Final Report

APPARATUS FOR COMPRESSION TESTING OF HOLLOW-CYLINDER SOIL SAMPLES UNDER DIFFERENTIAL CONFINING PRESSURE

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INTRODUCTION

This report describes the component parts and operation of an apparatus designed for compression tests on hollow, cylindrical soil samples under differential inside and outside confining pressures. With this apparatus it is possible to monitor the stress distribution at the base of hollow-cylinder soil samples subjected to triaxial compression. The stress distribution is recorded by means of a pressure sensitive pedestal consisting of concentric rings each of which acts as an independent load cell.

The apparatus was designed in order to test the applicability of the theory of ideally plastic bodies to soils. The initial design and development was carried out in the Soil Mechanics Laboratory at The University of Michigan. The apparatus has been used for preliminary tests on hollow-cylinder samples of a medium-grained, Ottawa sand.

In addition to describing the design of the apparatus itself, steps in sample preparation and conduct of a typical hollow-cylinder compression test are also outlined. The report concludes with an evaluation of the performance of the apparatus, notes deficiencies in present design or testing procedure, and recommends appropriate modifications for future testing.

DESCRIPTION OF APPARATUS

1. GENERAL FEATURES OF TEST SETUP

A schematic drawing of the general layout is shown in Figure 1. Various features of the hollow-cylinder apparatus and ancillary test equipment are shown in Figures 5-7 at the end of the report. The Soil Mechanics Laboratory at The University of Michigan is equipped with Norwegian (Geonor) triaxial testing equipment. It was convenient, therefore, to adapt this equipment to the hollow-cylinder testing program whenever possible. The Norwegian triaxial equipment is described in detail elsewhere.[1]

The test setup basically consists of a triaxial cell (A) containing a hollow, cylindrical soil specimen (B) which rests on a "pressure sensitive" pedestal (C). Axial load to the sample is applied through a plunger passing through the triaxial cell and bearing against a proving ring (D). The proving ring in turn bears against a yoke or loading frame (E) at the top. The axial load itself comes from a gear motor (F) which drives a table (G), on which the triaxial cell rests, up against the loading frame at a constant rate of strain. Two consolidation units, each consisting of a constant pressure cell (H), a Bourdon gauge (I), an oil-water interface cell (J), a fluid reservoir (K), and the necessary connections and valves, provide the desired inside and outside cell pressures. The internal void space of the sample can be vented to the atmosphere or connected to a vacuum pump. If so desired, the sample can be saturated and the internal pore pressure recorded by means of a pressure transducer (L). The output from the pedestal unit (consisting of concentric rings each acting as a load cell) is recorded by means of a multichannel, digital strain indicator (M).

2. THE TRIAXIAL CELL

A triaxial cell was designed in which hollow-cylinder samples could be subjected to differential confining pressures, i.e., two pressures of different magnitude—one acting on the outside, circumferential area of the sample and the other, on the inside, annular area. Simultaneously, it was possible to subject the specimen to axial load.

The minimum size of the cell was determined by the dimensions of the sample and pedestal unit. The maximum size was limited by the width of the Geonor

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[1] A. Anderson and N. E. Simons, "Norwegian Triaxial Equipment," Proc., Research Conference on Shear Strength of Cohesive Soils, ASCE, Boulder, Colorado (1960), p. 695.

