0.7377	1.4965	28.8010	10.0000	18.8010	0.0138	-0.0140	-1.8000
9/11/86	717	44.7000	3.4400	-2.3700	0.7388	1.4973	29.8530	10.0000	19.8530	0.0143	-0.0138	-1.8000
9/11/86	718	46.2000	3.4380	-2.3200	0.7398	1.4982	30.8370	10.0000	20.8370	0.0149	-0.0135	-1.8000
9/11/86	719	47.7000	3.4360	-2.2700	0.7408	1.4991	31.8198	10.0000	21.8198	0.0155	-0.0132	-1.8000
9/11/86	720	49.3000	3.4340	-2.2200	0.7418	1.4999	32.8682	10.0000	22.8682	0.0160	-0.0129	-1.8000
9/11/86	721	50.8000	3.4320	-2.1700	0.7428	1.5008	33.8487	10.0000	23.8487	0.0166	-0.0126	-1.8200
9/11/86	722	52.3000	3.4290	-2.1200	0.7438	1.5017	34.8283	10.0000	24.8283	0.0175	-0.0123	-1.8200
9/11/86	723	55.3000	3.4240	-2.0700	0.7449	1.5025	36.8056	10.0000	26.8056	0.0189	-0.0121	-1.8300
9/11/86	724	56.9000	3.4200	-2.0200	0.7459	1.5033	37.8491	10.0000	27.8491	0.0201	-0.0118	-1.8300
9/11/86	725	58.4000	3.4160	-1.9200	0.7479	1.5051	38.8019	10.0000	28.8019	0.0212	-0.0112	-1.8300
9/11/86	726	60.0000	3.4100	-1.7200	0.7520	1.5086	39.7720	10.0000	29.7720	0.0229	-0.0100	-1.8400
9/11/86	727	63.2000	3.3900	-1.3200	0.7601	1.5156	41.6991	10.0000	31.6991	0.0287	-0.0077	-1.8400
9/11/86	728	64.7000	3.3750	-0.9200	0.7682	1.5227	42.4890	10.0000	32.4890	0.0330	-0.0054	-1.8000
9/11/86	729	66.2000	3.3600	-0.4200	0.7783	1.5318	43.2185	10.0000	33.2185	0.0372	-0.0025	-1.7500
9/11/86	730	69.2000	3.3300	1.0800	0.8088	1.5592	44.3825	10.0000	34.3825	0.0458	0.0064	-1.7500
9/11/86	731	73.1000	3.3000	2.0800	0.8291	1.5778	46.3291	10.0000	36.3290	0.0544	0.0124	-1.7500
9/11/86	731	75.5000	3.2640	3.0800	0.8494	1.5970	47.2772	10.0000	37.2772	0.0648	0.0185	-1.7200
9/11/86	732	77.0000	3.2380	4.0800	0.8697	1.6163	47.6405	10.0000	37.6405	0.0722	0.0247	-1.6700
9/11/86	733	78.5000	3.2100	4.8800	0.8859	1.6322	48.0960	10.0000	38.0960	0.0802	0.0297	-1.6200
9/11/86	734	80.0000	3.1850	5.4300	0.8971	1.6434	48.6790	10.0000	38.6790	0.0874	0.0332	-1.5900
9/11/86	735	81.6000	3.1400	6.3800	0.9164	1.6634	49.0570	10.0000	39.0570	0.1003	0.0395	-1.5700
9/11/86	736	84.7000	3.0420	9.3800	0.9772	1.7275	49.0291	10.0000	39.0291	0.1284	0.0594	-1.5500
9/11/86	737	86.2000	2.9280	11.5000	1.0203	1.7791	48.4526	10.0000	38.4526	0.1610	0.0750	-1.5200

Note: See Table A1 for definition of terms.

Table A4

Results Test 3 Boring 6DC-419 23 Ft Depth

INITIAL VOLUME = 89.80428
WET DENSITY = 1.956143
WATER CONTENT = .275522
VOID RATIO = .7605613

"DATE "	TIME	F LBS	L IN.	DELTAJ2 CC	VOID RATIO	A IN.2	SIGMA1 PSI	SIGMA3 PSI	SIGMA PSI	STRAIN1 IN./IN.	STRAIN3 IN./IN.	DELTAJ1" CC"
9/11/86	1135	3.1000	3.5600	0.0000	0.7606	1.5394	2.0138	1.0000	1.0138	0.0000	-0.0000	0.0000
9/12/86	726	28.4000	3.5650	-0.1500	0.7576	1.5368	18.4798	18.0000	0.4798	-0.0014	-0.0008	0.0000
9/15/86	645	35.3000	3.5650	-0.2500	0.7557	1.5351	22.9952	21.0000	1.9952	-0.0014	-0.0014	0.4300
9/16/86	646	64.2000	3.5550	-0.5000	0.7508	1.5308	41.9389	40.0000	1.9389	0.0014	-0.0028	-0.0500
9/17/86	647	125.7000	3.5370	-1.4200	0.7327	1.5149	82.9768	80.0000	2.9768	0.0065	-0.0080	-1.3500
9/18/86	650	33.9000	3.5390	-0.3000	0.7547	1.5342	22.0961	20.0000	2.0961	0.0059	-0.0017	-0.0500
9/18/86	700	41.7000	3.5380	-0.3000	0.7547	1.5342	27.1802	20.0000	7.1802	0.0062	-0.0017	-0.0500
9/18/86	701	46.2000	3.5370	-0.3000	0.7547	1.5342	30.1133	20.0000	10.1133	0.0065	-0.0017	-0.0500
9/18/86	702	53.8000	3.5370	-0.3000	0.7547	1.5342	35.0670	20.0000	15.0670	0.0065	-0.0017	-0.0500
9/18/86	703	61.6000	3.5350	-0.3000	0.7547	1.5342	40.1512	20.0000	20.1512	0.0070	-0.0017	-0.0500
9/18/86	704	69.4000	3.5340	-0.3000	0.7547	1.5342	45.2353	20.0000	25.2353	0.0073	-0.0017	-0.0500
9/18/86	705	77.0000	3.5320	-0.3000	0.7547	1.5342	50.1891	20.0000	30.1891	0.0079	-0.0017	-0.0500
9/18/86	706	84.7000	3.5300	-0.3000	0.7547	1.5342	55.2081	20.0000	35.2081	0.0084	-0.0017	-0.0500
9/18/86	707	92.3000	3.5280	-0.3000	0.7547	1.5342	60.1620	20.0000	40.1620	0.0090	-0.0017	-0.0500
9/18/86	708	95.4000	3.5270	-0.3000	0.7547	1.5342	62.1827	20.0000	42.1827	0.0093	-0.0017	-0.0500
9/18/86	709	98.4000	3.5260	-0.2500	0.7557	1.5351	64.1020	20.0000	44.1020	0.0096	-0.0014	-0.0500
9/18/86	710	101.5000	3.5250	-0.2500	0.7557	1.5351	66.1215	20.0000	46.1215	0.0098	-0.0014	-0.0500
9/18/86	711	104.6000	3.5240	-0.2000	0.7566	1.5359	68.1026	20.0000	48.1026	0.0101	-0.0011	-0.0500
9/18/86	712	107.7000	3.5230	-0.2000	0.7566	1.5359	70.1210	20.0000	50.1210	0.0104	-0.0011	-0.0500
9/18/86	713	110.5000	3.5220	-0.1500	0.7576	1.5368	71.9035	20.0000	51.9035	0.0107	-0.0008	-0.0500
9/18/86	714	113.7000	3.5210	-0.1500	0.7576	1.5368	73.9858	20.0000	53.9858	0.0110	-0.0008	-0.0500
9/18/86	715	117.0000	3.5190	-0.1000	0.7586	1.5376	76.0903	20.0000	56.0903	0.0115	-0.0006	-0.0500
9/18/86	716	120.0000	3.5180	-0.0500	0.7596	1.5385	77.9974	20.0000	57.9974	0.0118	-0.0003	-0.0500
9/18/86	717	123.0000	3.5170	0.0000	0.7606	1.5394	79.9023	20.0000	59.9023	0.0121	-0.0000	-0.0500
9/18/86	718	126.0000	3.5160	0.0000	0.7606	1.5394	81.8511	20.0000	61.8511	0.0124	-0.0000	-0.0500
9/18/86	719	129.1000	3.5140	0.0500	0.7615	1.5402	83.8176	20.0000	63.8176	0.0129	0.0003	-0.0500
9/18/86	720	132.3000	3.5120	0.1000	0.7625	1.5411	85.8468	20.0000	65.8468	0.0135	0.0006	-0.0500
9/18/86	721	135.2000	3.5100	0.1500	0.7635	1.5420	87.6790	20.0000	67.6790	0.0140	0.0008	-0.0500
9/18/86	722	138.3000	3.5090	0.1500	0.7635	1.5420	89.6894	20.0000	69.6894	0.0143	0.0008	-0.0500
9/18/86	723	141.4000	3.5070	0.2000	0.7645	1.5429	91.6480	20.0000	71.6480	0.0149	0.0011	-0.0500
9/18/86	724	144.6000	3.5050	0.2500	0.7655	1.5437	93.6691	20.0000	73.6691	0.0154	0.0014	-0.0500
9/18/86	725	147.7000	3.5030	0.3000	0.7664	1.5446	95.6231	20.0000	75.6231	0.0160	0.0017	-0.0500
9/18/86	726	150.6000	3.5010	0.3500	0.7674	1.5455	97.4454	20.0000	77.4454	0.0166	0.0020	-0.0500
9/18/86	727	153.7000	3.4980	0.4000	0.7684	1.5464	99.3948	20.0000	79.3948	0.0174	0.0023	-0.0500
9/18/86	728	157.0000	3.4960	0.4500	0.7694	1.5472	101.4713	20.0000	81.4713	0.0180	0.0025	-0.0500
9/18/86	729	160.0000	3.4940	0.5000	0.7704	1.5481	103.3516	20.0000	83.3516	0.0185	0.0028	-0.0500
9/18/86	730	163.3000	3.4920	0.5500	0.7713	1.5490	105.4234	20.0000	85.4234	0.0191	0.0031	-0.0500
9/18/86	731	166.6000	3.4890	0.6000	0.7723	1.5499	107.4926	20.0000	87.4926	0.0199	0.0034	-0.0500
9/18/86	732	169.4000	3.4870	0.7000	0.7743	1.5516	109.1755	20.0000	89.1755	0.0205	0.0040	-0.0500
9/18/86	733	172.4000	3.4840	0.7500	0.7753	1.5525	111.0455	20.0000	91.0455	0.0213	0.0043	-0.0500
9/18/86	734	175.4000	3.4820	0.8000	0.7762	1.5534	112.9136	20.0000	92.9136	0.0219	0.0045	-0.0500
9/18/86	735	178.6000	3.4800	0.9000	0.7782	1.5552	114.8433	20.0000	94.8433	0.0225	0.0051	-0.0500
9/18/86	736	181.7000	3.4770	0.9500	0.7792	1.5561	116.7698	20.0000	96.7698	0.0233	0.0054	-0.0500
9/18/86	737	184.8000	3.4740	1.0000	0.7802	1.5569	118.6939	20.0000	98.6939	0.0242	0.0057	-0.0500
9/18/86	738	187.8000	3.4710	1.0500	0.7811	1.5578	120.5515	20.0000	100.5515	0.0250	0.0060	-0.0500
9/18/86	739	190.8000	3.4690	1.1000	0.7821	1.5587	122.4073	20.0000	102.4073	0.0256	0.0063	-0.0500
9/18/86	740	193.9000	3.4670	1.1500	0.7831	1.5596	124.3250	20.0000	104.3250	0.0261	0.0066	-0.0500
9/18/86	741	197.0000	3.4640	1.2500	0.7851	1.5614	126.1687	20.0000	106.1687	0.0270	0.0071	-0.0500
9/18/86	742	200.0000	3.4610	1.3000	0.7860	1.5623	128.0163	20.0000	108.0163	0.0278	0.0074	-0.0500
9/18/86	743	203.0000	3.4580	1.4000	0.7880	1.5641	129.7882	20.0000	109.7882	0.0287	0.0080	-0.0500
9/18/86	744	206.2000	3.4540	1.5000	0.7900	1.5659	131.6830	20.0000	111.6830	0.0298	0.0086	-0.0500
9/18/86	745	209.2000	3.4500	1.6000	0.7919	1.5677	133.4455	20.0000	113.4455	0.0309	0.0092	-0.0500
9/18/86	746	212.5000	3.4450	1.7000	0.7939	1.5695	135.3940	20.0000	115.3940	0.0323	0.0097	-0.0500
9/18/86	747	215.5000	2.9630	1.7000	0.7939	1.5744	136.8782	20.0000	116.8782	0.1677	0.0113	-0.0500

