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**TRIAXIAL EQUIPMENT
AND
COMPUTER PROGRAM
FOR
MEASURING THE
STRENGTH BEHAVIOR
OF STABILIZED SOILS**

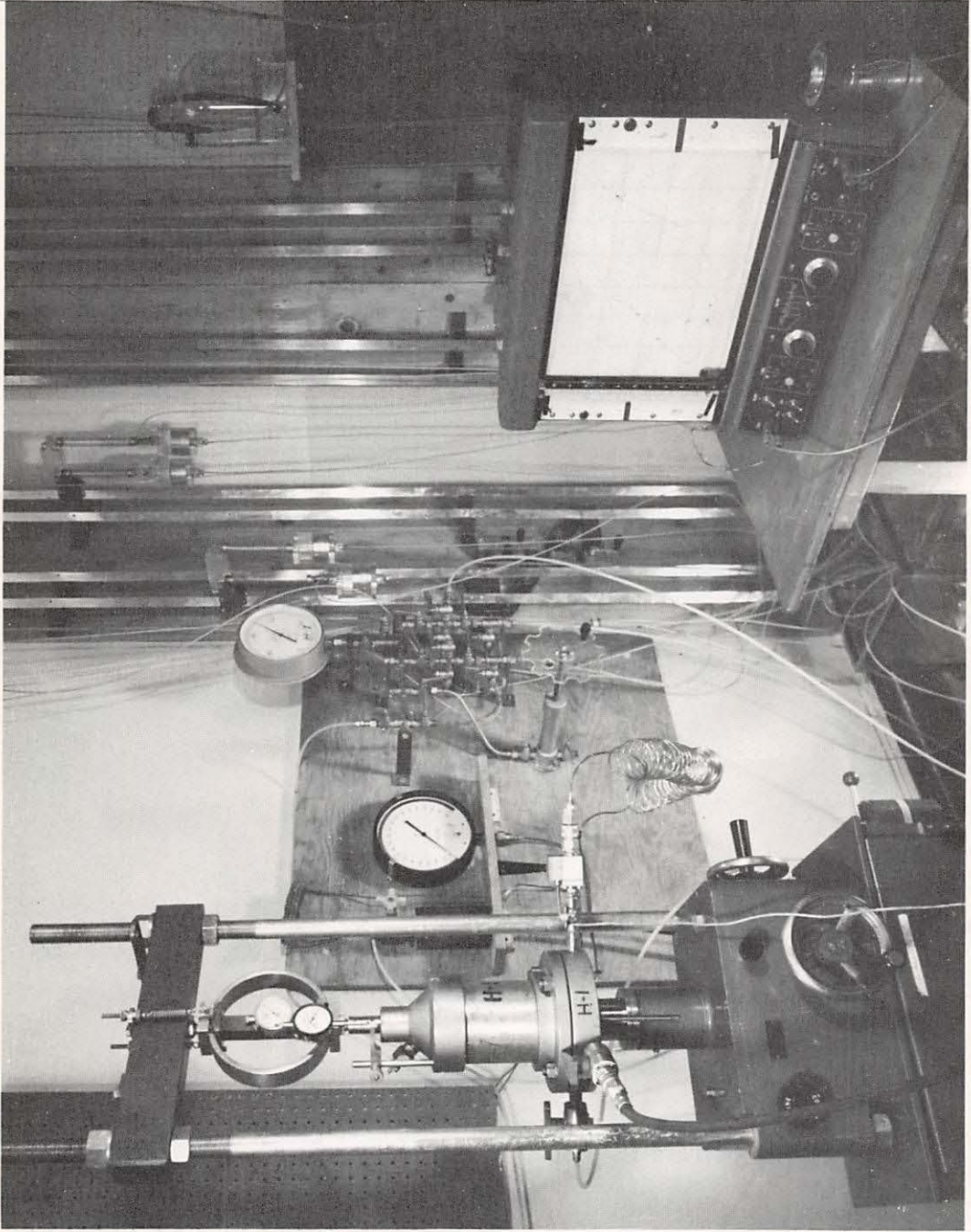
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Frontispiece: Photograph of High Pressure Triaxial Setup at M.I.T.

TRIAXIAL EQUIPMENT AND COMPUTER PROGRAM
FOR MEASURING THE STRENGTH BEHAVIOR
OF STABILIZED SOILS

Conducted for

U. S. Army Material Command,

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ABSTRACT

Part I of this report describes the triaxial test equipment which is being used at the Soils Research Laboratories of M. I. T. to investigate the effective stress-strength behavior of stabilized soils in undrained shear. This equipment includes:

- (1) Triaxial cells for confining pressures up to 1000 psi
- (2) Constant pressure supplies
- (3) Pore pressure measuring equipment
- (4) Compression test machines.

Appendix I gives the operational procedures for the test equipment described in Part I.

Part II presents a computer program for calculating and plotting the results of consolidated-undrained triaxial tests with pore pressure measurements. This program was prepared for the IBM 1620 computer with on-line plotting facility of the Civil Engineering Systems Laboratory at M. I. T.

PREFACE

The work described in this report was performed under Contract No. DA-22-079-eng-288 entitled "Research Studies on Soil Solidification" between the U. S. Army Engineer Waterways Experiment Station (WES) and the Massachusetts Institute of Technology. The research was conducted for the U.S. Army Material Command under research and development projects 1-T-0-21701-A-046-05, "Mobility Engineering Support" and 1-A-0-11001-B-021-30, "Basic Research in Earth Physics (Terrain analysis)".

This contract represents a continuation of research in soil stabilization under the sponsorship of the Corps of Engineers which was initiated in June 1946. The major portion of the research effort during the period 1946 through 1960 was directed towards the development of new chemical stabilizers and methods for improving the effectiveness of the conventional stabilizers. The stabilization research shifted emphasis in 1961 with the present contract towards a study of the fundamentals of shear generation in stabilized soils. Phase Report No. 1 presented data on the compression and strength characteristics of a partly saturated compacted clay.

Part I of this report describes the equipment presently being used at M. I. T. for investigating the shear strength behavior of saturated stabilized soils. Part II gives a computer program developed at M. I. T. for computing and plotting the results of undrained triaxial tests with pore pressure measurements which are being used to investigate the shear behavior of stabilized soils.

The triaxial equipment was developed by Mr. Anwar E. Z. Wissa, Instructor of Civil Engineering, and the computer program was prepared by Mr. Jin H. Kim, Research Assistant in Soils. Mr. Wissa and Mr. Kim prepared this report under the general supervision of Dr. Charles C. Ladd, Assistant Professor of Civil Engineering. Dr. T. William Lambe, Professor of Civil Engineering had over-all responsibility for the work.

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PART I. TRIAXIAL EQUIPMENT

A. INTRODUCTION

1. Background

Since October 1961, soil stabilization research at M.I.T. has been concerned primarily with the fundamentals of strength generation in chemically stabilized soils. A research program was therefore initiated to determine the effective stress-strength behavior of carefully controlled soil-stabilizer systems in the hope of elucidating the mechanisms by which the components of strength are generated.

2. Objectives

At the present time the most suitable test for measuring the shear strength properties of soils is the cylindrical compression test which is a special case of the general triaxial test*. In this test the major and minor principal stresses can be controlled independently while the intermediate principal is maintained equal to the minor principal stress. The outstanding advantages of this test are the control of drainage conditions and the possibility of measuring pore pressures as well as knowing the three principal total stresses at any time during the test.

Since stabilized soils are essentially compacted soils in which small amounts of chemicals have been added to increase their strength and reduce their

* The general triaxial test is a test in which the three principal stresses can be varied independently of each other both in tension and compression.

compressibility and water-susceptibility, the cylindrical compression test is in principle suitable for investigating the effective stress-strength behavior of stabilized soils. However the following additional features are required of the triaxial equipment:

- (1) The ability to completely saturate the samples after mounting in the triaxial cells even when their initial degree of saturation is as low as 70 per cent.
- (2) To overcome the prestress effects due to compaction and to keep to the same strength/consolidation pressure ratios as used with untreated soils the triaxial cells must be able to withstand confining pressures up to 1000 psi.
- (3) At high consolidation pressures the excess pore pressure developed during undrained shear may be very large. This requires pore pressure measuring equipment which has an insignificant volume change over the wide range of excess pore pressures which may be encountered during undrained shear (0 to 1000 psi).

The following paragraphs describe the triaxial equipment presently being used to investigate the shear behavior of untreated and chemically stabilized compacted soils which are fully saturated.

B. DESCRIPTION OF EQUIPMENT*

The general layouts of the low pressure and high pressure triaxial systems are given in Figs. I-1 and I-2 respectively. Step by step operational procedures are given in Appendix I.

1. Triaxial Cells

a. Low pressure cells (Fig. I-1)

These cells are essentially as described in pp. 33 to 39 of Bishop and Henkel (1962)** and are designed for a maximum cell pressure of 160 psi and 1.405 in. dia. (10 cm^2) samples. The main modification is an extra port in the lower platen of the triaxial cell; with two connections to the sample base it is then possible to flush out any air entrapped in the pore pressure lines. One of these connections provides drainage during consolidation under a back pressure, while the other is used for measuring the pore pressures during undrained shear (Fig. I-1). All connections in the cell base are equipped with no volume change Klinger valves. The sample is sealed from the surrounding water in the triaxial cell by enclosing it in two thin rubber prophylactics with silicon grease between them. The membranes are sealed

* See Table I-1 for names of suppliers of equipment and components.

** See list of references at the end of the report.

to the cell base and top loading cap by means of neoprene O-rings. The top loading cap has a 3/4 in. long collar which is guided by the loading ram thus preventing it from tilting during shear.

b. High Pressure Cells (Fig. I- 2 and I-3)

This cell is also for 1.405 in. dia. samples but can be used for cell pressures up to 1000 psi. The main differences between this cell and the low pressure cell are:

- (1) The removable cell cylinder is made of steel instead of lucite.
- (2) The loading ram is made of high grade high tensile steel and is 1 in. in diameter instead of the 0.5 in. diameter used with the low pressure cell. The ram runs in a honed bronze bushing with 0.0003 in. clearance but in addition an O-ring seal is used between the ram and the bushing to prevent excessive leakage at high cell pressures.
- (3) The Klinger valves are replaced by stainless steel ball valves with teflon seatings. These valves are also no volume change and have a maximum working pressure of 3000 psi.
- (4) The samples are enclosed in 0.01 in. thick isoprene rubber membranes, rather than two

0.002 in. thick rubber prophylactics, to reduce membrane leakage. The guided top loading cap is made of stainless steel. To prevent damage to rubber membranes at high confining pressures, a rubber sleeve 0.1 cm thick and 1.5 cm long is placed around the top joint between the sample and loading cap. A similar sleeve surrounds the bottom of the sample, the porous stone and the top of the cell base pedestal.

2. Constant Pressure Supplies

a. Low Pressures (Fig. I-1).

For pressures up to 160 psi self-compensating mercury controls* are used. The main advantages of this apparatus are:

- (1) It is entirely free from hunting and can maintain a constant pressure (within 0.1 psi) for months without adjustment since it can compensate for about 150 cc of flow before refilling is required.
- (2) It directly applies a water pressure. The water in it will not become saturated with air from the atmosphere since it is a closed system in which only the mercury is in direct contact with the atmosphere.

* See Bishop and Henkel (1962) pp. 45 to 52 for the principle and practical details of this equipment.

The mercury control apparatus is used for applying the back pressure to both the low and high pressure tests. It reduces the back pressure required to saturate the samples since the deaired water in the system will dissolve the air in the sample without becoming saturated with air from the atmosphere.

The mercury control apparatus is also used for applying the cell pressure to the low pressure triaxial cells.

b. High Pressures (Fig. I-2)

For pressures much above 160 psi a mercury control is not readily adaptable, and therefore pressures up to 1000 psi are obtained from nitrogen tanks and controlled by means of pressure regulators. The pressure is measured on an 8 in. Bourdon-tube type of test gauge which has a range of 0 to 1000 psi and can be read to the closest 1 psi. This system is not entirely free from hunting but at cell pressures above 600 psi the fluctuation is less than 1 per cent and therefore of no major concern.

The nitrogen pressure can not be applied directly to the cell chamber because the rubber membranes in which the samples are enclosed are about ten thousand times more permeable to gases than to water. To overcome this problem the nitrogen pressure is converted to a water pressure by means of a nitrogen-water interchange.

The cell chamber is connected to the water side of the interchange by 10 ft of high pressure rubber hose. The water between the cell and the water-nitrogen interface is sufficient to prevent diffusion of nitrogen into the sample for at least four or five days. The main disadvantage of this system is that it is necessary to replace the water in it prior to each test with freshly deaired water; however, this only takes about 5 minutes which is not too serious.

3. Pore Pressure Measuring Equipment

a. For small excess pore pressures (Fig. I-1)

Manually operated mercury null systems* are used to measure the pore pressures during undrained shear in samples consolidated in the low pressure triaxial cells. These systems can measure pore pressures up to 160 psi and have an overall flexibility (i.e. volume change of the pore pressure measuring system) of about 6×10^{-6} in.³ per psi when properly deaired. Provided the compressibility of the soil skeleton is greater than 10^{-3} cm²/kg the flexibility of the measuring equipment reduces the pore pressures during undrained shear by less than 2 per cent** which is within the accuracy of the rest of the equipment.

* Both the Imperial College "glass tube" unit and the NGI "lucite" unit are used. For details see Bishop and Henkel (1962) pp. 52-60 and Andersen et. al., (1957), respectively.

** This calculation is based on a triaxial sample which is 80 cc in volume and has a porosity 0.30.

b. For large excess pore pressures (Fig. I-2)

With the high pressure triaxial cell the pore pressures during undrained shear of samples consolidated to pressures up to 60 kg/cm^2 may reach values well above the maximum pressure which can be measured with the mercury null systems. Further, at high consolidation pressures the compressibility of the soil skeleton is a magnitude or more less than $10^{-3} \text{ cm}^2/\text{kg}$ and therefore the flexibility of the mercury null systems would substantially reduce the excess pore pressures during undrained shear. This would not alter the effective stress-strength envelope, since the actual pore pressures are still being measured, as long as the rate of shearing is slow enough for the fluid pressures in the soil pores and in the measuring equipment to equalize. However the magnitude of the excess pore pressures will always be numerically smaller due to the flexibility of the equipment and therefore the measured shear strengths will be higher than the truly undrained shear strengths if positive excess pore pressures exist at failure. Similarly the measured pore pressure responses* will always be too low.

* The pore pressure response is identical to Skempton's (1954) pore pressure coefficient B (also called B factor and B parameter).

To reduce the flexibility of the pore pressure measuring devices and to measure excess pore pressures up to 1000 psi the mercury null systems have been replaced by electrical transducers on the high pressure triaxial cells. The transducers, which were manufactured by the Dynamic Instrument Company, employ unbonded strain wires attached to a diaphragm. The transducers are excited at six volts and the output can be measured with a millivoltmeter. For this apparatus differential pressure transducers are used to measure the difference between the cell pressure and the pore pressure, and since the cell pressures are known (measured on a Bourdon-tube gauge) the pore pressures can be calculated. Two high pressure cells are presently in use, one of which has a 1000 psi differential transducer and the other a 500 psi differential transducer. The outputs of these transducers are plotted on an X-Y recorder, which is adjusted to give 1 in. = 50 psi differential.