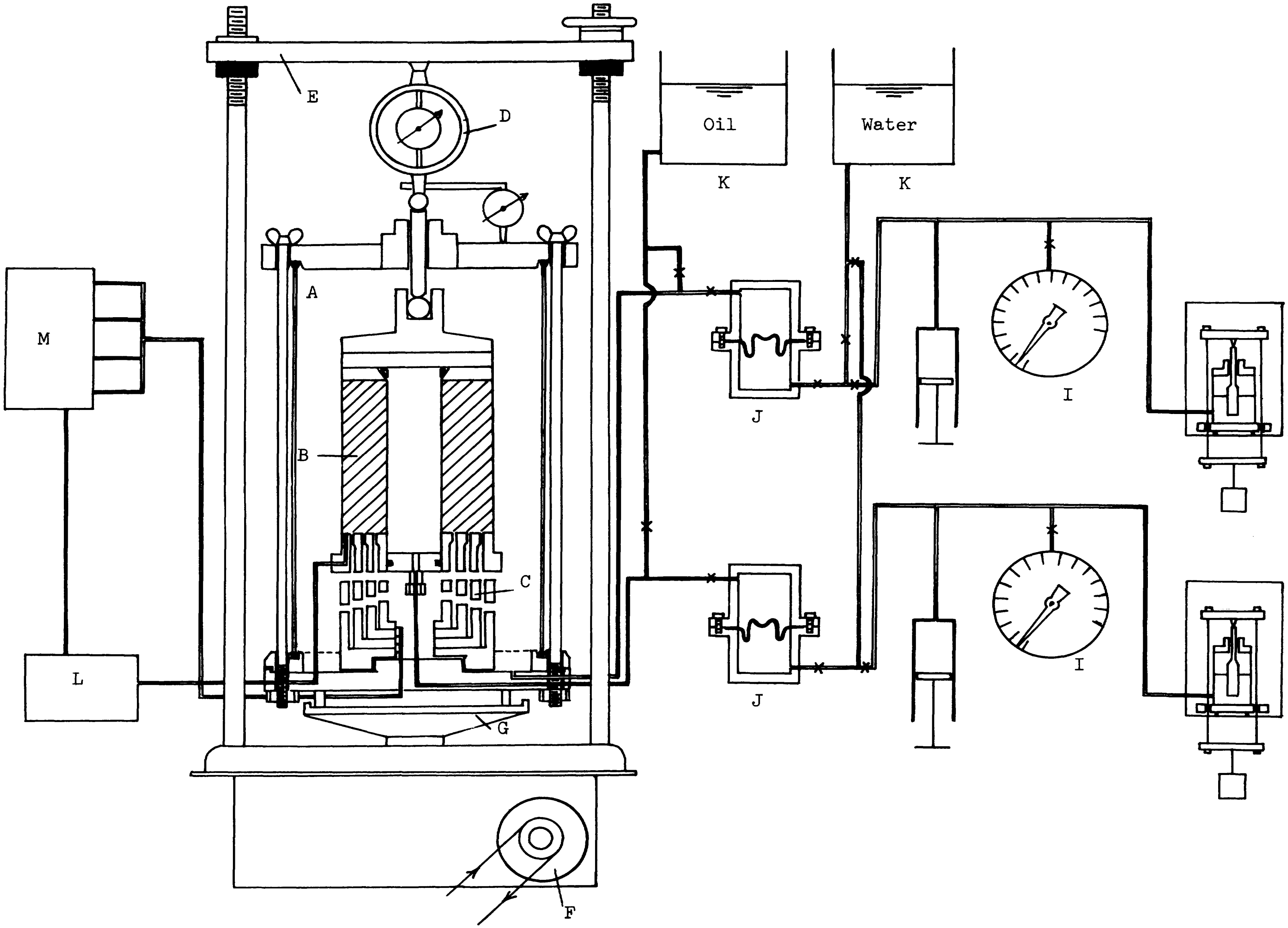

Figure 1. Schematic diagram of hollow-cylinder apparatus and test equipment.

loading frame and driving table.

The triaxial cell itself is made up of several parts: base plate, top plate and bushing assembly, cylindrical shell, and pedestal unit. The base plate consists of two pieces and supports the pedestal on which the hollow-cylinder sample is mounted. The upper plate contains a bushing through which the axial load piston passes. The two plates are separated by a clear, Plexiglas cylinder (cast acrylic, 7 in. O.D., 1/4 in. thick). This whole assembly is bolted together by four threaded, steel rods (3/8 in. O.D.) and large wing nuts. The Plexiglas cylinder is sealed against O-rings in circular grooves machined in both top and bottom plates. This cylinder can safely withstand internal cell pressures up to 80 psig. The base plate has three access ports: one for the inside confining (cell) pressure, another for the outside confining pressure, and the third one for application of vacuum or measurement of internal pore pressure. The top plate has an air bleed valve to permit filling of the cell. The total height of the cell including bushing and legs is approximately 19 in.

The stainless steel piston through which the load is applied has a diameter of 5/8 in. and a length of 10 in. The bushing through which the piston passes contains two Thompson A-101824 ball bushings. An O-ring located between these ball bushings seals the cell fluid from the outside. This O-ring tends to cause an undesirable amount of friction on the piston and should be replaced by a Quad-ring seal for future testing. The bottom end of the piston seats in a loading-cap made out of Plexiglas. The load is applied through a stainless steel ball resting on a metal bearing ring in the loading cap. The total applied load is measured by a Karol-Warner proving ring. This proving ring has a sensitivity of 6.57 lb/division and a capacity of 2500 lb.