Note: See Table A1 for definition of terms.

Table A5

Results Test 4 Boring 2-2B, Incirlik Air Force Base 5 Ft Depth

INITIAL VOLUME = 89.29976
WET DENSITY = 1.885
WATER CONTENT = .3242932
VOID RATIO = .8968661

"DATE	TIME	F	L	DELTAJ2	VOID	A	SIGMA1	SIGMA3	SIGMA	STRAIN1	STRAIN3	DELTAJ1"
"		LBS	IN.	CC	RATIO	IN.2	PSI	PSI	PSI	IN./IN.	IN./IN.	CC"
11/03/86	919	3.1000	3.5400	0.0000	0.8969	1.5394	2.0138	1.0000	1.0138	0.0000	-0.0000	0.0000
11/04/86	645	9.2000	3.5400	-0.2000	0.8926	1.5359	5.9898	4.0000	1.9898	0.0000	-0.0011	0.0000
11/06/86	645	21.5000	3.5400	-0.3800	0.8888	1.5328	14.0263	12.0000	2.0263	0.0000	-0.0021	0.7900
11/06/86	700	24.6000	3.5400	-0.3800	0.8888	1.5328	16.0487	12.0000	4.0487	0.0000	-0.0021	0.7900
11/06/86	701	27.7000	3.5400	-0.3800	0.8888	1.5328	18.0712	12.0000	6.0712	0.0000	-0.0021	0.7900
11/06/86	702	30.8000	3.5400	-0.3300	0.8899	1.5337	20.0823	12.0000	8.0823	0.0000	-0.0018	0.7900
11/06/86	703	33.9000	3.5390	-0.3300	0.8899	1.5337	22.1036	12.0000	10.1036	0.0003	-0.0019	0.7900
11/06/86	704	36.9000	3.5390	-0.3300	0.8899	1.5337	24.0596	12.0000	12.0596	0.0003	-0.0019	0.7900
11/06/86	705	40.0000	3.5380	-0.2800	0.8909	1.5346	26.0663	12.0000	14.0663	0.0006	-0.0016	0.7900
11/06/86	706	43.2000	3.5370	-0.2500	0.8916	1.5351	28.1421	12.0000	16.1421	0.0008	-0.0014	0.7900
11/06/86	707	46.2000	3.5370	-0.2300	0.8920	1.5354	30.0896	12.0000	18.0896	0.0008	-0.0013	0.7900
11/06/86	708	49.2000	3.5350	-0.2300	0.8920	1.5354	32.0436	12.0000	20.0436	0.0014	-0.0013	0.7900
11/06/86	709	52.3000	3.5340	-0.2000	0.8926	1.5359	34.0511	12.0000	22.0511	0.0017	-0.0011	0.7900
11/06/86	710	55.4000	3.5300	-0.1300	0.8941	1.5371	36.0411	12.0000	24.0411	0.0028	-0.0007	0.7900
11/06/86	711	58.5000	3.5250	0.0200	0.8973	1.5397	37.9938	12.0000	25.9938	0.0042	0.0001	0.7900
11/06/86	712	61.6000	3.5250	0.1700	0.9005	1.5423	39.9397	12.0000	27.9397	0.0042	0.0010	0.7900
11/06/86	713	64.7000	3.5020	0.6700	0.9111	1.5511	41.7135	12.0000	29.7135	0.0107	0.0038	0.7900
11/06/86	714	67.7000	3.4140	2.8700	0.9578	1.5907	42.5604	12.0000	30.5604	0.0356	0.0165	0.7900
11/06/86	715	70.8000	3.2960	5.7700	1.0194	1.6462	43.0079	12.0000	31.0079	0.0689	0.0341	0.7900
11/06/86	716	73.8000	3.2030	7.0700	1.0470	1.6741	44.0840	12.0000	32.0840	0.0952	0.0428	0.7900
11/06/86	717	77.0000	3.0600	9.2700	1.0938	1.7230	44.6883	12.0000	32.6883	0.1299	0.0580	0.7900
11/06/86	718	77.0000	2.9290	10.2700	1.1150	1.7533	43.9160	12.0000	31.9160	0.1726	0.0672	0.7900
11/06/86	719	77.0000	2.8760	12.2700	1.1575	1.7997	42.7842	12.0000	30.7842	0.1876	0.0813	0.7900

Note: See Table A1 for definition of terms.