Each transducer has two ports. The high pressure port, which is on the uninsulated side of the diaphragm, is connected to the nitrogen side of the cell pressure line. A calcium chloride trap is used in this line to prevent water vapor from the cell pressure system condensing on the uninsulated

side of the transducer. This trap is not fully effective, which sometimes causes the zero output of the transducer to shift. The low pressure port connects the insulated side of the diaphragm to the no volume change valve of one of the pore pressure ports in the cell base. The full range displacement of the diaphragm of these transducers is about 350×10^{-6} in., which represents flexibilities of 14×10^{-8} and 7×10^{-8} in. per psi differential for the 1000 psi and 500 psi transducers respectively. The pore pressure lines between the sample and the transducer contains about 0.5 cu in. of water. Since these lines are extremely rigid the flexibility of the system between the sample and the transducer is solely due to the compressibility of the water, i. e., 170×10^{-8} in.³ per psi. In other words when a transducer is used to measure pore pressures most of the flexibility in the measuring system is due to the compressibility of water. The overall flexibility of these measuring systems is about 1.8×10^{-6} in.³ per psi, which causes less than 5 per cent reduction in the pore pressures when the compressibility of the soil skeleton is greater than 10^{-4} cm²/kg. This accuracy is acceptable since most of the soil-stabilizer systems presently being investigated do not have such a rigid soil skeleton.

It is useful to note that the reduction in pore pressures can be made considerably smaller by decreasing the volume of water in the system which in turn will decrease its flexibility, e.g., if the volume of water in the system is reduced to 0.1 cu in., the overall flexibility of the system is reduced to about 42×10^{-8} in.³ per psi which causes a pore pressure drop of a little over 1 per cent when the rigidity of the soil skeleton is 10^{-4} cm²/kg.

4. Compression Test Machines

The compression test machines are strain controlled by a synchronous motor and gear box. The gear box has six 5-1 reductions and additional change wheels giving a total of thirty different rates of feed ranging from 0.3 to 0.000024 inches/minute. The capacity of the machines is 5 tons. The axial load is measured on a proving ring. For low pressure tests a number of proving rings having capacities of 300 to 1000 lb are used and sensitivities ranging from 0.125 to 0.725 lb/div. For high pressure tests proving rings with 3000 lb capacity and a sensitivity of about 2 lb/div. are used.

C. PERFORMANCE OF EQUIPMENT

The equipment described herein has been in operation since May 1962 and on the whole has proved to be satisfactory. The following modifications, however, are being contemplated to improve the performance of the high pressure equipment:

1. Replacement of the present differential pressure transducers by similar transducers which are electrically insulated on high pressure side as well as the low pressure side. This will prevent a zero shift due to water vapor condensing on the uninsulated side of the transducers, which presently occurs over long periods of time.
2. Reduction of the volume of water in the pore pressure lines to reduce the flexibility of the pore pressure measuring system.
3. Try to lower the permeability of the rubber membranes used in the high pressure test by a factor of 100 without increasing their restraint on the samples. This can be done by replacing the present isoprene membranes by butyl membranes; however manufacturing such membranes is still a problem.

PART II. COMPUTER PROGRAM

A. INTRODUCTION

A complete IBM 1620 (LOAD-andGO)* computer program for computation and plotting of triaxial test results was written to minimize the time consumed in analyzing triaxial test data and to reduce the possible human errors involved in the computations.

The program described herein was written in LOAD-and-GO FORTRAN for a 20K IBM 1620 Data Processing System. Although written for a particular machine, the system itself is based on principles which apply to a wide variety of digital computers.

B. LOAD-and-GO SYSTEM*

LOAD-and-GO is a system which embodies a FORTRAN source language and an automatic compile and computation procedure.

LOAD-and-GO has been designed by the staff of the Civil Engineering Systems Laboratory at M.I.T. for use with their IBM 1620 computer.

In the following programs LOAD-and-GO FORTRAN with online plotting facility** was used.

C. COMPUTER PROGRAM

It was necessary to separate the complete program into two parts due to the limited storage capacity of the system if the computation and the plotting were to be executed simultaneously.

*See Sillay (1961).

**See Gladding (1961) and Gladding (1962).

1. Program for Computing Triaxial Test Results and Plotting Effective Stress Paths*

A FORTRAN source program was written so that a complete computation of test results, punch out of minimum necessary answer cards, and effective stress path plotting were all simultaneously executed. With this system the results from a number of tests could be continuously computed and plotted.

The calibrations of seven proving rings having maximum capacities ranging from 300 lbs to 3000 lbs were included in this program. This was done to enable the appropriate proving ring to be used with samples having larger differences in strength without having to change the program.

The initial Counter Readings of 0, 100, 200, 300, 400, 500, and 600 were assigned to the proving rings which were programmed.

A special type of paper* was used for all the plotting, and for each set of curves proper factors were chosen by the computer for pre-fixed graph size of 10 in. by 18 in.

a. Input

Three types of input data are required for this part of the operation. They are in the following program order:

(1) ID Number; One Half of Stress Difference (max.):

Needed for the computer to determine the scale factor of effective stress path. This is only inserted at front of constant card (2) when new effective stress path (or new group of paths) are to be drawn separately from a previous set.

*An IBM 1620 ON-LINE PLOTTING FACILITY and paper manufactured by California Computer Products, Inc., Downey, Calif. were used.

(2) ID Number; Counter Reading (initial);
Sample Length (initial); Load (initial); Area (initial);
Pore Pressure (initial); Consolidation Pressure:
A constant card with proper identification number and
six constants necessary for the results computation
is inserted at front of the sets of variables (readings)
cards (3).

(3) ID Number; Pore Pressure Reading; Counter Reading;
Proving Ring Reading:
Each variable card contains the above set of readings
corresponding to any one time during the test.

b. Output

One of each scale factor and condensed constant card at the
beginning of each test (or each group of tests) and a set of
two answer cards for each set of readings are punched out
in the following order:

(1) Factor for Effective Stress Path Plot:

A scale factor chosen by the computer for plotting
each group of effective stress paths is punched out.

(2) ID Number; Counter Reading (initial); Load (initial);

A condensed constant card with the above constant is
punched out at the beginning of the computation of each
triaxial test result and is used in distinguishing the
particular test when the results of several tests are
continuously punched out.

(3) ID Number; Strain; Obliquity; Stress Difference:

(4) Pore Pressure Change; \bar{A} Factor; Average Effective Stress;
One Half of Stress Difference:

A set of complete answers for each set of readings is given by these two cards which are later used for the plotting of Strain vs. Obliquity, Stress Difference, Pore Pressure Change and \bar{A} Factor.

(5) Effective Stress Path Plot:

A plot of Average Effective Stress vs. One Half of Stress Difference [$1/2(\bar{\sigma}_1 + \bar{\sigma}_3)$ vs. $1/2(\sigma_1 - \sigma_3)$] drawn with selected scale factor is simultaneously obtained with all the preceding output.

A flow chart, shown in Fig. II-1, explains the step by step process as well as the overall organization of the program. For better understanding of the process each box in the flow chart is numbered and fully explained below. (See Table II-3 for nomenclature used in flow chart).

Box (1): State the dimensions of the plot functions (IXY(4)*); assign the coordinate origin of the graph at IXY(1)*=0 and IXY(2)*=-100 and the initial value of AB=-1900. (Absolute magnitude of AB= paper length of an Effective Stress Path plot.) The actual cumulative AB, (i.e. AB=AB+1900) is the IXY(1) coordinate of the origin of the plot. Note: IXY(1) and IXY(2) in this program represent the horizontal and vertical direction respectively.

Box (2): Read the Identification Number (ID) which precedes the data on the data card.

*See Gladding (1961) and Gladding (1962).

- Box (3): Check the Identification Number which was read at Box 2.
- Box (4): Direct execution to Box 5 on finding ID=3.
- Box (5): Halt execution temporarily until the START key is pressed.
This allows the operator to remove completed set of data, output, and Effective Stress Path plot if necessary when many sets of test data are continuously executed.
- Box (6): Read DHMAX (max. value of One Half of Stress Difference) with proper ID. This card (3 DHMAX) is only read in when new Effective Stress Path (or new group of paths) are to be drawn separately from a previous set.
- Box (7): Compute AB in order to determine the IXY(1) coordinate of the origin of the Effective Stress Path plot.
- Box (8): Draw axes (10 in. vertical and 18 in. horizontal) from the assigned origin for the Effective Stress Path plot.
- Box (9): Scale the vertical (IXY(2)) axis in 1 inch spacing with 0.06 in. long straight line.
- Box (10): Scale the horizontal axis as in Box 9.
- Box (11): Divide each horizontal segment into $1/2$ in. size with 0.03 in. long straight line.
- Box (12): Divide each vertical segment as in Box 11.
- Box (13): Determine the scaling factor (FACTV) for Effective Stress Path plot.
- Box (14): Punch out the FACTV on an output card.
- Box (15): Return to Box 2 and read ID on the next card.
- Box (16): Direct execution to Box 17 on finding ID=1.
- Box (17): Pause (see Box 5).

- Box (18): Read all the constants used for particular test on card with proper ID of 1.
- Box (19): Punch out these four constants to distinguish each test.
- Box (20): Return to Box 2 (see Box 15).
- Box (21): Direct execution to Box 22 on finding ID=2.
- Box (22): Compare the Initial Counter Reading (CTI) and transfer execution according to the results of the comparison.
- Box (23): Direct execution to Box 24 on finding CTI=0 in Box 22.
- Box (24): Read each of a set of readings - Pore Pressure, Counter and Proving Ring - as they were taken during the tests.
- Box (25): Transfer the execution to Box 26.
- Box (26): Compute from the calibration chart for proving ring No. 625 (0 to 300 lbs) the corresponding load in pounds. Transfer to Box 53.
- Box (27): Direct execution to Box 28 on finding CTI=100 in Box 22.
- Box (28): Read a set of test readings as in Box 24.
- Box (29): Transfer execution to Box 30.
- Box (30): Compute as in Box 26. Proving ring No. N-1 (0 to 600 lbs) is used. Transfer to Box 53.
- Box (31): Compare the Initial Counter Reading (CTI) on finding CTI greater than 100 at Box 22.
- Box (32): Direct execution to Box 33 on finding CTI=200 in Box 31.
- Box (33): Read a set of test readings as in Box 24.
- Box (34): Transfer execution to Box 35.
- Box (35): Compute as in Box 26. Proving ring No. N-4 (0 to 1100 lbs) is used. Transfer to Box 53.

Box (36): Direct execution to Box 37 on finding CTI=300 in Box 31.

Box (37): Read a set of test readings as in Box 24.

Box (38): Transfer execution to Box 39.

Box (39): Compute as in Box 30. Proving ring No. N-3 (0 to 450 lbs) is used. Transfer to Box 53.

Box (40): Compare the Initial Counter Reading (CTI) on finding CTI greater than 300 in Box 31.

Box (41): Direct execution to Box 42 on finding CTI=400 in Box 40.

Box (42): Read a set of test readings as in Box 24.

Box (43): Transfer execution to Box 44.

Box (44): Compute as in Box 26. Proving ring No. N-5 (0 to 2000 lbs) is used. Transfer to Box 53.

Box (45): Direct execution to Box 46 on finding CTI=500 in Box 40.

Box (46): Read a set of test readings as in Box 24.

Box (47): Transfer execution to Box 48.

Box (48): Compute as in Box 26. Proving ring No. 945 (0 to 3000 lbs) is used. Transfer to Box 53.

Box (49): Direct execution to Box 50 on finding CTI=600 in Box 40.

Box (50): Read a set of test readings as in Box 24.

Box (51): Transfer execution to Box 52.

Box (52): Compute as in Box 26. Proving ring No. 1124 (0 to 3000 lbs) is used. Transfer to Box 53.

Box (53): Compute net load in pounds.

Box (54): Transfer execution to Box 55.

Box (55): Compute the Strain (E), Net Load (PEK), Area (A), Stress Difference (B) and One Half of Stress Difference (DH).

- Box (56): Compare the CTI and transfer execution according to the value.
- Box (57): Direct execution to Box 58 on finding CTI less than 500 in Box 56.
- Box (58): Compute the Pore Pressure Change (Δu) and the Effective Stress in minor direction ($\bar{\sigma}_3$).
- Box (59): Transfer the execution to Box 68.
- Box (60): Direct execution to Box 61 on finding CTI=500 in Box 56.
- Box (61): Assign the factor (i.e. FP=2.5) for Y coordinate (intermediately high pressure) of X-Y recorder.
- Box (62): Compute as in Box 58.
- Box (63): Transfer execution to Box 68.
- Box (64): Direct execution to Box 65 on finding CTI greater than 500 in Box 56.
- Box (65): Assign the factor (i.e., FP=3.0) for X coordinate (high pressure) of X-Y recorder.
- Box (66): Compute as in Box 58.
- Box (67): Transfer execution to Box 68.
- Box (68): Compute the Effective Stress in major direction (axial direction in this test) (SIGE1), the Obliquity (R), the Average Effective Stress (AES) and the \bar{A} Factor (AF) for the particular set of data corresponding to any one time during the test.
- Box (69): Punch out the computed answer from the Boxes 55, 58, 62, 66 and 68.

Box (70): Compute the AESP (the coordinate of Average Effective Stress, AES x FACTV) and the DHP (the coordinate of One Half of Stress Difference, DHP x FACTV).

Box (71): Check AESP. The maximum graph size of AESP is 1800 (18 in.; 100=1 in.) as discussed in section C-1.

Box (72) and (73): Transfer execution to Box 2 when AESP > 1800, without plotting the point. The relation, AESP \leq 1800, should always be satisfied since the FACTV was selected to include all the points within the pre-assigned max. size of 18 in., but mistake in data punching could cause violation.

Boxes (74) and (75): Check DHP when AESP \leq 1800. The max. graph size of DHP is 997 (9.97 in., 100=1 in.). Note: The DHP max. is 0.03 in. less than actual max. graph paper size of 10 in. because the plotting requires 0.03 in. in all directions (up, down, and both sides).

Boxes (76) and (77): Transfer to Box 2 if violation occurs as in Boxes 72 and 73.

Boxes (78) and (79): Plot the points [DH vs. AES, $1/2 (\bar{\sigma}_1 + \bar{\sigma}_3)$ vs. $1/2 (\sigma_1 - \sigma_3)$] when DHP \leq 997.

Box (80): Returns to Box 2 and repeat the whole process until the last data card is read in and plotted.

Box (81): End run.

A program, a sample set of input and output, and a corresponding plot of Effective Stress Path are given respectively in Table II-1 and Fig. II-2.

2. Program for Plotting Strain versus Obliquity, Stress Difference, Pore Pressure Change and \bar{A} Factor

The program executes the operation of fine scaling factor determinations and of plotting four curves simultaneously. A set of four curves for each test is plotted in a 6 in. by 9 in. graph size. The program plots the negative parts of curves as well as the positive parts.

a. Input

Three types of input data and a dummy card are required in the following order:

- (1) Identification Number ; Strain (max.) ;
Obliquity (max.) ; Stress Difference (max.) ;
Pore Pressure Change (max. positive) ;
Pore Pressure Change (max. negative) ;
 \bar{A} Factor (max. positive) ; \bar{A} Factor (max. negative) ;
These are required for the computer to determine the scaling factors; namely, scaling factor of Strain (FACTE), of Obliquity (FACTR), of Stress Difference (FACTD), of Pore Pressure Change (FACTU), and of \bar{A} Factor (FACTA). At the beginning of several sets of continuous plotting this card follows a control card (*DATA), but from the second set of plotting on, it follows a dummy card.
- (2) Identification Number ; Strain ; Obliquity ;
Stress Difference :

- (3) Pore Pressure Change; \bar{A} Factor; Average Effective Stress; One Half of Stress Difference:

The above set of two cards per set which were directly obtained from the output of preceding program, are required for the plotting of four graphs (Strain vs. Obliquity, Stress Difference, Pore Pressure Change and \bar{A} Factor).