The axial deformation of the sample is measured by a dial gage (sensitivity 0.01 mm/division).

The pressure sensitive pedestal consists of four concentric, cylindrical units as shown in Figure 2. Each of these units acts as an independent load cell. In this case, the stress sensing element is a short, curved beam instrumented with strain gages at the locations of highest tension and compression. All strain gages are miniature, bonded type gages[2] with a gage factor of 2.00 and a resistance of 120 ohms. The gages on each of the three outer units are connected to form a four-arm bridge circuit; those of the innermost unit form a two-arm bridge. The strain gage circuitry is shown schematically in Figure 3. The wires from each unit are brought out of the triaxial cell through four individual tube fittings in the bottom plate. The four wires can then be connected to a multichannel digital strain recorder. A Datron-Alinco Digital strain

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[2] Type EA-06-062ED-120, manufactured by Micromeasurements, Inc., Romulus, Michigan.

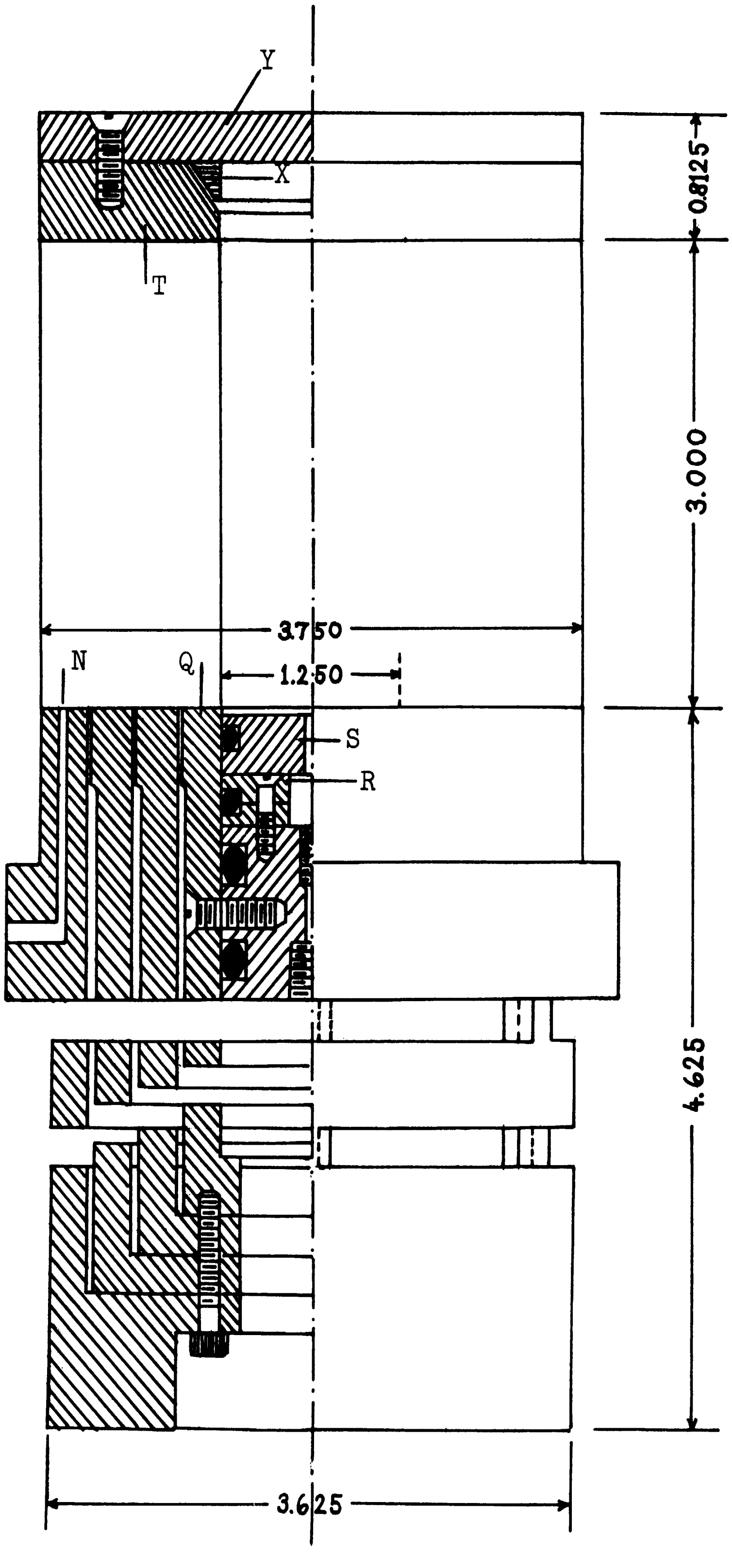

Figure 2. Details of pedestal unit and sample top cap.