Table A6

Results Test 5 Boring 2-2B, Incirlik Air Force Base 5 Ft Depth

```
INITIAL VOLUME =  88.29072
WET DENSITY    =  1.870072
WATER CONTENT  =  .3349725
VOID RATIO     =  .9274263
```

"DATE	TIME	F LBS	L IN.	DELTAJ2 CC	VOID RATIO	A IN.2	SIGMA1 PSI	SIGMA3 PSI	SIGMA PSI	STRAIN1 IN./IN.	STRAIN3 IN./IN.	DELTAJ1" CC"
11/10/86	820	3.1000	3.5000	0.0000	0.9274	1.5394	2.0138	1.0000	1.0138	0.0000	-0.0000	0.0000
11/12/86	645	9.2000	3.5000	-0.1000	0.9252	1.5376	5.9832	4.0000	1.9832	0.0000	-0.0006	0.0000
11/14/86	655	23.0000	3.5000	-0.2500	0.9220	1.5350	14.9835	10.0000	4.9835	0.0000	-0.0014	0.4500
11/17/86	619	39.2000	3.4960	-0.5000	0.9165	1.5307	25.6100	20.0000	5.6100	0.0011	-0.0028	-0.4000
11/18/86	645	66.3000	3.4860	-1.2000	0.9012	1.5184	43.6651	40.0000	3.6651	0.0040	-0.0068	-1.4300
11/19/86	645	127.4000	3.4510	-2.9500	0.8630	1.4872	85.6634	80.0000	5.6634	0.0140	-0.0171	-3.8300
11/20/86	644	35.6000	3.4750	-1.5000	0.8947	1.5130	23.5288	20.0000	3.5288	0.0071	-0.0086	-1.8300
11/21/86	645	18.4000	3.4840	-0.8100	0.9097	1.5252	12.0640	10.0000	2.0640	0.0046	-0.0046	-0.9300
11/21/86	650	21.5000	3.4830	-0.8100	0.9097	1.5252	14.0966	10.0000	4.0966	0.0049	-0.0046	-0.9300
11/21/86	651	24.6000	3.4830	-0.8100	0.9097	1.5252	16.1292	10.0000	6.1292	0.0049	-0.0046	-0.9300
11/21/66	652	27.7000	3.4830	-0.8100	0.9097	1.5252	18.1617	10.0000	8.1617	0.0049	-0.0046	-0.9300
11/21/86	653	30.8000	3.4820	-0.7800	0.9104	1.5257	20.1873	10.0000	10.1873	0.0051	-0.0044	-0.9300
11/21/86	654	33.9000	3.4820	-0.7800	0.9104	1.5257	22.2192	10.0000	12.2192	0.0051	-0.0044	-0.9300
11/21/66	655	36.9000	3.4810	-0.7600	0.9108	1.5261	24.1800	10.0000	14.1800	0.0054	-0.0043	-0.9300
11/21/86	656	40.0000	3.4810	-0.7600	0.9108	1.5261	26.2113	10.0000	16.2113	0.0054	-0.0043	-0.9300
11/21/86	657	43.2000	3.4800	-0.7400	0.9113	1.5264	28.3018	10.0000	18.3018	0.0057	-0.0042	-0.9300
11/21/86	658	46.2000	3.4790	-0.7100	0.9119	1.5269	30.2569	10.0000	20.2569	0.0060	-0.0041	-0.9300
11/21/86	659	49.2000	3.4780	-0.6800	0.9126	1.5274	32.2106	10.0000	22.2106	0.0063	-0.0039	-0.9300
11/21/86	700	52.3000	3.4770	-0.6600	0.9130	1.5278	34.2323	10.0000	24.2323	0.0066	-0.0038	-0.9300
11/21/86	701	55.4000	3.4750	-0.6100	0.9141	1.5287	36.2407	10.0000	26.2407	0.0071	-0.0035	-0.9300
11/21/86	702	58.5000	3.4740	-0.5700	0.9150	1.5294	38.2511	10.0000	28.2511	0.0074	-0.0033	-0.9300
11/21/86	703	61.5000	3.4730	-0.5500	0.9154	1.5297	40.2035	10.0000	30.2035	0.0077	-0.0031	-0.9300
11/21/86	704	65.3000	3.4700	-0.4600	0.9174	1.5313	42.6438	10.0000	32.6438	0.0086	-0.0026	-0.9300
11/21/86	705	67.7000	3.4660	-0.3600	0.9196	1.5330	44.1606	10.0000	34.1606	0.0097	-0.0021	-0.9300
11/21/86	706	70.7000	3.4600	-0.2100	0.9228	1.5357	46.0383	10.0000	36.0383	0.0114	-0.0012	-0.9300
11/21/86	707	73.8000	3.4520	0.0400	0.9283	1.5401	47.9194	10.0000	37.9194	0.0137	0.0002	-0.9300
11/21/86	708	77.0000	3.4320	0.5900	0.9403	1.5499	49.6816	10.0000	39.6816	0.0194	0.0034	-0.9300
11/21/86	709	77.0000	3.4130	1.0900	0.9512	1.5589	49.3948	10.0000	39.3948	0.0249	0.0063	-0.9300
11/21/86	710	80.0000	3.3840	1.8400	0.9676	1.5726	50.8724	10.0000	40.8724	0.0331	0.0107	-0.9300
11/21/86	710	80.0000	3.3420	2.9400	0.9916	1.5931	50.2177	10.0000	40.2177	0.0451	0.0173	-0.9300
11/21/86	711	83.2000	3.2860	4.4400	1.0244	1.6218	51.2999	10.0000	41.2999	0.0611	0.0264	-0.9300
11/21/86	712	83.2000	3.1840	7.0400	1.0811	1.6743	49.6922	10.0000	39.6922	0.0903	0.0429	-0.9300
11/21/86	713	86.2000	3.1270	8.5400	1.1139	1.7060	50.5264	10.0000	40.5264	0.1066	0.0527	-0.9300
11/21/86	714	86.2000	3.0760	10.0400	1.1466	1.7386	49.5812	10.0000	39.5812	0.1211	0.0627	-0.9300
11/21/86	715	86.2000	3.0120	11.5400	1.1793	1.7732	48.6131	10.0000	38.6131	0.1394	0.0733	-0.9300
11/21/86	716	86.2000	2.9790	12.0400	1.1903	1.7860	48.2639	10.0000	38.2639	0.1489	0.0771	-0.9300

Note: See Table A1 for definition of terms.