- (4) Identification Number; Strain; Obliquity; Stress Difference:

A dummy card is merely used to fulfill the operational instruction for starting new graph for the following test. A dummy card must have Identification Number of 1 and any value of strain, obliquity and stress difference, and is inserted between every last and first data card of the following test.

b. Output

- (1) A set of two cards containing five scaling factors - FACTE, FACTR and FACTD on card 1 and FACTU and FACTA on card 2 - for four curves for every test is punched out. These are a complete set of scaling factors chosen by the computer for the four plots:
- (2) A set of four plots:
- i) Strain vs. Obliquity
 - ii) Strain vs. Stress Difference
 - iii) Strain vs. Pore Pressure Changes
 - iv) Strain vs. \bar{A} Factor

A flow chart as shown in Fig. II-3 explains the step by step process as well as the overall organization of the program. For a better understanding the program, each box of the flow chart is explained in detail below.

Box (1): Initialize as in Box 1 of previous program. $XY(1)=0$ $XY(2)=-200$
 $AB=-1100$. Note: $XY(1)$ is vertical and $XY(2)$ is horizontal direction of the graph.

Box (2): Read in the maximum values of Strain, of Obliquity, of Stress Difference, of Pore Pressure Change (positive), of Pore Pressure Change (negative), of \bar{A} Factor (positive) and \bar{A} Factor (negative) to determine the factors for graphs.

Box (3): Determine FACTR (scaling factor of Obliquity)

Box (4): Determine FACTA (scaling factor of \bar{A} Factor).

Box (5): Determine FACTD (scaling factor of Stress Difference)

Box (6): Determine FACTU (scaling factor of Pore Pressure Change).

Box (7): Determine FACTE (scaling factor of Strain).

Box (8): Punch out all of the above five factors.

Box (9): Assign seven arbitrary words (ABB, ABBC, ABC, ABCC, ABCC, EEU and EEF) equal to the above five factors as well as to the Max. Pore Pressure Change (negative) and to the Max. \bar{A} Factor (negative) in order to be able to refer to them later.

- Box (10): Compute the origins of each graph (see Fig. II-4).
- Box (11): Assign four arbitrary words (RA, DA, UDA and FFA) to the origins (AR, AD, ADU and AFF) of four graphs.
- Box (12): Draw vertical and horizontal axes of four graphs to the pre-assigned sizes (see Fig. II-4).
- Box (13): Scale the vertical axes of four graphs (see Fig. II-4).
- Box (14): Divide the Stress Difference ($\sigma_1 - \sigma_3$) axes into 1/2 in. segments with 0.06 in. long straight line.
- Box (15): Scale Obliquity axis as in Box 14.
- Box (16): Divide each segment of the above into one half (1/4 in.) size with 0.03 in. long straight line.
- Box (17): Scale the Stress Difference axis as in Box 16. Transfer execution to Box 21.
- Box (18): Compute the negative scaled portion of Pore Pressure Change axis.
- Box (19): Scale above axis as follows: When it is equal to or longer 1/4 in. it is divided into 1/4 in. segments by 0.06 in. long straight line.
- Box (20): Divide the positive portion of Pore Pressure Change axis into 1/4 in. segments by 0.06 in. long straight line.
- Box (21): Compare the two products (FACTU x UMAXN and FACTA x FMAXN). These two should never be identical unless they are set equal as in Box 24.
- Box (22): Transfer execution to Box 24 on finding products unequal in Box 21.

- Box (23): Set scale factor of \bar{A} Factor (FACTA), the Max. \bar{A} Factor (negative) and the origin of \bar{A} Factor vs. Strain (AFF) equal to those of Pore Pressure Change. Transfer execution to Box 18. \bar{A} Factor axis is scaled as Pore Pressure Change axis.
- Box (24): Transfer execution to Box 25 on finding products equal in Box 21.
- Box (25): Set ADU and AFF back to their original values so that they can be used correctly again.
- Box (26): Divide the Strain axis of Obliquity vs. Strain plot into 1/2 in. segments with 0.06 in. long straight line.
- Box (27): Divide each of the above segments into one half (1/4 in.) size with 0.03 in. long straight line.
- Box (28): Compare AR with AD, ADU and AFF, and then transfer the execution according to the results. Note: AR should never be equal to AD, ADU and AFF unless it is set equal as in Boxes 31, 34 and 37.
- Box (29): Direct execution to Box 30 on finding all three variable pairs unequal.
- Boxes (30) and (31): Set AR=AD, returning the execution to Box 26, and scale the Strain axis of Stress Difference vs. Strain plot.
- Box (32): Transfer execution to Box 33 on finding only AR=AD in Box 28.
- Boxes (33) and (34): Set AR=ADU to scale Strain axis of Pore Pressure Change vs. Strain plot as in Boxes 30 and 31.
- Box (35): Transfer execution to Box 36 on finding AR=ADU and AR=AD.
- Boxes (36) and (37): Set AR=AFF to scale Strain axis on \bar{A} Factor vs. Strain plot.

- Box (38): Transfer execution to Box 39 on the fourth time through Box 28 since the conditions of Box 38 are all satisfied.
- Box (39): Read a data card with ID Number, Strain, Obliquity and Stress Difference.
- Box (40): Compare ID Number, and then transfer execution according to the results.
- Box (41): Direct execution to Box 42 on finding $ID=1$.
- Box (42): Transfer execution to Box 2.
- Box (43): Direct execution to Box 44 on finding $ID=2$.
- Box (44): Read in a data card with Pore Pressure Change, \bar{A} Factor, Average Effective Stress and One Half of Stress Difference.
- Box (45): Reset items listed to the original values as they were assigned in the Boxes 9 and 11.
- Box (46): Compute the coordinate on the Obliquity axis.
- Box (47): Check the above, and then transfer the execution according to the result.
- Box (48): Direct execution to Box 49 on finding $ARF \leq 175$.
- Box (49): Check the value of Obliquity. It should never be smaller than 1.
- Boxes (50) and (51): Plot point on the graph of Obliquity vs. Strain (the first graph on Fig. II-4) when $R \geq 1$.
- Box (52): Plot the appropriate ordinate on the graph of Stress Difference vs. Strain (the second graph on Fig. II-4).
- Box (53): Transfer execution to Box 52 without plotting Obliquity ordinate on finding $ARF > 175$. This occurs in some tests where the Obliquity reaches almost infinity at small portion of early strain.

Box (54): Transfer execution to Box 52, without plotting Obliquity ordinate on finding $R < 1$ in Box 49, indicating an error.

Box (55): Compare AD with ADU and AFF, and transfer execution according to their relationship.

Box (56): Direct execution to Box 56 on finding both parts unequal.

Boxes (57) and (58): Prepare to plot Pore Pressure Change vs. Strain point by setting AD=ADU (the proper graph origin), FACTD=FACTU (the proper scaling), and B=DU (the appropriate ordinate). Transfer execution to Box 52, and plot the point as B vs. E.

Box (59): Direct execution to Box 60 on finding only AD=ADU in Box 55.

Boxes (60) and (61): Prepare to plot \bar{A} Factor vs. Strain as in Boxes 57 and 58.

Boxes (62) and (63): Transfer execution to Box 64 on finding both equalities satisfied in Box 55 on the third time through.

Box (64): Return to Box 39 to read next set of data card and run through the plot routine until the last data card is read and plotted.

Box (65): End run.

A program, a sample set of input and output, and a set of corresponding plots are given in Table II-2 and Fig. II-4.

For further details - FORTRAN language and card punching, etc. - consult Part II of the list of references given at the end of the report.

D. COST ANALYSIS*

The computer time used for each part of the program is as follows:

1. Computing triaxial test results and plotting effective stress paths:
 - a. LOAD-and-GO Processor + Source + Subroutine:
7 1/2 minutes
 - b. Computation and plotting: 4 minutes.
2. Plotting Strain vs. Obliquity, Stress Difference, Pore Pressure Change and A Factor:
 - a. LOAD-and-GO Processor + Source + Subrouting:
7 minutes.
 - b. Plotting: 12 minutes (the travelling time (between the plot) of the pen of the plotter is approximately 80% of this).

The computer time for parts 1a and 2a are independent of the number of tests and number of readings taken per test.

The times required for computing the results from the data and for plotting the results will obviously depend on the number of readings taken per test. The results computation from the data and plotting time given are typical for an average number of readings per test.

*The current rate of IBM 1620 Computer is \$40 per hour.

LIST OF REFERENCES

PART I

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PART II

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TABLE I-1

List of Suppliers of Triaxial Equipment

Equipment	Manufacturer
Low Pressure Triaxial Cells (0 to 160 psi)	Clockhouse Engineering Ltd. Wykeham Farrance Engineering Ltd.
High Pressure Triaxial Cells (0 to 1000 psi)	Wykeham Farrance Engineering Ltd.
Self Compensating Mercury Controls (0 to 160 psi)	Wykeham Farrance Engineering Ltd.
Compression Test Machines	Wykeham Farrance Engineering Ltd. (Model 57 and 56)
High Pressure Test Gauges (0 to 1000 psi)	U. S. Gauge (Series 1400)
High Pressure Nitrogen Tank Regulators	Air Reduction Co., Inc. (Style 1143)
Proving Rings	A. S. Geonor Wykeham Farrance Engineering Ltd.
Mercury Null Indicators	A. S. Geonor Wykeham Farrance Engineering Ltd.
No Volume Change Valves (high pressure)	Hydromatics, Inc. (Series 715)
Differential Pressure Transducers	Dynisco Co. (Model P. T. 35)
X-Y Recorder	F. L. Mosely Co. (Model 4-S)

TABLE II-1 PROGRAM FOR COMPUTING TRIAXIAL TEST RESULTS AND PLOTTING
EFFECTIVE STRESS PATHS WITH A NUMERICAL EXAMPLE.

PROGRAM

```

C   TRIAXIAL TEST RESULTS COMPUTATION AND EFFECTIVE STRESS PATH PLOTTING
C   SOIL ENG. DIVISION, CIVIL ENG. DEPT., M. I. T.
C   INITIALIZING
    DIMENSION IXY(4)
    AB=-1900.
    IXY(1)=0
    IXY(2)=-100
    AA=PLT(0.0)
1   READ, ID
    IF (ID-2) 3,4,5
5   PAUSE
C   DRAW - HORIZ. AXIS
    READ, DHMAX
    AB=AB+1900.
    IXY(1)=AB+1800.
    IXY(2)=0
    AA=PLT(1.1)
    IXY(1)=0.+AB
    AA=PLT(1.2)
C   DRAW - VERT. AXIS
    IXY(2)=1000
    AA=PLT(1.2)
C   SCALING
    DO 702 I=1,10
    IXY(1)=0.+AB
    IXY(2)=1100-100*I
    AA=PLT(1.1)
    IXY(1)=IXY(1)+6
702 AA=PLT(1.2)
    DO 701 I=1,18
    IXY(1)=0.+AB
    IXY(1)=IXY(1)+100*I
    IXY(2)=0
    AA=PLT(1.1)
    IXY(2)=IXY(2)+6
701 AA=PLT(1.2)
    DO 703 I=1,18
    IXY(1)=1850-100*I
    IXY(2)=0
    AA=PLT(1.1)
    IXY(2)=IXY(2)+3
703 AA=PLT(1.2)
    DO 700 I=1,9
    IXY(1)=0.+AB
    IXY(2)=100*I-50
    AA=PLT(1.1)
    IXY(1)=IXY(1)+3
700 AA=PLT(1.2)
C   COMPUTATION OF FACTOR
    IF (DHMAX-10.) 705,705,706
705 FACTV=100.

```

TABLE II-1 CONTINUED

```

GO TO 713
706 IF (DHMAX-20.) 707,707,708
707 FACTV=50.
GO TO 713
708 IF (DHMAX-40.) 709,709,710
709 FACTV=25.
GO TO 713
710 IF (DHMAX-50.) 711,711,712
711 FACTV=20.
GO TO 713
712 FACTV=10.
GO TO 713
713 PUNCH,FACTV
GO TO 1
C READ DATA
3 PAUSE
READ,CTI,TI,PI,AI,PPI,SIGEC
PUNCH,ID,CTI,PI,SIGEC
GO TO 1
4 IF (CTI-100.) 7,6,10
7 READ,PP,CT,S
GO TO 90
6 READ,PP,CT,X
GO TO 100
C PROVING RING CALIBRATION
10 IF (CTI-200.) 11,11,20
11 READ,PP,CT,Y
GO TO 200
20 IF (CTI-300.) 21,21,30
21 READ,PP,CT,Z
GO TO 300
30 IF (CTI-400.) 31,31,40
31 READ,PP,CT,W
GO TO 400
40 IF (CTI-500.) 41,41,50
41 READ,PP,CT,V
GO TO 500
50 IF (CTI-600.) 51,51,60
51 READ,PP,CT,Z
GO TO 600
60 GO TO 1
90 IF (S-300.) 91,91,92
91 P=0.128*S
GO TO 900
92 IF (S-500.) 93,93,94
93 P=0.1269*(S-300.)+38.4
GO TO 900
94 IF (S-650.) 95,95,96
95 P=0.1258*(S-500.)+63.78
GO TO 900
96 P=0.1254*(S-650.)+82.65
GO TO 900
100 IF(X-50.) 101,102,103
101 P=0.64*X
GO TO 900

```

TABLE II-1 CONTINUED

102 P=32.
 GO TO 900
 103 IF(X-110.) 111,112,113
 111 P=0.48*(X-50.)+32.
 GO TO 900
 112 P=61.
 GO TO 900
 113 IF(X-260.) 121,122,123
 121 P=0.426*(X-110.)+61.
 GO TO 900
 122 P=125.
 GO TO 900
 123 IF(X-580.) 131,132,133
 131 P=0.395*(X-260.)+125.
 GO TO 900
 132 P=250.
 GO TO 900
 133 P=0.386*(X-580.)+250.
 GO TO 900
 200 IF (Y-80.) 201,202,203
 201 P=0.725*Y
 GO TO 900
 202 P=58.
 GO TO 900
 203 IF (Y-260.) 204,205,206
 204 P=0.627*(Y-80.)+58.
 GO TO 900
 205 P=171.
 GO TO 900
 206 IF (Y-500.) 207,208,209
 207 P=0.562*(Y-260.)+171.
 GO TO 900
 208 P=306.
 GO TO 900
 209 IF (Y-860.) 210,211,212
 210 P=0.539*(Y-500.)+306.
 GO TO 900
 211 P=500.
 GO TO 900
 212 P=0.52*(Y-860.)+500.
 GO TO 900
 300 IF(Z-50.) 301,302,303
 301 P=0.4*Z
 GO TO 900
 302 P=20.
 GO TO 900
 303 IF (Z-180.) 311,312,313
 311 P=0.323*(Z-50.)+20.
 GO TO 900
 312 P=72.
 GO TO 900
 313 IF(Z-310.) 321,322,323
 321 P=0.292*(Z-180.)+72.
 GO TO 900
 322 P=100.