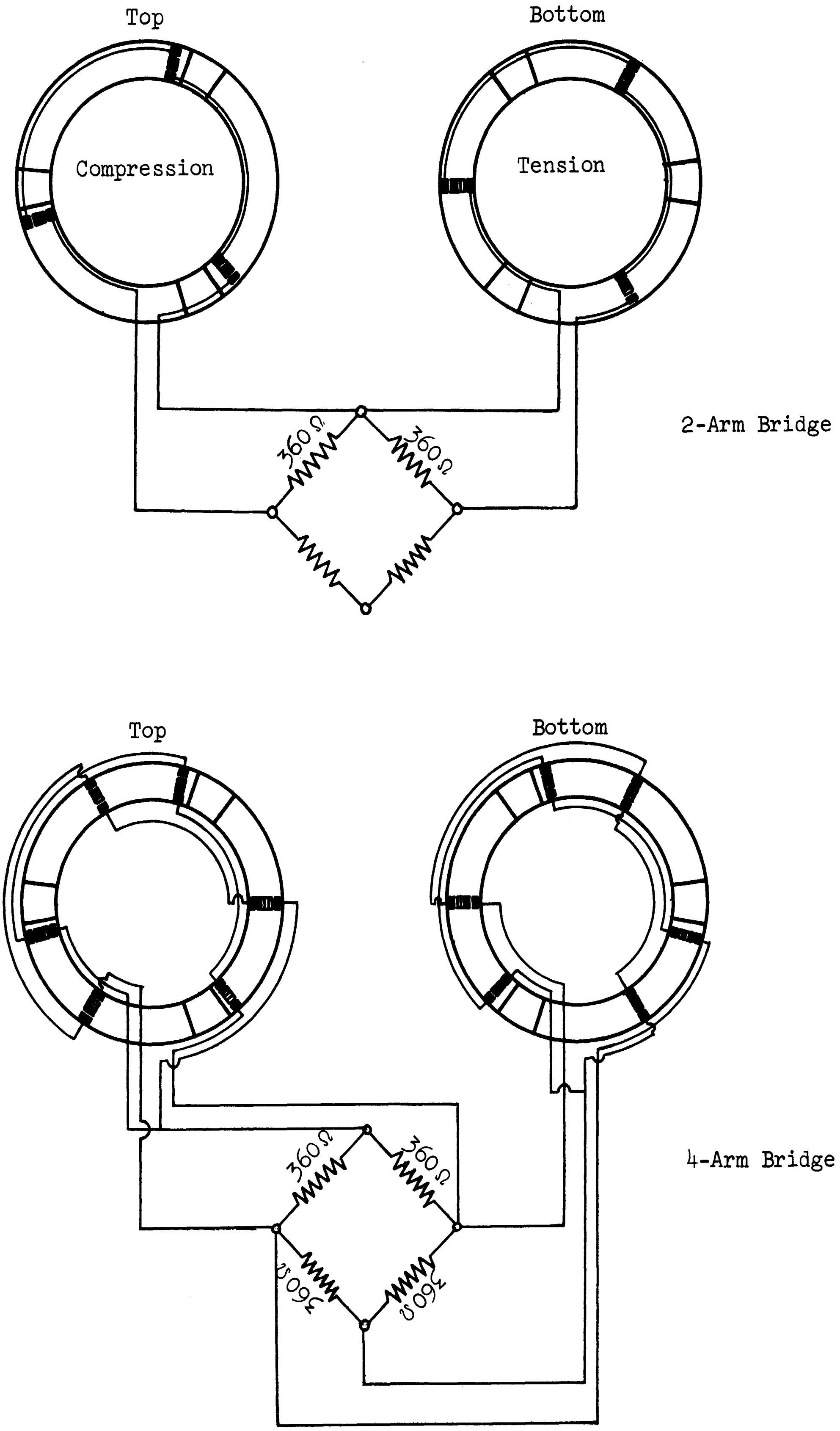

Figure 3. Strain gage circuits for load cell rings.

indicator[3] was employed for this purpose. The performance of this particular unit, however, was not entirely satisfactory. Each ring of the pedestal was individually calibrated on a Tinius Olsen universal testing machine; a strain-load calibration curve was thus obtained. All four calibration curves were essentially linear. The sensitivity of the load cell units varied between 1.067 and 1.667 μ in./in.-lb.