Table A7

Results Test 2 Boring 6DC-419 40 Ft Depth

INITIAL VOLUME = 89.02228
WET DENSITY = 1.948276
WATER CONTENT = .254559
VOID RATIO = .7579366

"DATE "	TIME	F LBS	L IN.	DELTAJ2 CC	VOID RATIO	A IN.2	SIGMA1 PSI	SIGMA3 PSI	SIGMA PSI	STRAIN1 IN./IN.	STRAIN3 IN./IN.	DELTAJ1" CC"
05/05/87	940	3.1000	3.5290	0.0000	0.7579	1.5394	2.0138	1.0000	1.0138	0.0000	-0.0000	0.0000
05/06/87	644	46.9000	3.5160	0.0500	0.7589	1.5402	30.4496	30.0000	0.4496	0.0037	0.0003	0.0000
05/08/87	639	52.3000	3.5150	-0.1500	0.7550	1.5368	34.0323	32.0000	2.0323	0.0040	-0.0008	-0.2500
05/08/87	700	56.9000	3.5150	-0.1500	0.7550	1.5368	37.0256	32.0000	5.0256	0.0040	-0.0008	-0.2500
05/08/87	701	64.6000	3.5140	-0.1500	0.7550	1.5368	42.0361	32.0000	10.0361	0.0043	-0.0008	-0.2500
05/08/87	702	72.3000	3.5140	-0.1500	0.7550	1.5368	47.0466	32.0000	15.0466	0.0043	-0.0008	-0.2500
05/08/87	703	80.0000	3.5130	-0.1000	0.7560	1.5376	52.0277	32.0000	20.0277	0.0045	-0.0006	-0.2500
05/08/87	704	87.7000	3.5120	-0.1000	0.7560	1.5376	57.0354	32.0000	25.0354	0.0048	-0.0006	-0.2500
05/08/87	705	95.4000	3.5100	-0.1000	0.7560	1.5376	62.0431	32.0000	30.0431	0.0054	-0.0006	-0.2500
05/08/87	706	103.1000	3.5090	-0.0500	0.7569	1.5385	67.0129	32.0000	35.0129	0.0057	-0.0003	-0.2500
05/08/87	707	110.8000	3.5080	-0.0500	0.7569	1.5385	72.0177	32.0000	40.0177	0.0060	-0.0003	-0.2500
05/08/87	708	118.5000	3.5070	-0.0500	0.7569	1.5385	77.0226	32.0000	45.0226	0.0062	-0.0003	-0.2500
05/08/87	709	126.2000	3.5060	0.0000	0.7579	1.5394	81.9810	32.0000	49.9810	0.0065	-0.0000	-0.2500
05/08/87	710	133.8000	3.5050	0.0000	0.7579	1.5394	86.9181	32.0000	54.9181	0.0068	-0.0000	-0.2500
05/08/87	711	141.5000	3.5040	0.0000	0.7579	1.5394	91.9201	32.0000	59.9201	0.0071	-0.0000	-0.2500
05/08/87	712	149.2000	3.5020	0.0000	0.7579	1.5394	96.9221	32.0000	64.9221	0.0077	-0.0000	-0.2500
05/08/87	713	156.9000	3.5000	0.0500	0.7589	1.5403	101.8664	32.0000	69.8664	0.0082	0.0003	-0.2500
05/08/87	714	164.6000	3.4990	0.1000	0.7599	1.5411	106.8052	32.0000	74.8051	0.0085	0.0006	-0.2500
05/08/87	715	172.3000	3.4980	0.1000	0.7599	1.5411	111.8015	32.0000	79.8015	0.0088	0.0006	-0.2500
05/08/87	716	180.0000	3.4960	0.1500	0.7609	1.5420	116.7316	32.0000	84.7316	0.0094	0.0009	-0.2500
05/08/87	717	187.7000	3.4950	0.1500	0.7609	1.5420	121.7251	32.0000	89.7251	0.0096	0.0009	-0.2500
05/08/87	718	195.4000	3.4940	0.2000	0.7619	1.5429	126.6468	32.0000	94.6468	0.0099	0.0011	-0.2500
05/08/87	719	203.1000	3.4920	0.2500	0.7629	1.5437	131.5628	32.0000	99.5628	0.0105	0.0014	-0.2500
05/08/87	720	210.8000	3.4910	0.2500	0.7629	1.5438	136.5506	32.0000	104.5506	0.0108	0.0014	-0.2500
05/08/87	721	218.5000	3.4890	0.3000	0.7639	1.5446	141.4581	32.0000	109.4581	0.0113	0.0017	-0.2500
05/08/87	722	226.2000	3.4870	0.3000	0.7639	1.5446	146.4428	32.0000	114.4428	0.0119	0.0017	-0.2500
05/08/87	723	233.8000	3.4860	0.3500	0.7648	1.5455	151.2772	32.0000	119.2772	0.0122	0.0020	-0.2500
05/08/87	724	241.5000	3.4840	0.4000	0.7658	1.5464	156.1705	32.0000	124.1705	0.0128	0.0023	-0.2500
05/08/87	725	249.2000	3.4820	0.4500	0.7668	1.5473	161.0582	32.0000	129.0582	0.0133	0.0026	-0.2500
05/08/87	726	256.9000	3.4810	0.5000	0.7678	1.5481	165.9405	32.0000	133.9405	0.0136	0.0028	-0.2500
05/08/87	727	264.6000	3.4790	0.5500	0.7688	1.5490	170.8168	32.0000	138.8168	0.0142	0.0031	-0.2500
05/08/87	728	272.3000	3.4770	0.6000	0.7698	1.5499	175.6875	32.0000	143.6875	0.0147	0.0034	-0.2500
05/08/87	729	280.0000	3.4750	0.6500	0.7708	1.5508	180.5526	32.0000	148.5526	0.0153	0.0037	-0.2500
05/08/87	730	287.7000	3.4720	0.7000	0.7718	1.5517	185.4115	32.0000	153.4115	0.0162	0.0040	-0.2500
05/08/87	731	295.4000	3.4700	0.7500	0.7727	1.5526	190.2652	32.0000	158.2652	0.0167	0.0043	-0.2500
05/08/87	732	303.1000	3.4670	0.8000	0.7737	1.5535	195.1127	32.0000	163.1127	0.0176	0.0046	-0.2500
05/08/87	733	310.8000	3.4650	0.8500	0.7747	1.5544	199.9550	32.0000	167.9550	0.0181	0.0049	-0.2500
05/08/87	734	318.5000	3.4630	0.9000	0.7757	1.5552	204.7916	32.0000	172.7916	0.0187	0.0051	-0.2500
05/08/87	735	326.2000	3.4600	1.0000	0.7777	1.5570	209.5031	32.0000	177.5031	0.0196	0.0057	-0.2500
05/08/87	736	333.8000	3.4570	1.0500	0.7787	1.5579	214.2607	32.0000	182.2607	0.0204	0.0060	-0.2500
05/08/87	737	341.5000	3.4540	1.1000	0.7797	1.5588	219.0767	32.0000	187.0767	0.0213	0.0063	-0.2500
05/08/87	738	349.2000	3.4500	1.2000	0.7816	1.5606	223.7593	32.0000	191.7593	0.0224	0.0069	-0.2500

Note: See Table A1 for definition of terms.

APPENDIX B

ONE-DIMENSIONAL CONSOLIDOMETER SWELL TESTS

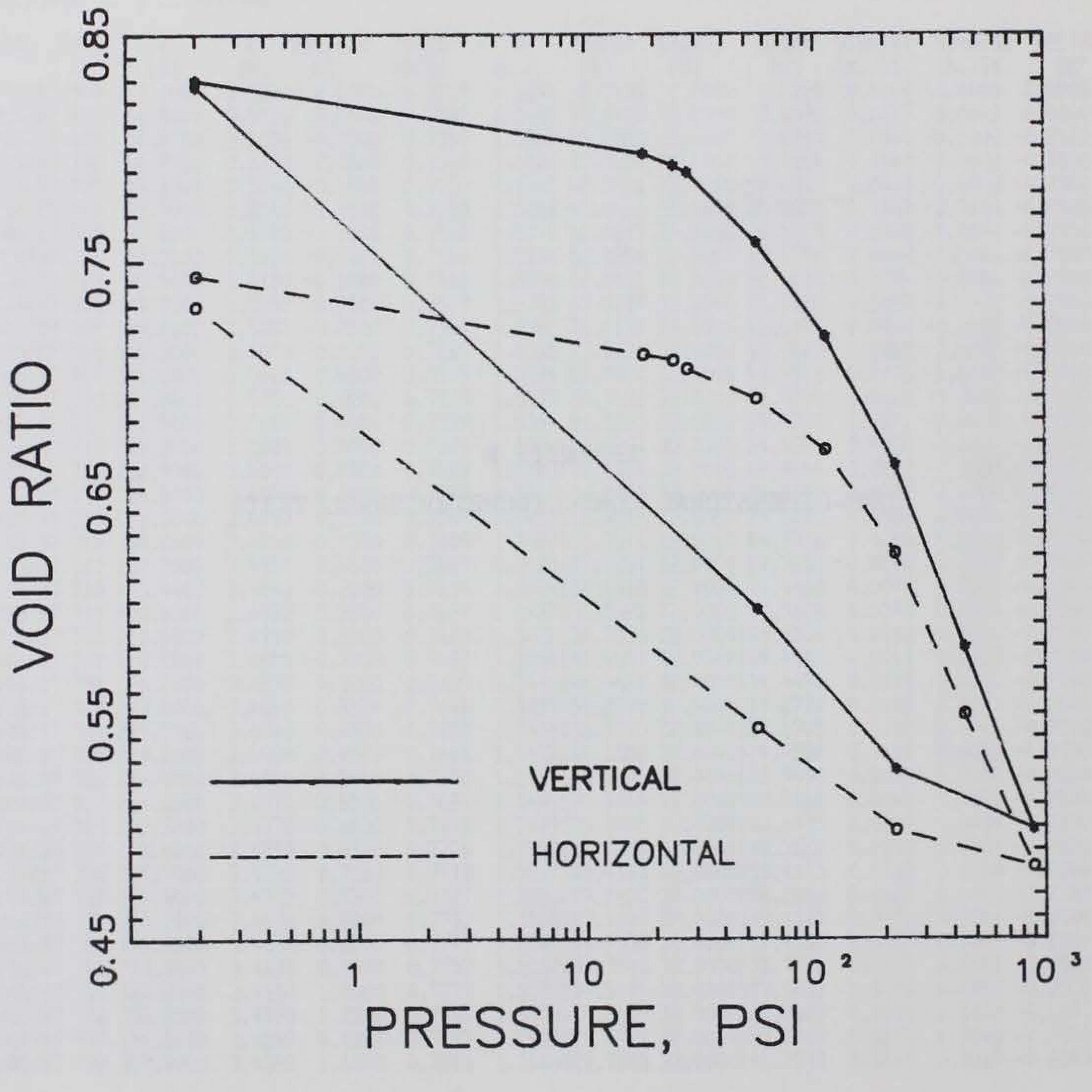


Figure B1. Consolidation of vertical and horizontal companion specimens from boring 6DC-419, Red River Army Depot at 23 ft depth