TABLE II-1 CONTINUED

```

GO TO 900
323 IF (Z-835.) 331,332,333
331 P=0.286*(Z-310.)+100.
GO TO 900
332 P=250.
GO TO 900
333 P=0.276*(Z-835.)+250.
GO TO 900
400 IF (W-13.) 401,402,403
401 P=(20./13.)*W
GO TO 900
402 P=20.
GO TO 900
403 IF (W-90.) 411,412,413
411 P=(100./77.)*(W-13.)+20.
GO TO 900
412 P=120.
GO TO 900
413 IF (W-200.) 421,422,423
421 P=(120./110.)*(W-90.)+120.
GO TO 900
422 P=240.
GO TO 900
423 IF (W-300.) 431,432,433
431 P=(W-200.)+240.
GO TO 900
432 P=340.
GO TO 900
433 IF (W-600.) 441,442,443
441 P=(267./300.)*(W-300.)+340.
GO TO 900
442 P=607.
GO TO 900
443 IF (W-1425.) 451,452,453
451 P=(693./825.)*(W-600.)+607.
GO TO 900
452 P=1300.
GO TO 900
453 P=(700./870.)*(W-1425.)+1300.
GO TO 900
500 P=1.889*V
GO TO 900
600 P=1.98*Z
C COMPUTATION
900 O=TI
E=(CT-CTI)/(100.*O)
PE=P-PI
PEK=PE/2.2
A=AI/(1.-(E/50.))
B=PEK/A
DH=B/2.
IF (CTI-500.) 901,902,906
901 DU=(PP-PPI)/14.22
SIGF3=SIGFC-DU
GO TO 903

```

TABLE II-1 CONTINUED

```

902 FP=2.5
    DU=FP*(PP1-PP)/14.22
    SIGE3=FP*PP/14.22
    GO TO 903
906 FP=3.0
    DU=FP*(PP1-PP)/14.22
    SIGE3=FP*PP/14.22
903 F=SIGE3
    SIGE1=B+F
    G=SIGE1
    R=G/F
    AES=(F+G)/2.
    AF=DU/B
    PUNCH,ID,E,R,B
    PUNCH,DU,AF,AES,DH
C   PLOTTING
    AESP=AES*FACTV
    DHP=DH*FACTV
    IF(AESP-1800.)904,904,1
904 IF(DHP-997.)905,905,1
905 IXY(1)=AESP+AB-3.
    IXY(2)=DHP
    AA=PLT(1.1)
    IXY(1)=IXY(1)+6
    AA=PLT(1.2)
    IXY(1)=IXY(1)-3
    IXY(2)=IXY(2)-3
    AA=PLT(1.1)
    IXY(2)=IXY(2)+6
    AA=PLT(1.2)
    GO TO 1
    END

```

TABLE II-1 CONTINUED

NUMERICAL EXAMPLE

INPUT

* DATA

ID DHMAX

3 20.

ID	CTI	TI	PI	AI	PPI	SIGEC
1	500.	3.14	331.0	10.	110.4	19.4

ID	PP	CT	X(U,V,W,.....,ETC.)
2	110.4	500.	175.2
2	107.2	505.	192.0
2	104.0	510.	212.0
2	97.0	520.	246.0
2	89.3	533.	274.0
2	80.2	551.	302.0
2	73.0	570.	320.0
2	69.4	580.	328.0
2	66.1	591.	335.0
2	63.7	600.	340.0
2	59.3	622.	349.0
2	56.4	642.	355.0
2	53.3	665.	360.0
2	50.9	690.	365.0
2	49.6	705.	367.0
2	47.3	737.	371.0
2	45.4	780.	375.5
2	44.4	802.	377.0
2	43.5	830.	379.0
2	43.0	850.	381.0
2	41.6	900.	383.0
2	40.6	950.	385.0
2	39.8	1000.	386.5
2	39.0	1050.	388.0
2	38.3	1103.	388.
2	38.1	1150.	389.5
2	37.7	1200.	390.0
2	37.3	1250.	390.0
2	37.0	1302.	390.5
2	36.6	1350.	390.5
2	36.2	1400.	390.6
2	36.0	1450.	390.8
2	35.8	1500.	391.0
2	35.7	1555.	391.2
2	35.6	1600.	391.2
2	35.2	1700.	391.3
2	34.8	1800.	391.7
2	34.6	1900.	392.0
2	34.3	2100.	392.8
2	34.2	2200.	393.5
2	34.2	2302.	394.0

TABLE II-1 CONTINUED

2	34.1	2400.	394.9
2	34.0	2505.	396.0
2	34.0	2600.	396.0
2	33.8	2705.	397.5
2	33.8	2800.	398.4
2	33.8	2900.	399.3
2	33.8	3000.	400.0
2	33.8	3140.	401.7
2	33.9	3200.	402.2
2	33.9	3315.	403.3
2	33.9	3415.	404.5
2	34.0	3500.	405.0
2	34.0	3610.	406.0
2	34.0	3700.	407.0
2	34.1	3800.	408.0
2	34.1	3910.	408.5
2	34.1	4020.	409.6
2	34.4	4180.	411.0
2	34.4	4390.	413.0
2	35.0	4790.	416.0
2	35.0	5000.	418.0

OUTPUT

FACTV
50.000000

ID	CTI	PI	SIGEC	
1	500.00000	331.00000	19.400000	
ID	E	R	B	
2	.00000000	1.0000000	.00000000	127
DU	AF	AES	DH	
.00000000	.00000000	19.400000	.00000000	128
2	1.5923566E-02	1.0755551	1.4399049	129
.35161744	.24419490	19.777617	.71995245	130
2	3.1847133E-02	1.1706197	3.1556252	131
.91420534	.28970656	20.072889	1.5778126	132
2	6.3694267E-02	1.3515473	6.0692592	133
2.1448663	.35339836	20.299045	3.0346296	134
2	.10509554	1.5319288	8.4633554	135
3.4985935	.41338137	20.142366	4.2316777	136
2	.16242038	1.7581673	10.850003	137
5.0984528	.46990335	19.735830	5.4250015	138
2	.22292993	1.9486760	12.375486	139
6.3642756	.51426470	19.232750	6.1877430	140
2	.25477707	2.0514725	13.050977	141
6.9971870	.53614277	18.937583	6.5254885	142
2	.28980891	2.1527580	13.639348	143

TABLE II-1 CONTINUED

7.5773558	.55555117	18.651600	6.8196740	144
2	.31847133	2.2320844	14.058065	145
7.9992967	.56901833	18.439017	7.0290325	146
2	.38853503	2.3919155	14.805008	147
8.7728551	.59255997	18.038931	7.4025040	148
2	.45222929	2.5105317	15.296524	149
9.2827004	.60685031	17.774844	7.6482620	150
2	.52547770	2.6384274	15.698716	151
9.8277074	.62601982	17.430933	7.8493580	152
2	.60509554	2.7574473	16.097575	153
10.249648	.63672000	17.208421	8.0487875	154
2	.65286624	2.8196551	16.251492	155
10.478199	.64475304	17.056828	8.1257460	156
2	.75477707	2.9416837	16.556200	157
10.882559	.65731019	16.804822	8.2781000	158
2	.89171974	3.0615527	16.889655	159
11.216596	.66411042	16.637513	8.4448275	160
2	.96178343	3.1195130	16.991877	161
11.392405	.67046183	16.512815	8.4959385	162
2	1.0509554	3.1796486	17.129096	163
11.550632	.67432817	16.423197	8.5645480	164
2	1.1146496	3.2230434	17.274705	165
11.638537	.67373289	16.408097	8.6373525	166
2	1.2738853	3.3105225	17.385789	167
11.884669	.68358525	16.217507	8.6928945	168
2	1.4331210	3.3807649	17.495777	169
12.060478	.68933651	16.096692	8.7478885	170
2	1.5923566	3.4365596	17.563106	171
12.201125	.69470200	15.989710	8.7815530	172
2	1.7515923	3.4944594	17.629619	173
12.341772	.70005891	15.882319	8.8148095	174
2	1.9203821	3.5297838	17.567944	175
12.464838	.70952172	15.728416	8.7839720	176
2	2.0700636	3.5526114	17.636715	177
12.500000	.70874876	15.727639	8.8183575	178
2	2.2292993	3.5762895	17.619139	179
12.570323	.71344706	15.648528	8.8095695	180
2	2.3885350	3.5943788	17.560406	181
12.640646	.71983791	15.548838	8.7802030	182
2	2.5541401	3.6117248	17.540065	183
12.693389	.72367970	15.485925	8.7700325	184
2	2.7070063	3.6308583	17.483553	185
12.763713	.73004114	15.387345	8.7417765	186
2	2.8662420	3.6512742	17.432781	187
12.834036	.73620129	15.291636	8.7163905	188
2	3.0254777	3.6589901	17.390020	189
12.869198	.74003353	15.235094	8.6950100	190
2	3.1847133	3.6667726	17.347150	191
12.904360	.74388934	15.178497	8.6735750	192
2	3.3598726	3.6664641	17.298265	193
12.921940	.74700786	15.136473	8.6491325	194
2	3.5031847	3.6654945	17.245113	195
12.939521	.75032973	15.092316	8.6225565	196
2	3.8216560	3.6775673	17.134925	197
13.009845	.75925894	14.966899	8.5674625	198

TABLE II-1 CONTINUED

2	4.1401273	3.6936238	17.048253	199
13.080168	.76724389	14.853239	8.5241265	200
2	4.4585987	3.6935897	16.953325	201
13.115330	.77361402	14.770614	8.4766625	202
2	5.0955414	3.6882458	16.777906	203
13.168073	.78484603	14.630162	8.3889530	204
2	5.4140127	3.6853320	16.712510	205
13.185654	.78896910	14.579883	8.3562550	206
2	5.7388535	3.6718741	16.628753	207
13.185654	.79294304	14.538004	8.3143765	208
2	6.0509554	3.6714941	16.579421	209
13.203234	.79636279	14.495757	8.2897105	210
2	6.3853503	3.6720125	16.535662	211
13.220815	.79953345	14.456297	8.2678310	212
2	6.6878980	3.6534774	16.420958	213
13.220815	.80511837	14.398945	8.2104790	214
2	7.0222929	3.6660281	16.404885	215
13.255977	.80805058	14.355747	8.2024425	216
2	7.3248407	3.6579789	16.355356	217
13.255977	.81049761	14.330983	8.1776780	218
2	7.6433121	3.6487822	16.298766	219
13.255977	.81331169	14.302688	8.1493830	220
2	7.9617834	3.6370791	16.226753	221
13.255977	.81692110	14.266681	8.1133765	222
2	8.4076433	3.6288430	16.176074	223
13.255977	.81948048	14.241342	8.0880370	224
2	8.5987261	3.6150713	16.137307	225
13.238396	.82035967	14.239539	8.0686535	226
2	8.9649681	3.6044995	16.072070	227
13.238396	.82368954	14.206921	8.0360350	228
2	9.2834394	3.5978830	16.031240	229
13.238396	.82578740	14.186506	8.0156200	230
2	9.5541401	3.5788914	15.959385	231
13.220815	.82840378	14.168158	7.9796925	232
2	9.9044585	3.5676810	15.890010	233
13.220815	.83202055	14.133471	7.9450050	234
2	10.191082	3.5603726	15.844782	235
13.220815	.83439551	14.110857	7.9223910	236
2	10.509554	3.5436220	15.785841	237
13.203234	.83639724	14.098967	7.8929205	238
2	10.859872	3.5264726	15.679411	239
13.203234	.84207461	14.045752	7.8397055	240
2	11.210191	3.5156664	15.612347	241
13.203234	.84569181	14.012220	7.8061735	242
2	11.719745	3.4764038	15.499293	243
13.150492	.84845753	14.008436	7.7496465	244
2	12.388535	3.4537783	15.357685	245
13.150492	.85628087	13.937632	7.6788425	246
2	13.662420	3.3607917	15.024730	247
13.045007	.86823570	13.876640	7.5123650	248
2	14.331210	3.3365905	14.870707	249
13.045007	.87722843	13.799628	7.4353535	250

TABLE II-2 Program for Plotting Strain versus Obliquity, Stress Difference, Pore Pressure Change and A Factor with a Numerical Example.

PROGRAM

```

C      SOIL ENG. DIVISION, CIVIL ENG. DEPT., M. I. T.
C      INITIALIZING
      DIMENSION IXY(4)
      AB=-1100.
      IXY(1)=0
      IXY(2)=-200
      AA=PLT(0.0)
C      COMPUTATION OF FACTORS
      3 READ,EMAX,RMAX,BMAX,UMAXP,UMAXN,FMAXP,FMAXN
      IF (RMAX-3.5) 10,10,11
      10 FACTR=50.
      GO TO 70
      11 IF (RMAX-7.) 12,12,13
      12 FACTR=25.
      GO TO 70
      13 IF (RMAX-17.5) 14,14,15
      14 FACTR=10.
      GO TO 70
      15 IF (RMAX-35.) 16,16,17
      16 FACTR=5.
      GO TO 70
      17 FACTR=5.
      70 AFMAX=FMAXP+FMAXN
      IF (AFMAX-0.2) 57,57,58
      57 FACTA=500.
      GO TO 110
      58 IF (AFMAX-0.4) 59,59,60
      59 FACTA=250.
      GO TO 110
      60 IF (AFMAX-0.5) 41,41,42
      41 FACTA=250.
      GO TO 110
      42 FACTA=125.
      110 IF (BMAX-4.) 18,18,19
      18 FACTD=100.
      GO TO 80
      19 IF (BMAX-8.) 20,20,21
      20 FACTD=50.
      GO TO 80
      21 IF (BMAX-17.) 22,22,23
      22 FACTD=25.
      GO TO 80
      23 IF (BMAX-32.) 220,220,221
      220 FACTD=12.5
      GO TO 80
      221 IF (BMAX-40.) 24,24,43
      24 FACTD=10.
      GO TO 80
      43 FACTD=5.
      80 DUMAX=UMAXP+UMAXN
      25 IF (DUMAX-0.5) 26,26,27
      26 FACTU=250.
      GO TO 90
      27 IF (DUMAX-1.) 28,28,29
      28 FACTU=100.
      GO TO 90

```

TABLE II-2 (Cont'd)

```

29 IF (DUMAX-2.) 30,30,31
30 FACTU=50.
   GO TO 90
31 IF (DUMAX-4.) 32,32,33
32 FACTU=25.
   GO TO 90
33 IF (DUMAX-8.) 61,61,62
61 FACTU=12.5
   GO TO 90
62 IF (DUMAX-16.) 63,63,64
63 FACTU=6.25
   GO TO 90
64 IF (DUMAX-20.) 34,34,35
34 FACTU=5.
   GO TO 90
35 IF (DUMAX-32.) 36,36,37
36 FACTU=3.125
   GO TO 90
37 FACTU=2.5
90 IF (EMAX-6.) 801,801,802
801 FACTE=100.
   GO TO 120
802 IF (EMAX-12.) 810,810,812
810 FACTE=50.
   GO TO 120
812 IF (EMAX-16.) 810,810,820
820 FACTE=25.
120 PUNCH,FACTE,FACTR,FACTD
    PUNCH,FACTU,FACTA
    ABB=FACTE
    ABBC=FACTR
    ABC=FACTD
    ABCC=FACTU
    ABBCC=FACTA
    EEU=UMAXN
    EEF=FMAXN
    AB=AB+1100.
    AR=AB+175.
    AD=AR+425.
    ADU=AD+150.-FACTU*UMAXN
    AFF=AD+300.-FACTA*FMAXN
    RA=AR
    DA=AD
    UDA=ADU
    FFA=AFF
C   DRAW - VERT. AXIS
    IXY(1)=AB
    IXY(2)=0
    AA=PLT(1.1)
    IXY(1)=AR
    AA=PLT(1.2)
    IXY(1)=AR+25.
    AA=PLT(1.1)
    IXY(1)=AD
    AA=PLT(1.2)
    IXY(1)=625.+AB
    AA=PLT(1.1)
    IXY(1)=750.+AB
    AA=PLT(1.2)