The units were designed so that equal pressure on them produced equal axial deformations. This was achieved by varying the thickness (height) of the curved beam. In order to satisfy this requirement the height of the beam (t) must be related to the radius (R) of the ring by, $t \alpha R^{4/3}$. The four units were tested together by means of a specially designed cap which made it possible to apply a uniform fluid pressure in the Tinius Olsen press as shown schematically in Figure 4. The response of the individual units when tested together in this manner was found to be almost identical to their individual calibration curves; this proves that little or no friction occurs between the rings which are spaced apart from one another by only .004 in. The arrangement of the pedestal into four individual parts permits measurement not only of the radial distribution of axial pressure on the base of specimens but also allows the construction of samples with four different thickness ratios.[4] For example, the inner units can be removed gradually, thus increasing the inside diameter and reducing the annular thickness of the sample. At its top the largest unit has an outside diameter of 3.750 in. and the smallest unit has an inside diameter of 1.250 in. Each unit has a thickness of 5/16 in. at its top. This makes it possible to build four different samples with the following thickness ratios: $\beta_1 = 0.333$, $\beta_2 = 0.500$, $\beta_3 = 0.667$, and $\beta_4 = 0.833$. The outermost unit contains two diametrically opposed pressure ports which make it possible to apply a vacuum to the interior of the sample or to measure pore pressures within the sample. The initial height of the hollow sample can be varied from 2 to 4 in. During preliminary testing 3-in. high samples were used.

3. CONSTANT PRESSURE CELL

The constant pressure cell and the screw control (with Bourdon gauge) form part of the standard Geonor equipment. Fluctuations in cell pressure (inside or outside) due to volume change of the sample, the triaxial cell, leakage, temperature variations, or movement of the piston within the triaxial cell, are prevented by the compensating displacement of a hydraulic piston in the constant pressure cell. The unit is basically a closed hydraulic system connected to the triaxial cell. The required cell pressure is obtained by applying weights to

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[3] Allegany Instrument Company, Division of Textron Electronics.

[4] The thickness ratio, β, is the ratio of inside to outside diameter of the hollow-cylinder samples.