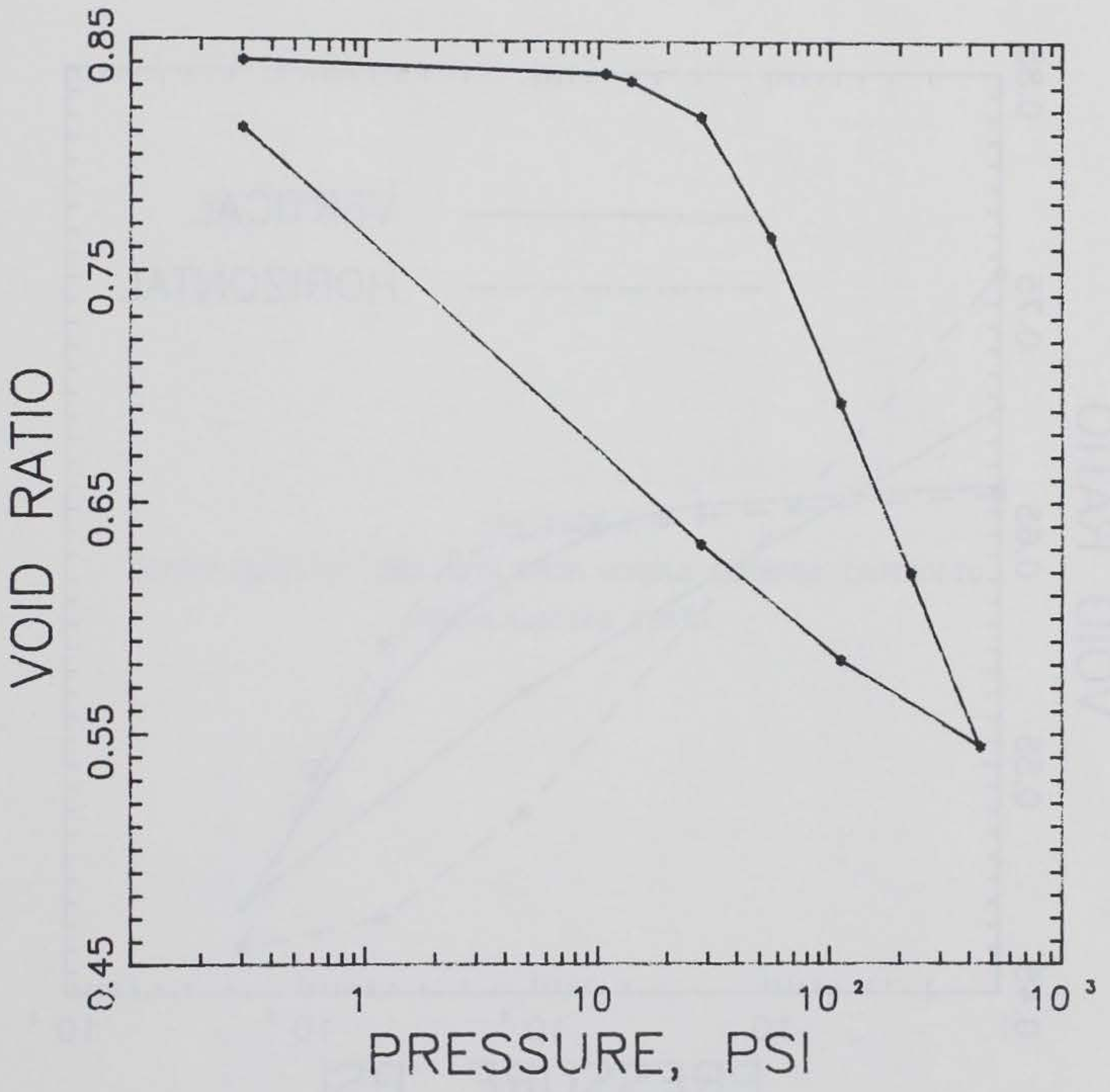


Figure B2. Behavior of a specimen from boring 2-2B, Incirlik Air Force Base at 5 ft depth consolidated in the vertical direction