```

TABLE II-2 (Cont'd)

```

        IXY(1)=775.+AB
        AA=PLT(1.1)
        IXY(1)=900.+AB
        AA=PLT(1.2)
C      DRAW - HORIZ. AXIS
        IXY(1)=AFF
        IXY(2)=0
        AA=PLT(1.1)
        IXY(2)=600
        AA=PLT(1.2)
        IXY(1)=ADU
        AA=PLT(1.1)
        IXY(2)=0
        AA=PLT(1.2)
        IXY(1)=AD
        AA=PLT(1.1)
        IXY(2)=600
        AA=PLT(1.2)
        IXY(1)=AR
        AA=PLT(1.1)
        IXY(2)=0
        AA=PLT(1.2)
C      SCALING - VERT. AXIS
        DO 742 I=1,8
        IXY(1)=AD
        IXY(1)=IXY(1)-50*I
        IXY(2)=0
        AA=PLT(1.1)
        IXY(2)=IXY(2)+6
742   AA=PLT(1.2)
        DO 741 I=1,3
        IXY(1)=AR
        IXY(1)=IXY(1)-50*I
        IXY(2)=0
        AA=PLT(1.1)
        IXY(2)=IXY(2)+6
741   AA=PLT(1.2)
        DO 740 I=1,4
        IXY(1)=AR
        IXY(1)=IXY(1)-175+50*(I-1)
        IXY(2)=0
        AA=PLT(1.1)
        IXY(2)=IXY(2)+3
740   AA=PLT(1.2)
        DO 720 I=1,8
        IXY(1)=AD
        IXY(1)=IXY(1)-375+50*(I-1)
        IXY(2)=0
        AA=PLT(1.1)
        IXY(2)=IXY(2)+3
720   AA=PLT(1.2)
700   IXY(1)=FACTU*UMAXN
        L=IXY(1)
        J=L/25
        IF (1-J) 998,999,999
998   DO 743 I=1,J
        IXY(1)=ADIJ
        IXY(1)=IXY(1)+25*I
        IXY(2)=0

```

TABLE II-2 (Cont'd)

```

      AA=PLT(1.1)
      IXY(2)=IXY(2)+6
743  AA=PLT(1.2)
999  K=5-J
      DO 744 I=1,K
      IXY(1)=ADU
      IXY(1)=IXY(1)-25*I
      IXY(2)=0
      AA=PLT(1.1)
      IXY(2)=IXY(2)+6
744  AA=PLT(1.2)
      IF (FACTU*UMAXN-FACTA*FMAXN) 658,750,658
750  IF (FACTU-FACTA) 658,931,658
658  FACTU=FACTA
      UMAXN=FMAXN
      ADU=AFF
      GO TO 700
931  ADU=UDA
      AFF=FFA
C    SCALING - HORIZ. AXIS
751  DO 752 I=1,12
      IXY(1)=AR
      IXY(2)=600
      IXY(2)=IXY(2)-50*I+50
      AA=PLT(1.1)
      IXY(1)=IXY(1)-6
752  AA=PLT(1.2)
      DO 753 I=1,12
      IXY(1)=AR
      IXY(2)=50*I-25
      AA=PLT(1.1)
      IXY(1)=IXY(1)-3
753  AA=PLT(1.2)
      IF (AR-AFF) 758,5,758
758  IF (AR-ADU) 760,761,760
760  IF (AR-AD) 770,780,770
770  AR=AD
      GO TO 751
780  AR=ADU
      GO TO 751
761  AR=AFF
      GO TO 751
C    READ DATA
      5 READ, ID, E, R, B
      IF (ID-2) 3,4,4
      4 READ, DU, AF, AES, DH
      AR=RA
      AD=DA
      ADU=UDA
      AFF=FFA
      FACTE=ABB
      FACTR=ABBC
      FACTD=ABC
      FACTU=ABCC
      FACTA=ABBCC
      UMAXN=EEU
      FMAXN=EEF
C    PLOTTING
      ARF=FACTR*(R-1.)

```

TABLE II-2 (Cont'd)

```

    IF (ARF-175.) 910,910,911
910 IF (1.-R) 921,921,911
921 IXY(1)=AR-ARF-3.
    IXY(2)=FACTE*E
    AA=PLT(1.1)
    IXY(1)=IXY(1)+6
    AA=PLT(1.2)
    IXY(1)=IXY(1)-3
    IXY(2)=IXY(2)-3
    AA=PLT(1.1)
    IXY(2)=IXY(2)+6
    AA=PLT(1.2)
911 IXY(1)=AD-FACTD*B-3.
    IXY(2)=FACTE*E
    AA=PLT(1.1)
    IXY(1)=IXY(1)+6
    AA=PLT(1.2)
    IXY(1)=IXY(1)-3
    IXY(2)=IXY(2)-3
    AA=PLT(1.1)
    IXY(2)=IXY(2)+6
    AA=PLT(1.2)
    IF (AD-AFF) 858,5,858
858 IF (AD-ADU) 860,861,860
860 AD=ADU
    FACTD=FACTU
    B=DU
    GO TO 911
861 AD=AFF
    FACTD=FACTA
    B=AF
    GO TO 911
    GO TO 5
    END

```

TABLE II-2 CONTINUED

NUMERICAL EXAMPLE

INPUT

* DATA

EMAX RMAX BMAX UMAXP UMAXN FMAXP FMAXN
 14.3 3.69 17.7 13.0 0. 0.85 0.

ID (ANY 3 NUMBERS)

1 0. 1.0 0.

ID	E	R	B	
2	.00000000	1.0000000	.00000000	127
DU	AF	AES	DH	
.00000000	.00000000	19.400000	.00000000	128
2	1.5923566E-02	1.0755551	1.4399049	129
.35161744	.24419490	19.777617	.71995245	130
2	3.1847133F-02	1.1706197	3.1556252	131
.91420534	.28970656	20.072889	1.5778126	132
2	6.3694267E-02	1.3515473	6.0692592	133
2.1448663	.35339836	20.299045	3.0346296	134
2	.10509554	1.5319288	8.4633554	135
3.4985935	.41338137	20.142366	4.2316777	136
2	.16242038	1.7581673	10.850003	137
5.0984528	.46990335	19.735830	5.4250015	138
2	.22292993	1.9486760	12.375486	139
6.3642756	.51426470	19.232750	6.1877430	140
2	.25477707	2.0514725	13.050977	141
6.9971870	.53614277	18.937583	6.5254885	142
2	.28980891	2.1527580	13.639348	143
7.5773558	.55555117	18.651600	6.8196740	144
2	.31847133	2.2320844	14.058065	145
7.9992967	.56901833	18.439017	7.0290325	146
2	.38853503	2.3919155	14.805008	147
8.7728551	.59255997	18.038931	7.4025040	148
2	.45222929	2.5105317	15.296524	149
9.2827004	.60685031	17.774844	7.6482620	150
2	.52547770	2.6384274	15.698716	151
9.8277074	.62601982	17.430933	7.8493580	152
2	.60509554	2.7574473	16.097575	153
10.249648	.63672000	17.208421	8.0487875	154
2	.65286624	2.8196551	16.251492	155
10.478199	.64475304	17.056828	8.1257460	156
2	.75477707	2.9416837	16.556200	157
10.882559	.65731019	16.804822	8.2781000	158
2	.89171974	3.0615527	16.889655	159
11.216596	.66411042	16.637513	8.4448275	160
2	.96178343	3.1195130	16.991877	161
11.392405	.67046183	16.512815	8.4959385	162
2	1.0509554	3.1796486	17.129096	163
11.550632	.67432817	16.423197	8.5645480	164
2	1.1146496	3.2230434	17.274705	165
11.638537	.67373289	16.408097	8.6373525	166

TABLE II-2 CONTINUED

2	1.2738853	3.3105225	17.385789	167
11.884669	.68358525	16.217507	8.6928945	168
2	1.4331210	3.3807649	17.495777	169
12.060478	.68933651	16.096692	8.7478885	170
2	1.5923566	3.4365596	17.563106	171
12.201125	.69470200	15.989710	8.7815530	172
2	1.7515923	3.4944594	17.629619	173
12.341772	.70005891	15.882319	8.8148095	174
2	1.9203821	3.5297838	17.567944	175
12.464838	.70952172	15.728416	8.7839720	176
2	2.0700636	3.5526114	17.636715	177
12.500000	.70874876	15.727639	8.8183575	178
2	2.2292993	3.5762895	17.619139	179
12.570323	.71344706	15.648528	8.8095695	180
2	2.3885350	3.5943788	17.560406	181
12.640646	.71983791	15.548838	8.7802030	182
2	2.5541401	3.6117248	17.540065	183
12.693389	.72367970	15.485925	8.7700325	184
2	2.7070063	3.6308583	17.483553	185
12.763713	.73004114	15.387345	8.7417765	186
2	2.8662420	3.6512742	17.432781	187
12.834036	.73620129	15.291636	8.7163905	188
2	3.0254777	3.6589901	17.390020	189
12.869198	.74003353	15.235094	8.6950100	190
2	3.1847133	3.6667726	17.347150	191
12.904360	.74388934	15.178497	8.6735750	192
2	3.3598726	3.6664641	17.298265	193
12.921940	.74700786	15.136473	8.6491325	194
2	3.5031847	3.6654945	17.245113	195
12.939521	.75032973	15.092316	8.6225565	196
2	3.8216560	3.6775673	17.134925	197
13.009845	.75925894	14.966899	8.5674625	198
2	4.1401273	3.6936238	17.048253	199
13.080168	.76724389	14.853239	8.5241265	200
2	4.4585987	3.6935897	16.953325	201
13.115330	.77361402	14.770614	8.4766625	202
2	5.0955414	3.6882458	16.777906	203
13.168073	.78484603	14.630162	8.3889530	204
2	5.4140127	3.6853320	16.712510	205
13.185654	.78896910	14.579883	8.3562550	206
2	5.7388535	3.6718741	16.628753	207
13.185654	.79294304	14.538004	8.3143765	208
2	6.0509554	3.6714941	16.579421	209
13.203234	.79636279	14.495757	8.2897105	210
2	6.3853503	3.6720125	16.535662	211
13.220815	.79953345	14.456297	8.2678310	212
2	6.6878980	3.6534774	16.420958	213
13.220815	.80511837	14.398945	8.2104790	214
2	7.0222929	3.6660281	16.404885	215
13.255977	.80805058	14.355747	8.2024425	216
2	7.3248407	3.6579789	16.355356	217
13.255977	.81049761	14.330983	8.1776780	218
2	7.6433121	3.6487822	16.298766	219
13.255977	.81331169	14.302688	8.1493830	220
2	7.9617834	3.6370791	16.226753	221

TABLE II-2 CONTINUED

13.255977	.81692110	14.266681	8.1133765	222
2	8.4076433	3.6288430	16.176074	223
13.255977	.81948048	14.241342	8.0880370	224
2	8.5987261	3.6150713	16.137307	225
13.238396	.82035967	14.239539	8.0686535	226
2	8.9649681	3.6044995	16.072070	227
13.238396	.82368954	14.206921	8.0360350	228
2	9.2834394	3.5978830	16.031240	229
13.238396	.82578740	14.186506	8.0156200	230
2	9.5541401	3.5788914	15.959385	231
13.220815	.82840378	14.168158	7.9796925	232
2	9.9044585	3.5676810	15.890010	233
13.220815	.83202055	14.133471	7.9450050	234
2	10.191082	3.5603726	15.844782	235
13.220815	.83439551	14.110857	7.9223910	236
2	10.509554	3.5436220	15.785841	237
13.203234	.83639724	14.098967	7.8929205	238
2	10.859872	3.5264726	15.679411	239
13.203234	.84207461	14.045752	7.8397055	240
2	11.210191	3.5156664	15.612347	241
13.203234	.84569181	14.012220	7.8061735	242
2	11.719745	3.4764038	15.499293	243
13.150492	.84845753	14.008436	7.7496465	244
2	12.388535	3.4537783	15.357685	245
13.150492	.85628087	13.937632	7.6788425	246
2	13.662420	3.3607917	15.024730	247
13.045007	.86823570	13.876640	7.5123650	248
2	14.331210	3.3365905	14.870707	249
13.045007	.87722843	13.799628	7.4353535	250

OUTPUT

FACTE	FACTR	FACTD	
50.000000	25.000000	12.500000	005
FACTU	FACTA		
6.2500000	250.00000		006

TABLE II-3

LIST OF NOMENCLATURES USED IN COMPUTER PROGRAM

A:	Area of sample at any time, cm^2
AB:	A paper length of an Effective Stress Path Plot
AB:	(i.e. $AB=AB + 1900$) The horizontal [IXY(1)] coordinate of the origin of the plot.
ABB:	An arbitrary word assigned to use in program.
ABBC:	An arbitrary word assigned to use in program.
ABC:	An arbitrary word assigned to use in program.
ABCC:	An arbitrary word assigned to use in program.
ABBCC:	An arbitrary word assigned to use in program.
AES:	Average effective stress, $1/2(\bar{\sigma}_1 + \bar{\sigma}_3)$, kg/cm^2 .
AESP:	AES x FACTV (scale factor for Effective Stress Path plot). This is equal to the coordinate on the average effective stress axis of Effective Stress Path plot.
AD:	Vertical coordinate of the origin of Strain vs. Stress Difference
ADU:	Vertical coordinate of the origin of Strain vs. Pore Pressure Change.
AF:	\bar{A} Factor
AFF:	Vertical coordinate of the origin of Strain vs. \bar{A} Factor.
AFMAX:	Sum of FMAXN (\bar{A} Factor, negative max.) and FMAXP (\bar{A} Factor, positive max.).
AI:	Initial area of sample, cm^2 .
AR:	Vertical coordinate of the origin of Strain vs. Obliquity.
ARF:	(Obliquity minus one) x FACTR (scale factor for Strain vs. Obliquity plot). This is equal to the coordinate on the Obliquity axis of Strain vs. Obliquity plot.
B:	Stress Difference, $(\sigma_1 - \sigma_3)$, kg/cm^2 .
BMAX:	Maximum Stress Difference, $(\sigma_1 - \sigma_3)$ max., kg/cm^2 .