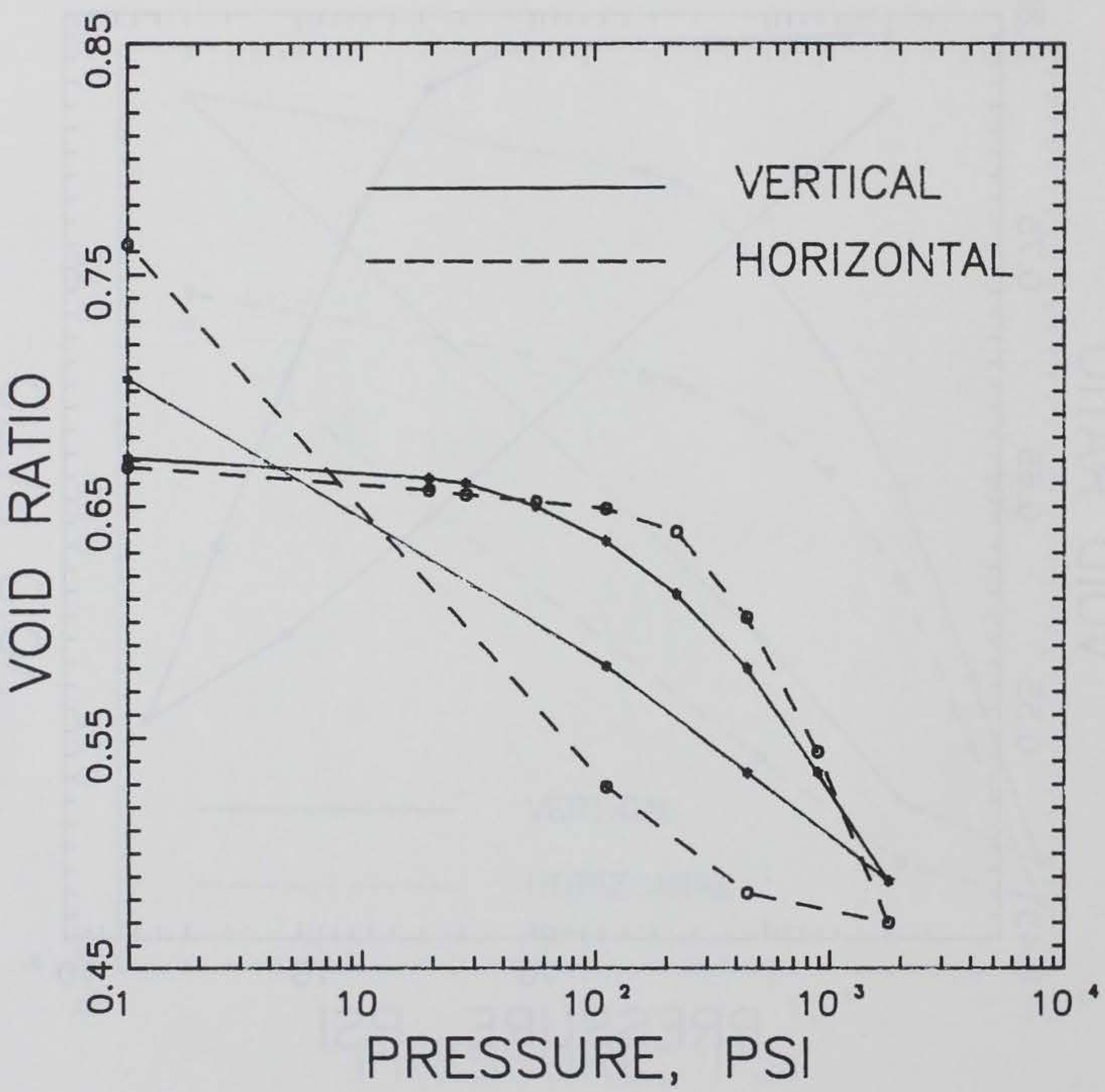
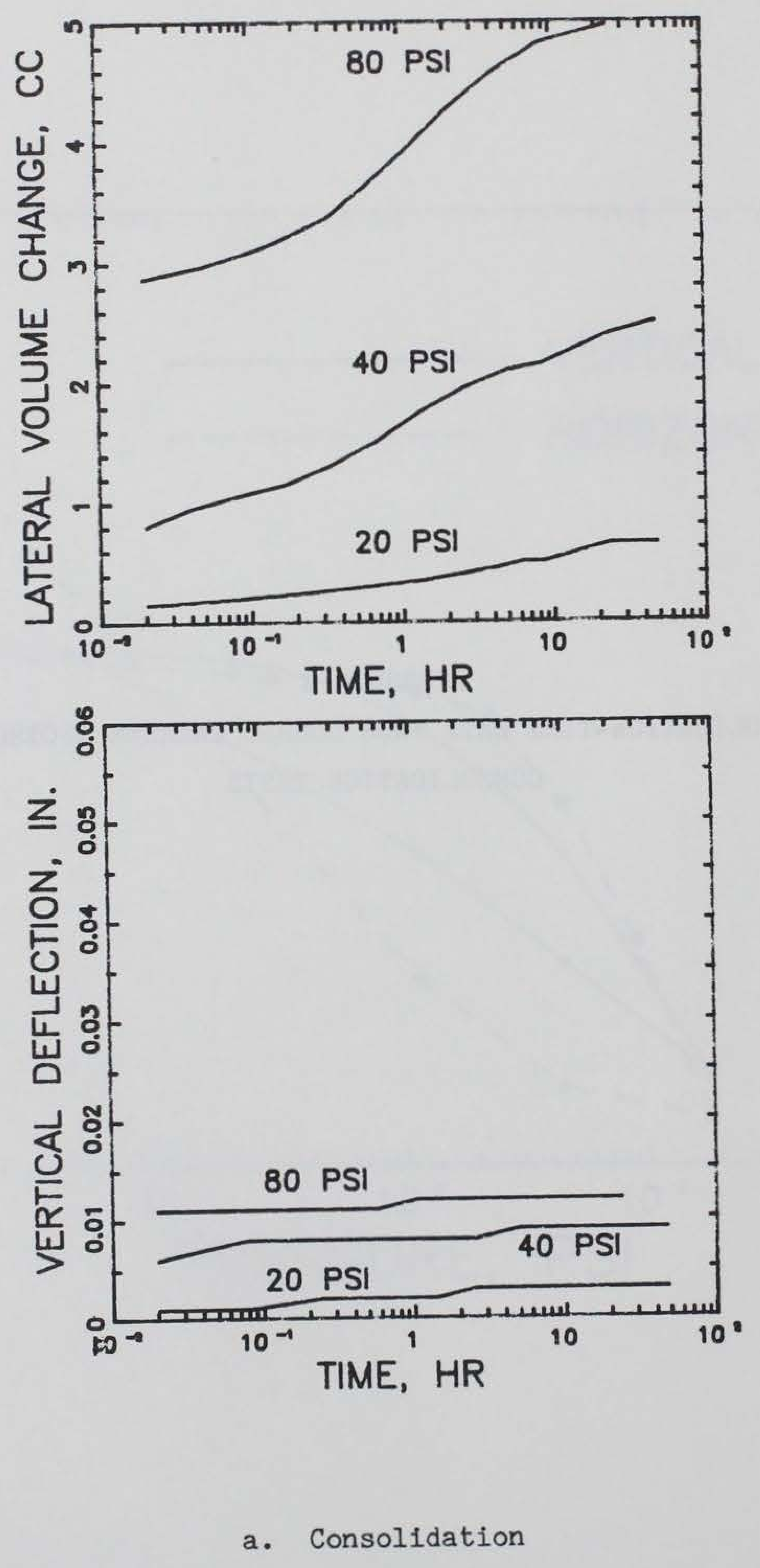


Figure B3. Consolidation of vertical and horizontal companion specimens from boring 6DC-419 at 40 ft depth