Table II-3 (Continued)
List of Nomenclatures Used in Computer Program

CT:	Counter reading at any time.
CTI:	Initial counter reading.
DA:	An arbitrary word assigned to use in program.
DH:	One half of stress difference, $1/2 (\sigma_1 - \sigma_3)$, kg/cm^2 .
DHMAX:	Maximum value of one half of stress difference, $1/2 (\sigma_1 - \sigma_3)$ max., kg/cm^2
DHP:	DH x FACTV. This is equal to the coordinate on the DH axis of Effective Stress Path plot.
DU:	Pore Pressure Change, Δu , kg/cm^2 .
DUMAX:	Sum of UMAXN (DU, negative max.) and UMAXP (DU, positive max.).
E:	Axial strain, %.
EEF:	An arbitrary word assigned to use in program.
EEU:	An arbitrary word assigned to use in program.
EMAX:	Maximum axial strain, 1 .
FACTA:	Scaling factor of \bar{A} Factor.
FACTD:	Scaling factor of Stress Difference.
FACTE:	Scaling factor of Strain.
FACTR:	Scaling factor of Obliquity.
FACTU:	Scaling factor of Δu .
FACTV:	Scaling factor of $1/2 (\sigma_1 - \sigma_3)$ and $1/2 (\bar{\sigma}_1 + \bar{\sigma}_3)$.
FFA:	An arbitrary word assigned to use in program.
FMAXN:	\bar{A} Factor, negative max., express in magnitude.
FMAXP:	\bar{A} Factor, positive max., express in magnitude.
FP:	Factor of X-Y recorder.
ID:	Statement identification number, any FIXED POINT NUMBER* from 1 to 999 and not FLOATING POINT NUMBER*.

*Any numeral as 9, 5, 199, 800 etc. is a FIXED POINT NUMBER.
Any numeral as 9., 8.5, 802. etc. is a FLOATING POINT NUMBER.

Table II-3 (Continued)
 List of Nomenclatures used in Computer Program

O:	TI, Initial length of sample, inch.	
P:	Load on proving ring at any time, lbs.	
PE:	Net load increase (load on sample) at any time, P-PI, lbs.	
PEK:	PE in kg.	
PI:	Initial load on proving ring, lbs.	
PP:	Pore Pressure at any time, corrected, kg/cm^2	Low Pressure
PPI:	Initial pore pressure, corrected, kg/cm^2	
PP:	X-Y reading at any time	High Pressure
PPI:	Initial X-Y reading	
R:	Obliquity .	
RA:	An arbitrary word assigned to use in program.	
RMAX:	Maximum Obliquity .	
S, X, Y, Z, W, V, Z:	Proving ring reading of ring No. 625, N-1, N-4, N-3, N-5, 945 and 1126 at any time.	
SIGEC:	$\bar{\sigma}_c$, kg/cm^2 .	
SIGEI:	$\bar{\sigma}_1$, kg/cm^2 .	
SIGE3:	$\bar{\sigma}_3$, kg/cm^2 .	
TI:	Initial length of sample, inch.	
UDA:	An arbitrary word assigned to use in program.	
UMAXP:	Δu maximum, positive, kg/cm^2 .	
UMAXN:	Δu maximum, negative, in magnitude only, kg/cm^2 .	
*:	Multiplication.	
/:	Division.	

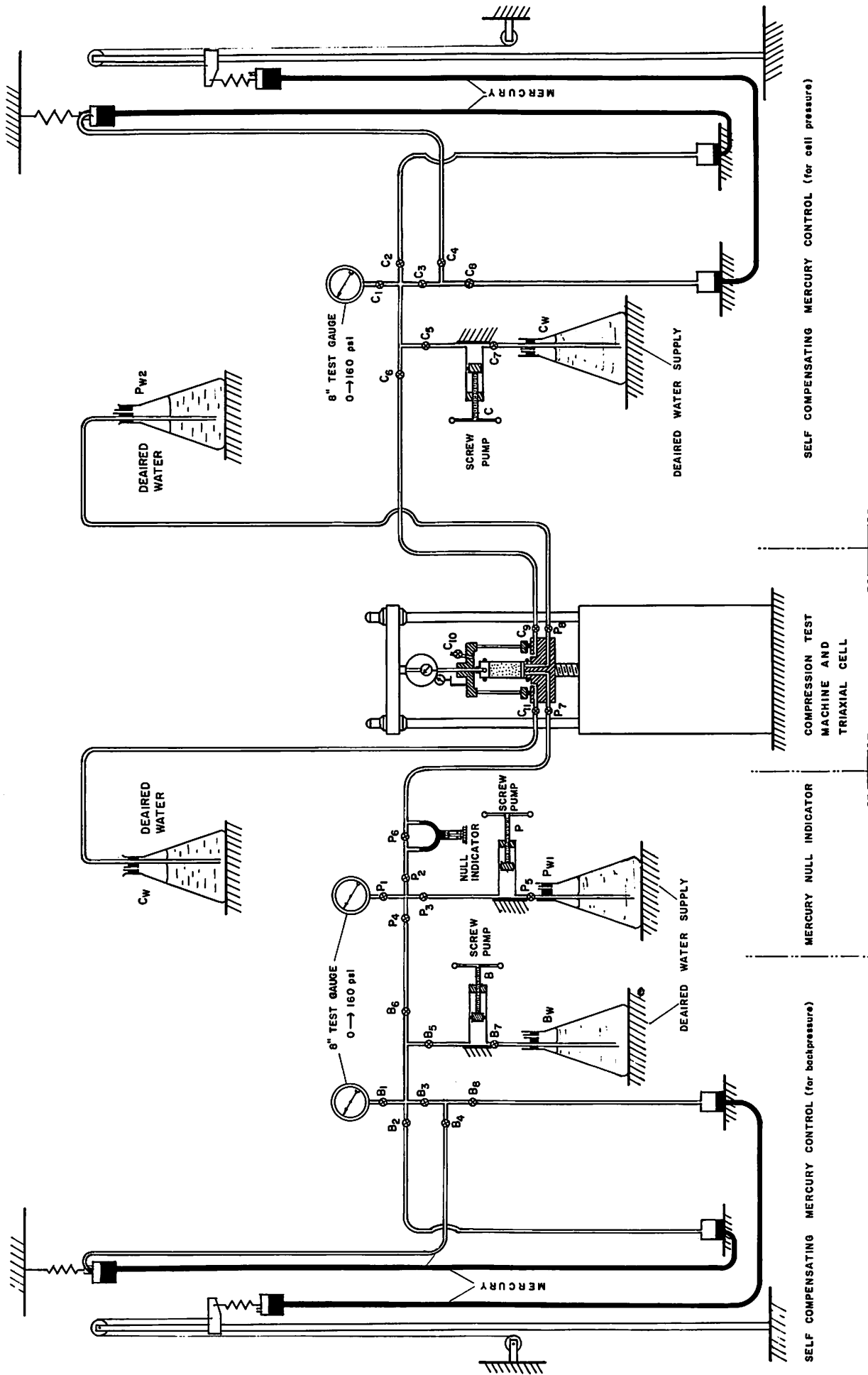


FIG. I-1 SCHEMATIC OF LOW PRESSURE TRIAXIAL SET UP

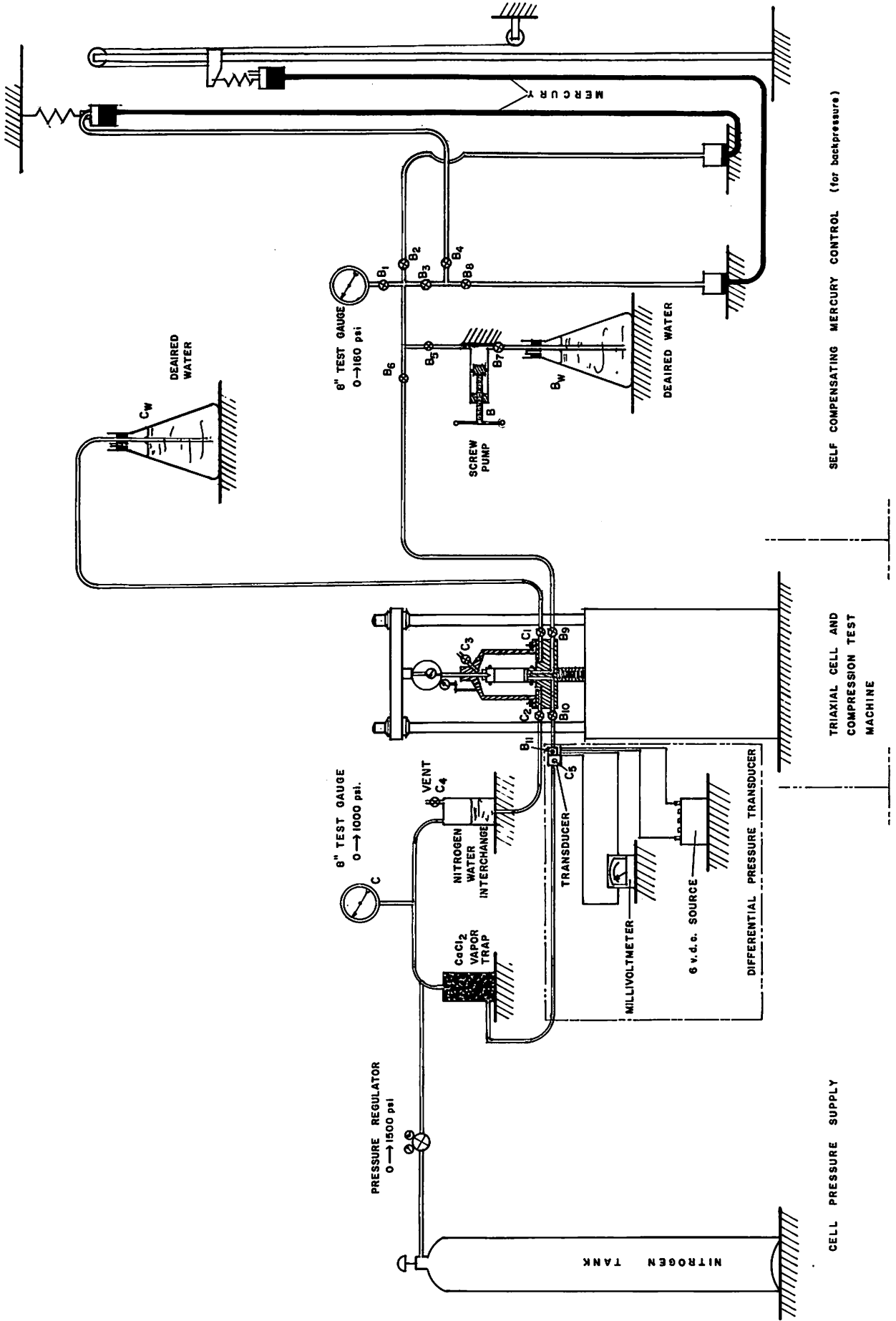


FIG. I-2 SCHEMATIC OF HIGH PRESSURE TRIAXIAL SET UP

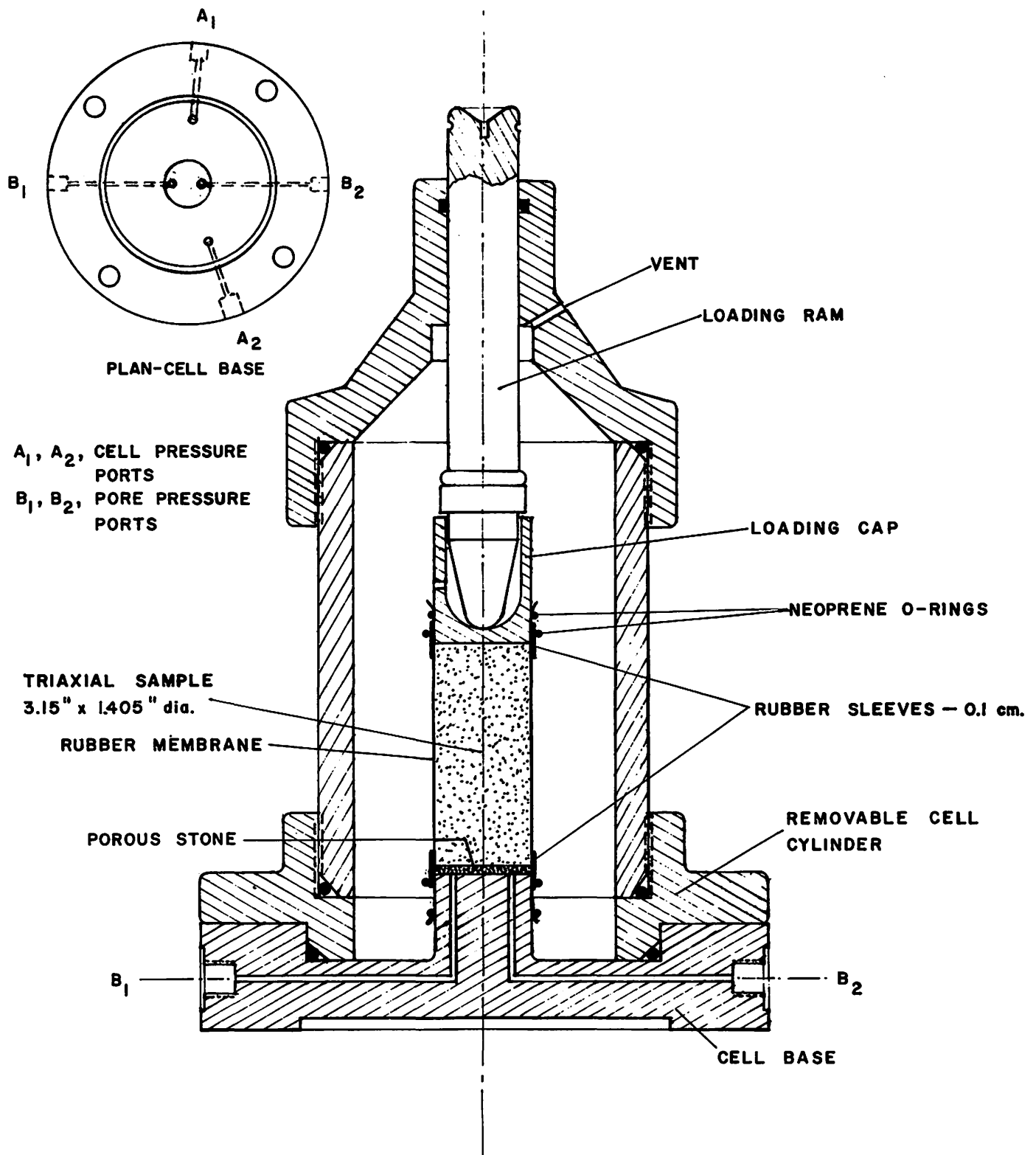
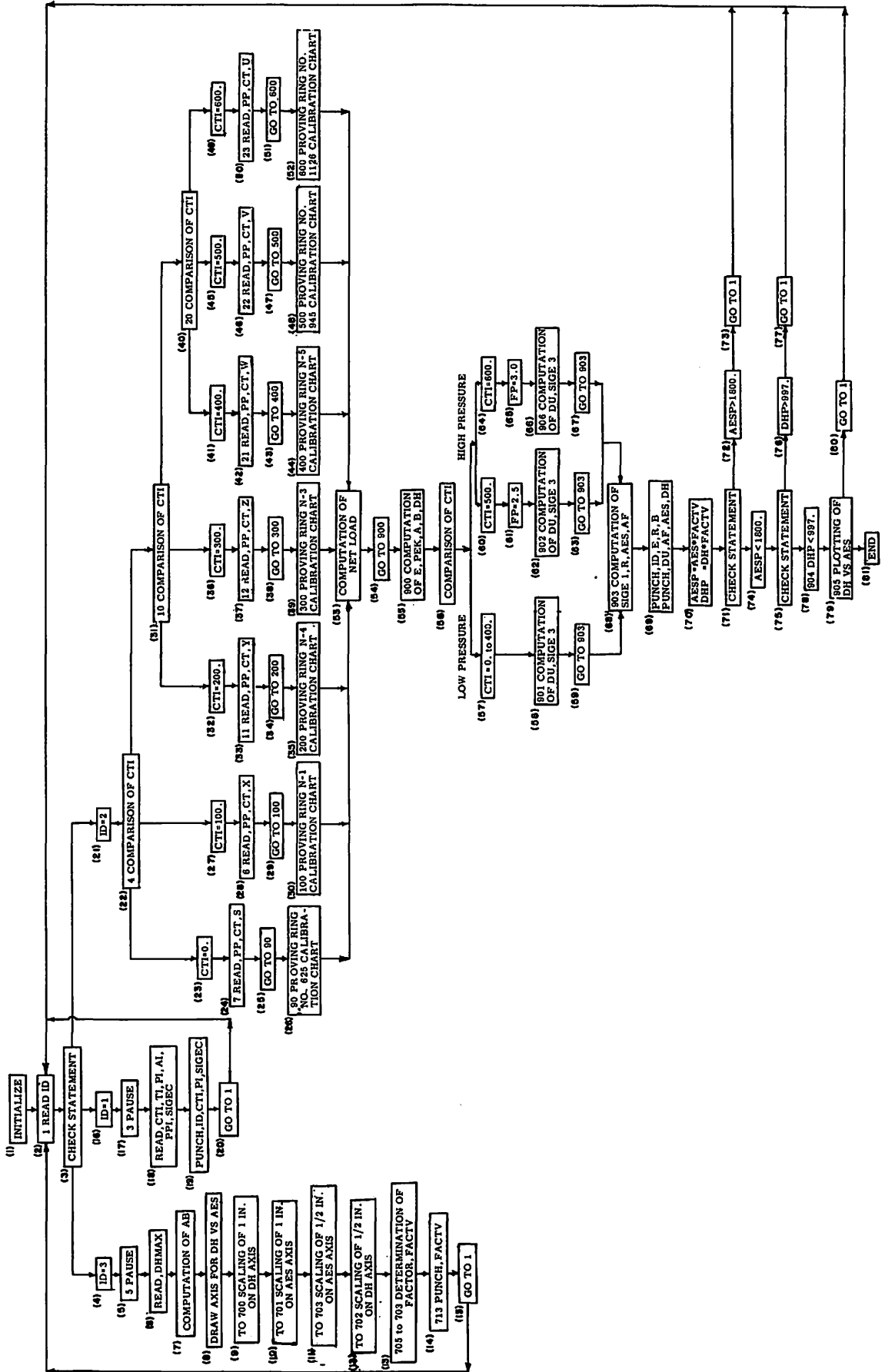