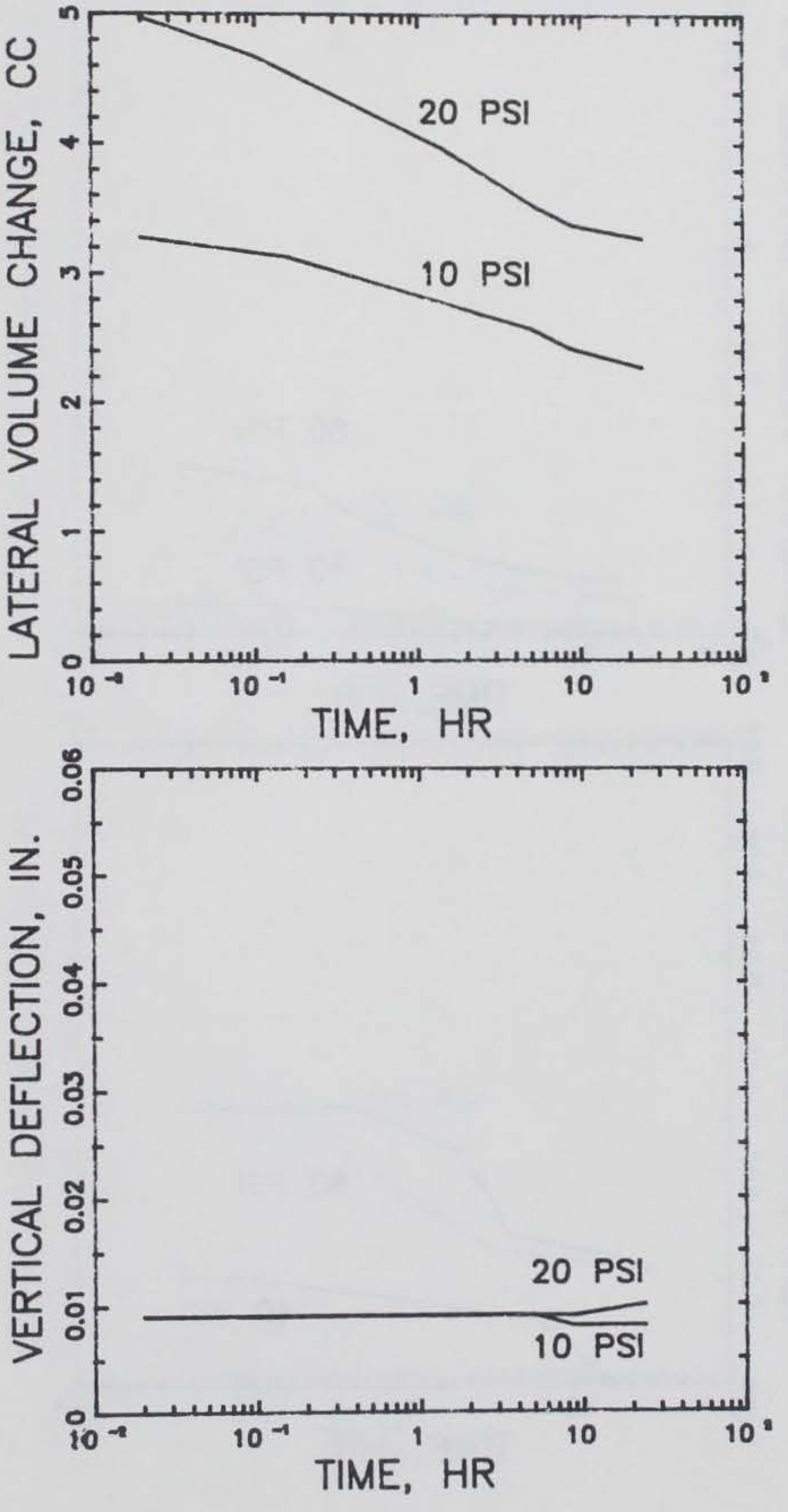
APPENDIX C

CONSOLIDATION-TIME DATA FROM DOUBLE CHAMBER ISOTROPIC CONSOLIDATION TESTS



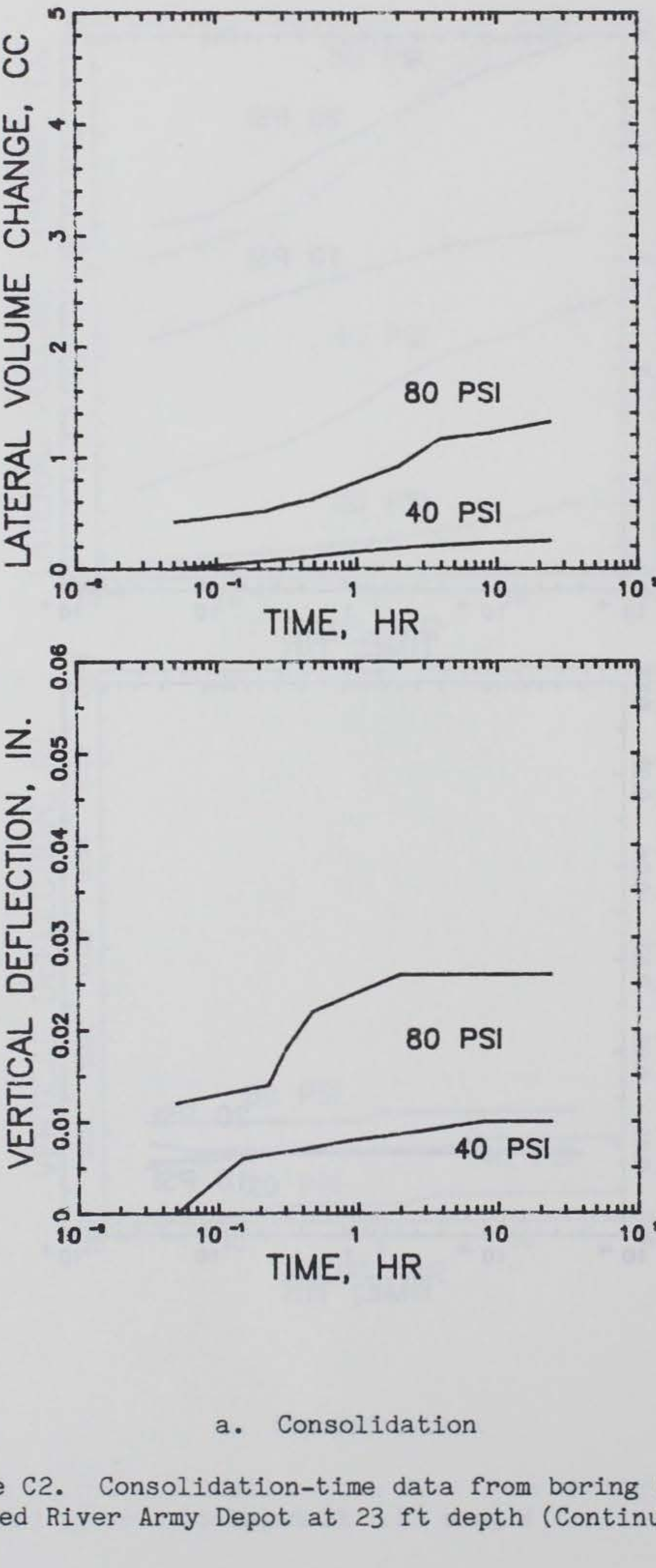
a. Consolidation

Figure C1. Consolidation-time data from boring 6DC-419, Red River Army Depot at 8 ft depth (Continued)



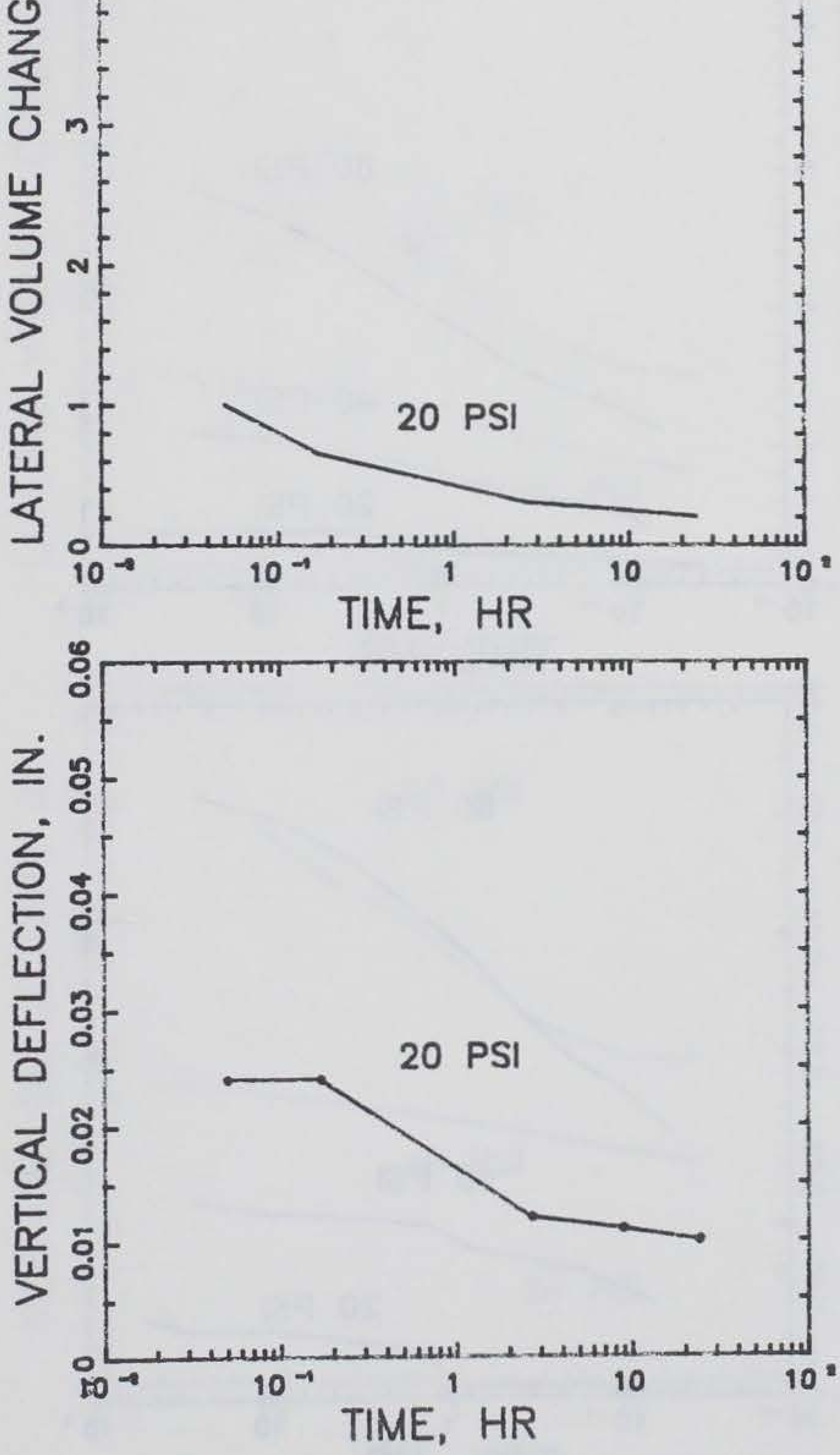
b. Rebound

Figure C1. (Concluded)