FIG. I-3 DETAILS OF THE HIGH PRESSURE TRIAXIAL CELL

FIGURE II - 1 FLOW CHART FOR COMPUTATIONS OF TRIAXIAL TEST RESULTS AND THE PLOTTING OF EFFECTIVE STRESS PATH



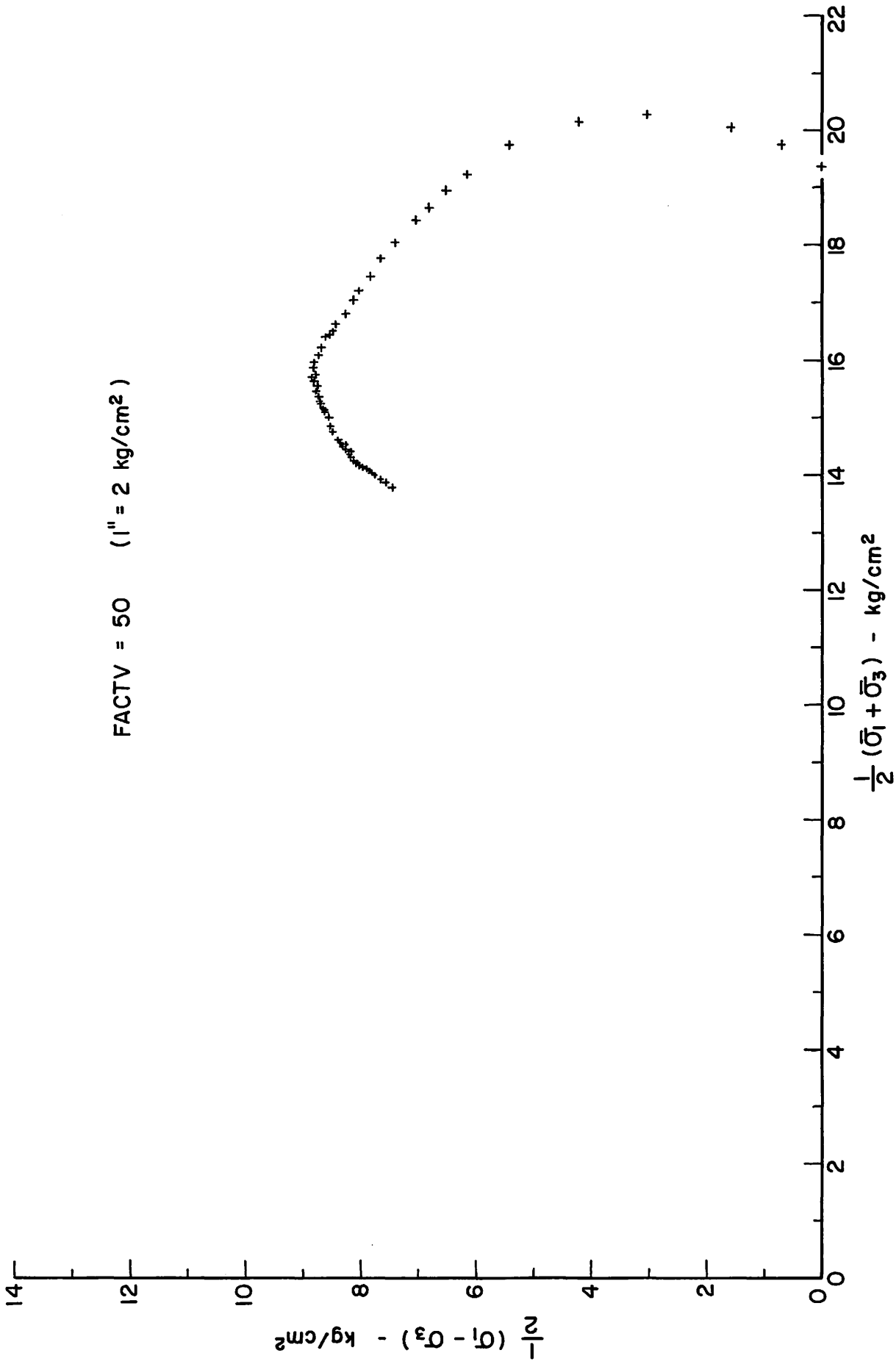
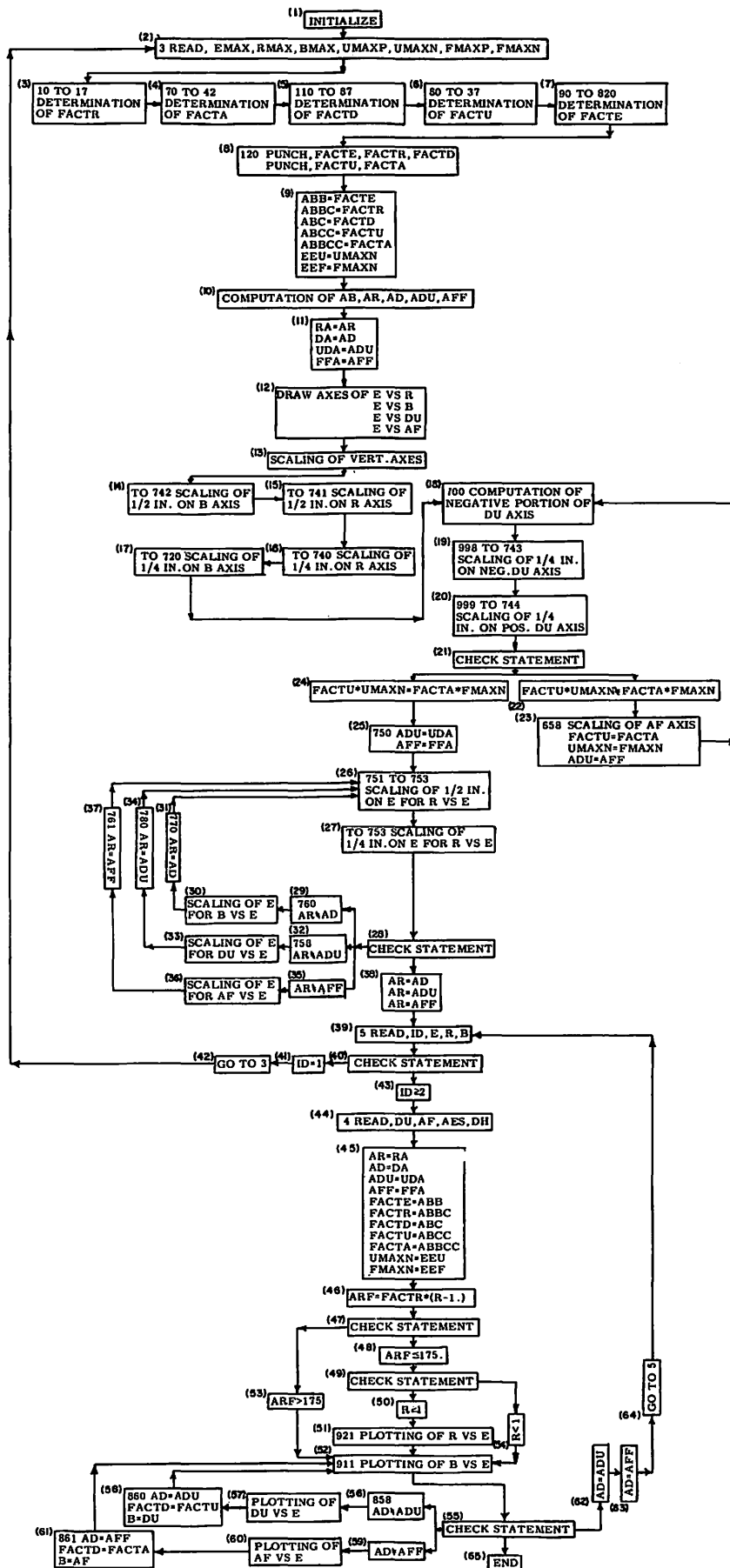


FIGURE II-2 EXAMPLE OF TRIAXIAL TEST EFFECTIVE STRESS PATH AS PLOTTED BY COMPUTER

FIGURE II-3 FLOW CHART FOR COMPUTATIONS OF TRIAXIAL TEST RESULTS AND THE PLOTTING OF OBLIQUITY, STRESS DIFFERENCE, PORE PRESSURE CHANGE AND λ FACTOR VS STRAIN



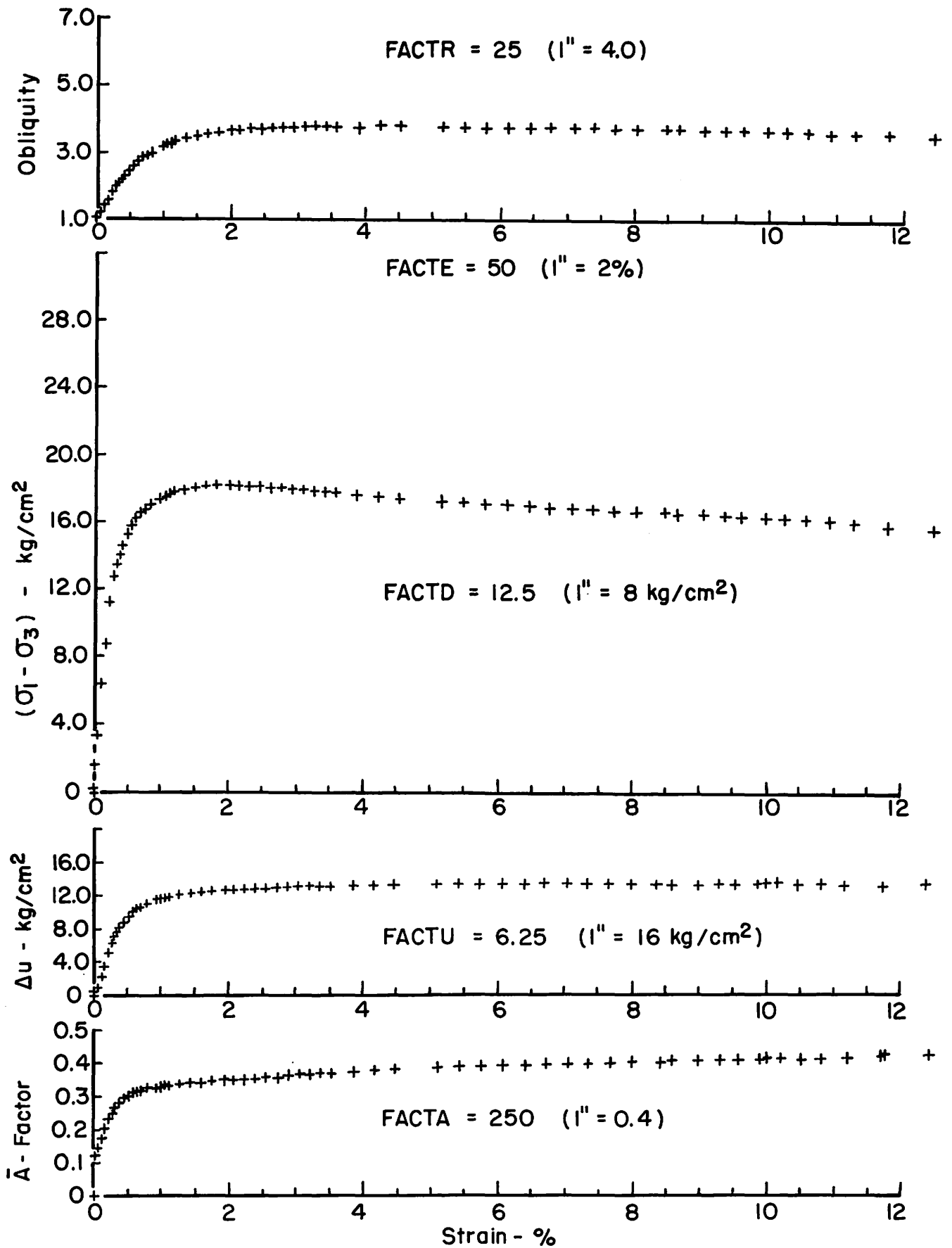


FIGURE II-4 EXAMPLE OF TRIAXIAL TEST STRESS-STRAIN CURVES AS PLOTTED BY COMPUTER

APPENDIX I

A. DEAIRING OF PORE PRESSURE LINES

Before mounting a test specimen in a triaxial cell the pore pressure lines are flushed with deaired water to get rid of any entrapped air. The procedures for the low pressure and high pressure systems are as follows:

1. Low Pressure System (Fig. I-1)

- a. Fill screw pump P with freshly deaired water* from reservoir P_{w1} by closing valve P_3 and opening P_5 . Draw in water with screw pump P until full. Close valve P_5 .
- b. With top of triaxial cell removed, open valves P_3 , P_2 , P_6 and P_7 . Flush line using screw pump P. Valve P_6 should always be kept open, except when pore pressures are being measured to prevent any accidental flow of mercury out of the null indicator. Close valves P_2 , P_3 and P_7 .
- c. Refill screw pump P.
- d. Open valve P_8 and flush pore pressure line with deaired water from P_{w2} by gravity flow. Close P_8 .

*Water is deaired by boiling under a vacuum for about half an hour at 60° to 70°C.

2. High Pressure System (Fig. I-2)

- a. Fill screw pump B with freshly deaired water from reservoir B_w by closing valve B_5 and opening valve B_7 . Draw in water with screw pump B until full. Close B_7 .
- b. With top of triaxial cell in place fill cell chamber with deaired water from reservoir C_w by opening valve C_1 and vent valve C_3 with C_2 closed. When chamber is full close C_1 and C_3 .
- c. Open valves B_5, B_6, B_9, B_{10} with all other B valves closed. Open transducer vent on low pressure side of diaphragm (B_{11}) and flush pore pressure lines using screw pump B. Close transducer vent B_{11} and all other B valves.
- d. Empty cell chamber into reservoir C_w by lowering C_w below elevation of cell and opening C_1 and C_3 . When empty close valve C_1 and raise C_w back to its original elevation above the cell.

B. MOUNTING OF TEST SPECIMEN IN TRIAXIAL CELL

1. Samples at Low Confining Pressures

- a. Coat sides of top loading cap and base pedestal with silicone grease.
- b. Unroll about one inch of each of two rubber prophylactic membranes and cut off closed ends. Attach the two unrolled ends of the membranes concentrically to the base pedestal of the cell with at least two neoprene O-rings.

- c. Place saturated porous stone* on pedestal and test specimen on top of stone.
 - d. Soak eight 1/4 in. wide by 3 1/2 in. long Whatman's No. 54 filter paper strips in deaired water, (do not boil strips). Place filter strips, equally spaced, vertically around sample. Make sure lower ends of filter strips are in contact with porous stone.
 - e. Place top loading cap on sample.
 - f. Roll up inner membrane and coat with silicone grease.
 - g. Roll up outer membrane over inner membrane and seal the membranes to the top cap with at least two neoprene O-rings.
2. Samples at High Confining Pressures
- a. Coat sides of top loading cap and base pedestal with silicone grease.
 - b. Place 0.1 cm thick 1.5 cm long rubber sleeves on top cap and base pedestal and then bend back about half length of sleeves. Position sleeves such that when turned back they will cover 0.2 cm of test specimen.
 - c. Place saturated porous stone on base pedestal and test specimen on top of stone. Place top loading cap on top of specimen.

*The 150 KV porous stones 0.2 inches thick are saturated by submerging in water and boiling under a vacuum for about half an hour.

- d. Place eight filters around sample in exactly same way as for low pressure specimens.
- e. Turn back both the top and bottom rubber sleeves and make sure the filter strips are still in place. Readjust strips if necessary. (Rubber sleeve at bottom should be covering a small length of the samples as well as the porous stone and part of the pedestal).
- f. Place 0.01 in. thick isoprene rubber membrane around specimen using a suction sleeve stretcher. The membrane must be long enough to cover the top cap and base pedestal beyond the rubber sleeves.
- g. Seal membrane to pedestal and cap beyond the rubber sleeves with three O-rings top and bottom.

C. CONSOLIDATION AND SATURATION

1. Samples at Low Confining Pressures (Fig. I-1)

- a. Assemble triaxial cell in compression test machine with top of cell and loading ram in place. Make sure proving ring is directly above and nearly in contact with the loading ram.
- b. Open valve C_{11} and vent valve C_{10} and fill triaxial chamber to about one centimeter from top of cell with deaired water from reservoir C_w . Close C_{11} . Fill remainder of cell chamber with Teresso 85 oil through vent at top of cell (not shown in Fig. I-1). Close oil vent and valve C_{10} .

- c. Check the cell pressure self compensating mercury control. If most of the mercury is in the lower pots pump the mercury back up into the upper pots as follows:
- (1) Fill screw pump C with freshly deaired water from reservoir C_w by closing valve C_5 and opening valve C_7 . Draw water into screw pump until full. Close C_7 .
 - (2) If both upper pots are low on mercury open valves C_5 , C_8 , C_4 and C_2 keeping valves C_7 , C_3 , C_6 and C_1 closed. Force water into lower pots using screw pump C which will in turn force mercury up into the upper pots. Continue until about one centimeter of mercury remains in lower pots. Stop pumping and close all C valves.
- d. Adjust self compensating mercury control to desired pressure. For the low pressure range, (0 to 80 psi), open valves C_8 , C_3 and C_1 and adjust the height of the movable upper mercury pot to give the required pressure reading on the 0 to 160 psi test gauge. For the high pressure range, (80 to 160 psi), close C_3 then open C_2 and C_4 as well as C_8 and C_1 . (This puts the fixed upper mercury pot in series with the movable upper pot). Adjust the height of the movable upper pot to give the required pressure.
- e. Check the backpressure self compensating mercury control. This is done in exactly the same way as for the cell pressure mercury control (Step c above), except the B valves are used instead of the C valves. (Note the B valves are numbered in exactly the same order as the C valves in Fig. I-1).

- f. Adjust the backpressure self compensating mercury control to the desired pressure in exactly the same way as outlined in Step d above.
 - g. Open valves B_6 , P_4 , P_2 and C_6 , (P_6 should be already open). Open valves P_7 and C_9 simultaneously so as to apply both the cell pressure and backpressure at the same time.
 - h. After consolidation against the backpressure for 24 hours flush pore pressure lines by opening valve P_8 until no further air bubbles come out through it. Close P_8 . (This usually takes about 10 seconds and 20 cc of flow).*
 - i. If another increment of consolidation pressure is to be applied, close valve C_9 and adjust the self compensating mercury control to the new cell pressure. Reopen C_9 .
2. Samples at High Confining Pressures (Fig. I-2)
 - a. Assemble cell carefully in compression test machine as for the low pressure samples.
 - b. Open valves C_1 , C_2 , C_3 and C_4 and fill by gravity the triaxial cell chamber with deaired water from reservoir C_w . Close valve C_3 when water starts coming out of it. When water starts to flow out of C_4 close C_1 and C_2 then C_4 . The cell chamber and nitrogen-water interchange are now full of water.
 - c. Check and adjust the self compensating mercury control to required backpressure. (See Steps c and d of low pressure above).

*Most of the backpressure remains so that essentially no consolidation occurs during this short time.

- d. Open nitrogen tank and adjust pressure regulator to desired cell pressure using the 8-inch test gauge C, (range 0 to 1000 psig).
- e. Open valves C₂ and B₉ simultaneously and allow test specimen to consolidate against the backpressure.
- f. After consolidation for 24 hours flush pore pressure lines by opening transducer vent B₁₁ until no further air bubbles come out with the water. Close vent B₁₁.
- g. If another increment of consolidation pressure is to be applied close valve C₂ and increase cell pressure to desired value using the regulator. Reopen C₂ to allow consolidation to proceed.

D. CHECKING OF PORE PRESSURE MEASURING EQUIPMENT

1. Low Pressure System with Mercury Null Indicator (Fig. I-1)

a. Check null indicator for excessive flexibility as follows:

- (1) Close valves P₇ and P₄ and open valves P₃ and P₂. (P₆ should be open at all times except while pore pressures are being measured).
- (2) Reduce pressure in null indicator to zero gauge using screw pump P.
- (3) Close P₆ and note level of mercury column on cell side of U-tube of null indicator.
- (4) Increase pressure in null system from 0 to 100 psi with screw pump P and measure movement of mercury in column on cell side of U-tube of null indicator.

- (5) An upward movement larger than $1/4$ in. of the mercury in column on cell side of U-tube of null indicator indicates air in the pore pressure line joining the cell to mercury null indicator which must be flushed out.
 - (6) Open P_6 , close P_3 and open P_4 to self compensating mercury control, then open P_7 .
 - (7) To flush line open P_8 . After flushing check flexibility again by repeating steps (1) through (6) above.
- b. Check null indicator for leaks as follows:
- (1) Close valves P_6 and P_7 with P_4 open.
 - (2) Note any movement of the mercury in column on cell side of U-tube for at least one hour.
 - (3) An upward movement of mercury in column indicates an external leak in the pore pressure line and/or valves between the mercury null indicator and cell base which must be repaired before running the test.
- c. Check for membrane leakage as follows:
- (1) With P_4 open and P_6 closed, open P_7 and note any movement of mercury in U-tube of null indicator for at least one hour. There should be essentially no movement, (less than 0.05 in/hr*).
 - (2) A downward movement of mercury in column on cell side of U-tube can be either due to incomplete consolidation or membrane leakage.

*A movement of 0.05 in/hr corresponds to 0.001 cc/hour.

- (3) Allow sample to consolidate for further 24 hours during which time flow out of sample should decrease considerably if due to incomplete consolidation.
 - (4) If flow rate does not decrease then must be due to membrane leakage and sample will have to be dismantled.
- d. Check pore pressure response as follows:
- (1) Open P_3 and close P_4 and P_6 . Note level of mercury column on cell side of U-tube of null indicator.
 - (2) Open C_5 . Close C_8 , C_4 and C_2 . Gradually raise cell pressure by 10 psi with screw pump C.
 - (3) As cell pressure is raised keep mercury level constant on cell side of U-tube of null indicator by adjusting pressure on back-pressure side of U-tube with screw pump P.
 - (4) Maintain 10 psi increment of cell pressure with screw pump C and keep mercury level in null indicator with screw pump P. After one minute read pore pressure with test gauge directly above P_1 .
 - (5) For an increment of cell pressure of 10 psi the pore pressure as read on the test gauge should increase by at least 9 psi in one minute. (i.e., pore pressure response of at least 90% in one minute).
 - (6) A pore pressure response of less than 90% very likely indicates incomplete saturation of sample and/or air in the pore pressure line.
 - (7) If pore pressure response is less than 90% gradually lower cell pressure to initial value (decrease by 10 psi) with screw pump C while maintaining mercury null indicator balanced (i.e., keeping

mercury level on cell side of U-tube at constant level) with screw pump P. Open P_6 and close C_5 . Open C_8 , C_4 , C_2 and P_4 . This puts the cell pressure and backpressure onto the self compensating mercury controls at their original magnitudes. Now flush pore pressure lines by opening P_8 . (In addition to flushing it is desirable if possible to increase cell pressure and backpressure by an equal increment.)

- (8) Allow to equilibrate for 24 hours before measuring pore pressure response again.
- (9) Continue flushing pore pressure lines every 24 hours until at least 90% pore pressure response is attained.

2. High Pressure System with Pressure Transducer (Fig. 1-2)

a. Calibrate differential pressure transducer against test gauge C as follows:

- (1) Close valves C_2 , B_{10} and pressure regulator. Open B_{11} to reduce to atmospheric water pressure on low pressure side of transducer. Open vent C_4 to reduce nitrogen pressure on high pressure side of transducer to atmospheric. The differential pressure across the transducer is now zero.
- (2) Adjust magnification of X-Y recorder to give approximately one inch per 50 psi differential by noting zero pressure reading on recorder, closing valve C_4 and applying a nitrogen pressure of 500 psi measured on test gauge C. Adjust magnification of recorder so that difference between reading at 500 psi and zero is exactly 10 inches.

- (3) Reduce nitrogen pressure to zero by closing regulator and opening C_4 . The zero pressure reading will have changed since the magnification of the recorder has been altered. Reset zero reading using the zero adjust of the recorder (do not touch magnification).
 - (4) Close valve C_4 . Apply nitrogen pressure in increments of 50 psi and measure corresponding output signals from transducer. Repeat calibration at least twice for both increasing and decreasing pressures.
 - (5) After calibrating transducer check voltage of d.c. supply by measuring the voltage drop across a standard resistance using the X-Y recorder as adjusted for the transducer. (This requires a standard resistance which will give a voltage drop within the range of the output voltages from the transducer).
 - (6) Close B_{11} and C_4 . Adjust pressure regulator to cell pressure. Open C_2 and B_{10} .
- b. Check for membrane leakage as follows
- (1) Close B_9 and take transducer reading on recorder.
 - (2) After at least one hour take another reading. There should be essentially no change in the transducer reading. (Small changes can be caused by cell pressure or d.c. excitation voltage fluctuations).
 - (3) A drop in the transducer reading (increase in pore pressure) can be either due to incomplete consolidation or membrane leakage. An increase in the transducer reading is due to a leak in the pore pressure lines which must be repaired.
 - (4) If there was a drop in transducer reading open B_9 and allow sample to consolidate for further 24 hours.

d. Check pore pressure response as follows:

- (1) Close valve B_9 and increase cell pressure in five increments of 20 psi each, noting the change in transducer reading for each increment.*
- (2) Compute the pore pressure response for each increment of cell pressure. If the system is saturated the pore pressure response will remain constant with increasing pressure.**
- (3) If the pore pressure response increases with increasing cell pressure the system is not saturated and must be flushed and if possible the backpressure increased. Do not forget to lower the cell pressure to its original value before flushing.
- (4) After flushing and/or increasing the backpressure allow sample to equilibrate for 24 hours before checking the response again.

E. SHEARING OF TEST SPECIMENS

1. Samples at Low Confining Pressures (Fig. I-1)

- a. Shift gears of compression test machine to obtain desired rate of feed.
- b. With clutch out bring loading ram in contact with top loading cap using the fine manual feed on the compression test machine. When contact is made the proving ring dial will start increasing smoothly.
- c. Open P_3 . Close backpressure with P_4 and close null indicator bypass with P_6 . These two valves must remain closed throughout the test.

*For a pore pressure response of 100% there is no change in reading.

**This is due to the fact that the compressibility of water is essentially constant over the range of pore pressures involved. For a partially saturated system the compressibility of the pore fluid decreases with increasing pore pressure because the compressibility of air decreases with increasing pressure.

- d. Switch on motor of compression test machine and push in clutch when ready to start shearing.
 - e. Keep level of mercury column in U-tube on side connecting to cell constant throughout the test by adjusting the pressure on the other side of the U-tube with screw pump P.
 - f. Take pore pressure readings with test gauge above valve P_1 , axial load readings with proving ring dial and axial deformations with Ames dial attached to loading ram.
 - g. When failure is reached close P_7 and unload using the coarse manual feed of the compression test machine. Close C_9 before draining cell chamber through C_{11} .
2. Samples at High Confining Pressures (Fig. I-2)
- a. Shift gears of compression test machine to obtain desired rate of feed.
 - b. With clutch out bring loading ram in contact with top loading cap using the fine manual feed on the compression test machine. When contact is made the proving ring dial will start increasing smoothly.
 - c. Close off backpressure with B_9 and keep this valve closed throughout test.
 - d. Switch on motor of compression test machine and push in clutch when ready to start shearing.
 - e. Take transducer readings with recorder, axial load readings with proving ring dial and axial deformations with Ames dial attached to loading ram.

- f. When failure is reached unload test specimen using the coarse feed of the compression test machine.
- g. Close nitrogen tank supply using pressure regulator. Then release cell pressure and empty cell chamber by gradually opening C_1 .
- h. After dismounting sample check zero output of transducer (i. e., output at zero pressure differential) and d. c. excitation voltage. If zero has shifted or the voltage changed re-calibrate transducer without altering zero or magnification of recorder. Use the new calibration for computing results.