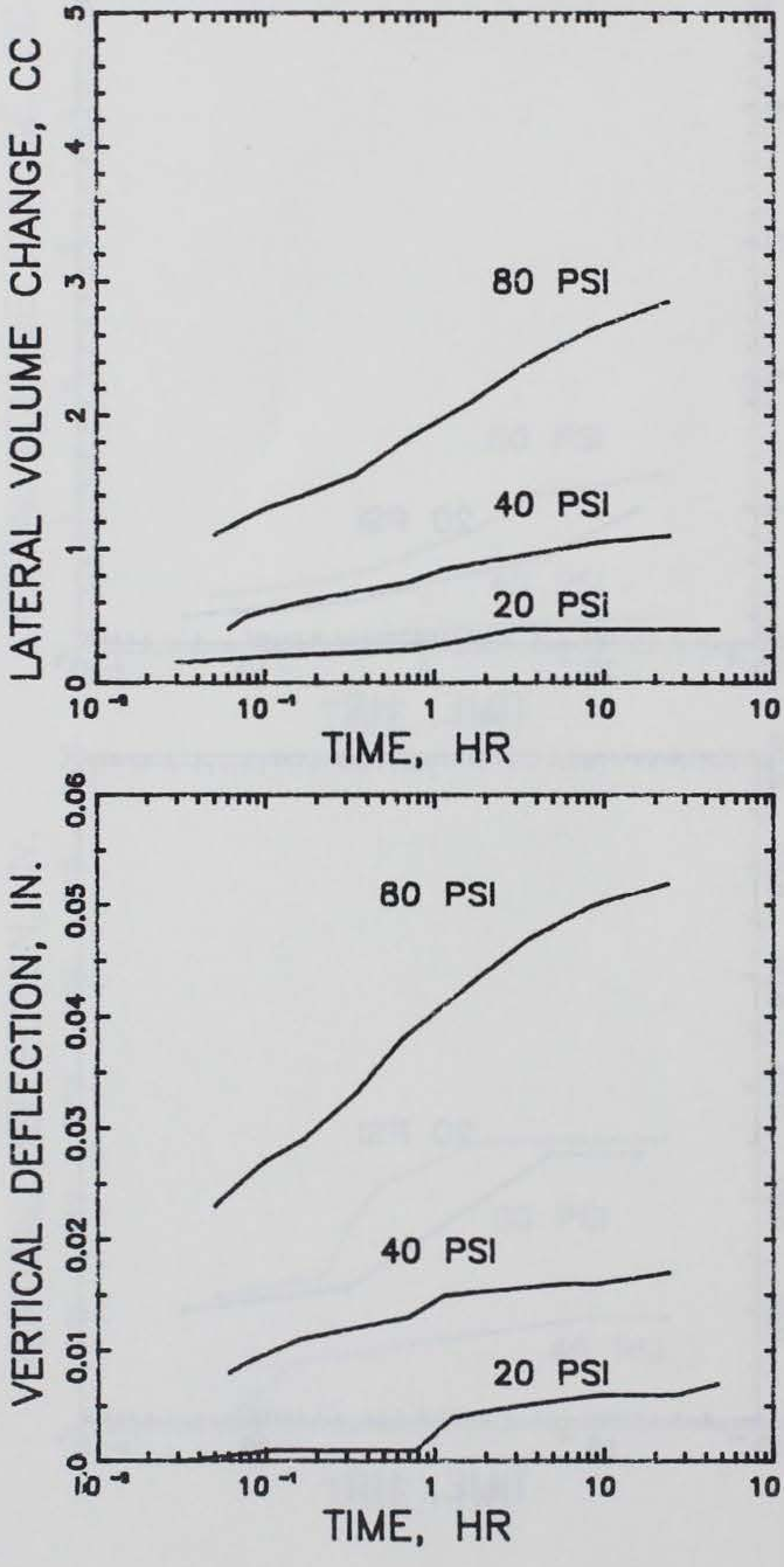
a. Consolidation

Figure C2. Consolidation-time data from boring 6DC-419, Red River Army Depot at 23 ft depth (Continued)



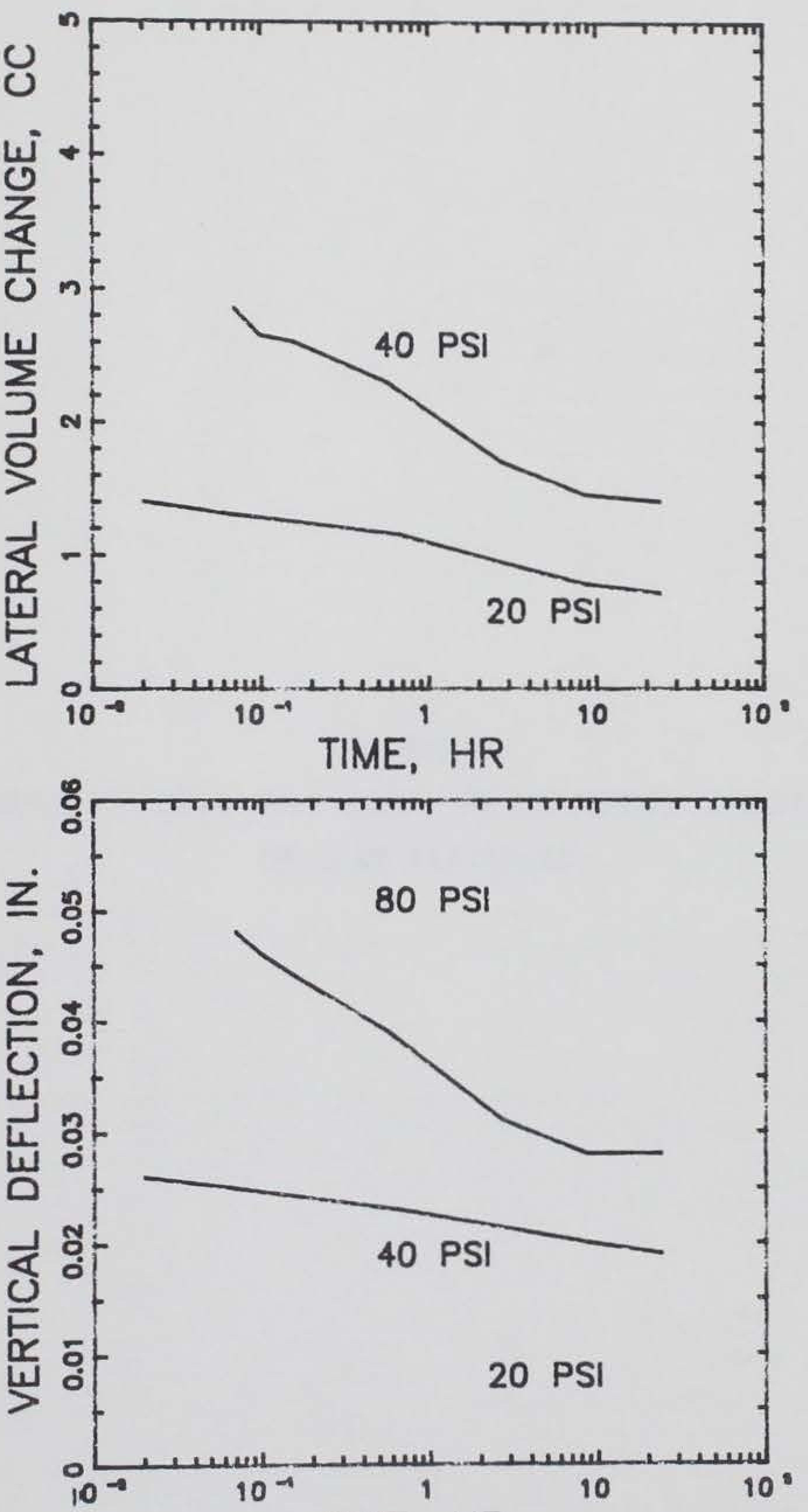
b. Rebound

Figure C2. (Concluded)



a. Consolidation

Figure C3. Consolidation-time data from boring 2-2B, Incirlik Air Force Base at 5 ft depth (Continued)



b. Rebound

Figure C3. (Concluded)

APPENDIX D

EXAMINATION OF A CLAY SHALE TO DETERMINE ORIENTATION OF CLAY PARTICLES

CEWES-SC-MG 23 June 1987

MEMORANDUM FOR: MR. LARRY JOHNSON, GEOTECHNICAL LABORATORY, RESEARCH GROUP

SUBJECT: Examination of a Clay Shale Sample to Determine Orientation of Clay Particles

1. You furnished the Petrography and X-ray Unit a sample of the clay shale from Texarkana, TX. It was requested that the shale be examined to determine the orientation of clay particles. The sample was a 6-in. core approximately 4-in. long.

2. Two thin sections were prepared from the shale. The material was oriented on glass slides so that the greatest number of laminations could be examined. The sections were ground to approximately 0.03 mm thick and examined with a polarizing microscope.

3. The shale consisted of alternating coarse and fine grained materials. The coarse material is silt size mineral grains surrounded by clay. The fine material is mainly clay. Some iron-bearing minerals have oxidized and caused rust staining.

4. The orientation of clay particles were determined by observing their birefringence (anisotropy) using crossed nicols.

5. The several lamina of clay material in the sample consisted of clay particles oriented with their c axes normal to the bedding. Birefringence and extinction of material in these clay lamina occurred simultaneously.

6. The lamina of silt size material contained some clay with random orientation. However, the majority of clay in these areas was also oriented with their c axes normal to bedding.

7. Using a polarizing microscope and thin sections prepared from the Day shale, the optical effects caused by the behavior of light in individual clay particles were observed. The results showed that the majority of clay in the sample are oriented with their c axis normal to the bedding.

J. Pete Burkes

J. PETE BURKES
Geologist
Concrete Technology Division