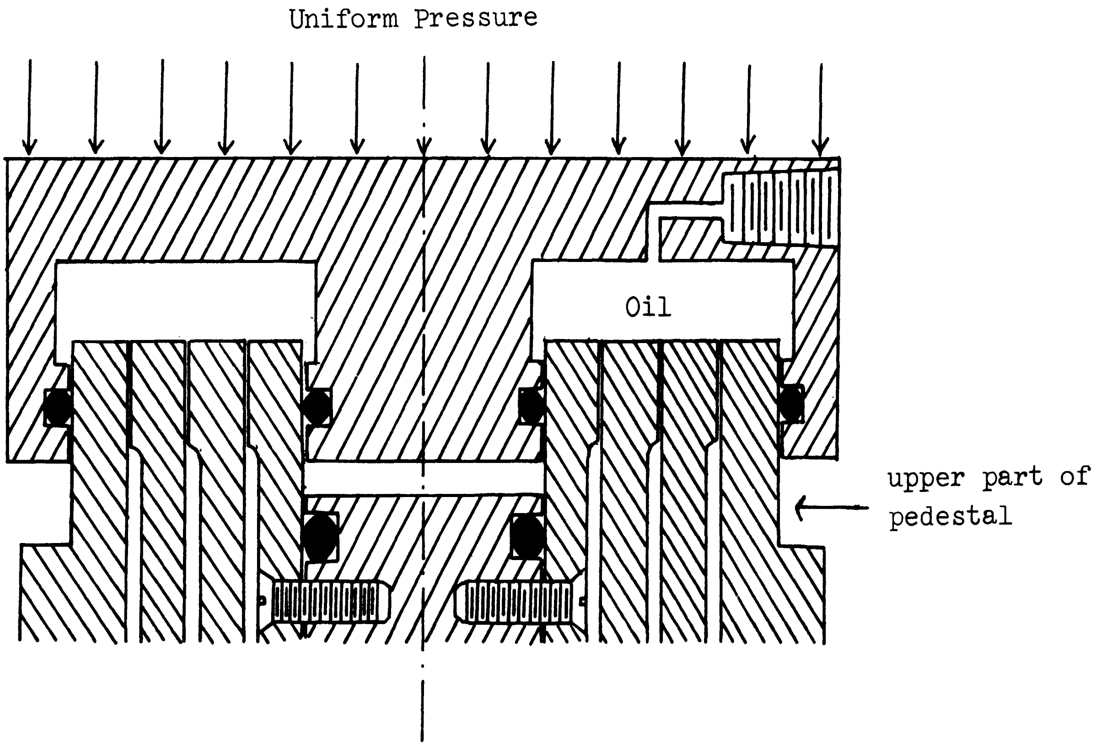

Figure 4. Stress calibration device for the pedestal unit.

the piston. The screw control is used to adjust the position of piston (by injecting or withdrawing fluid) in order that the piston does not reach the end of its travel. The tubing and valves belonging to the Geonor equipment are made out of copper and brass, respectively. Additional tubing required in the test setup was 1/4 in. O.D. polyethylene tubing. "Swagelok" tube fittings and "Hoke" needle valves were used in connecting these additional lines.

4. OIL-WATER INTERFACE

Mineral oil was used as a confining fluid in the triaxail cell so as to avoid potential trouble should the strain gages or their lead wires become exposed to the fluid. In order to use oil as a confining fluid it was necessary to modify the Geonor equipment slightly (it is designed for use with water as a confining fluid). This was done by interposing a flexible, rubber membrane between the oil in the triaxial cell and the water in the rest of the Geonor system. A Bellofram rubber membrane mounted in the middle of a Plexiglas cell served this purpose. Frictionless pressure transmission was achieved by this type of barrier or interface.

MEMBRANE FABRICATION AND SAMPLE PREPARATION

1. MEMBRANE FABRICATION

The hollow-cylinder samples must be confined between two rubber membranes. These membranes can be formed by dipping glass tubes of a certain diameter into liquid latex.[5] For the inside membrane, the glass tube should have an O.D. of approximately 30 mm and for the outside membrane, an O.D. of approximately 90 mm. In order to cover the top of the pedestal and seal the sample inside from the outer cell fluid, a special membrane must be made. This can be done by dipping a ring-shaped Plexiglas mold having exactly the dimensions of the upper part of the pedestal into liquid latex. The thickness of membranes fabricated in the above manner will vary between six- and twelve-thousandths of an inch.

2. SAMPLE PREPARATION

The base plate of the triaxial cell is first placed on the loading table of the Geonor press; the pedestal is then mounted and properly oriented on the base plate so that the strain gage lead wires can be connected to the terminal strips. The top of the pedestal is next covered with a thin layer of vacuum grease and then fitted with an annular membrane containing two minute holes. The membrane is positioned such that the holes are aligned with two drilled holes (N) in the outermost ring of the pedestal unit (refer to Figure 2). These latter holes, which provide pressure access to the interior of the sample, are threaded. A round-head screw with a hollow stem is inserted through the membrane and screwed into these holes. A 1/8-in. I.D. and 1/4-in. O.D. O-ring is inserted underneath the screw-head in order to insure a leakproof seal.

The inside membrane, cut to a length of approximately 6 in., is next anchored to the pedestal unit by means of a split-ring assembly (R), as shown in Figure 2. In order to insure against leakage an additional disc (S), girdled by an O-ring, is inserted which presses the membrane against the sides of the inner ring (Q) of the pedestal unit. Next a mandrel, consisting of two halves of a cylinder spaced by two brass discs, is positioned in the center of the pedestal and bolted into place. The rubber membrane is fitted over this making a form for the inside boundary of the sample. The outside membrane is fitted around the outside ring of the pedestal; an annular space between the inside and outside membranes is formed by sucking the outer membrane against the wall of a mold whose inside dimensions match the outside diameter of the sample. For this procedure a vacuum must be applied to the mold.

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[5] Latex LX-2560-B, Uniroyal Chemical, Division of Uniroyal Inc., 5901 Telegraph Road, Commerce, California 90022.

The soil to be tested is then placed into the annular space between the two membranes until it is flush with the top rim of the mold. In the case of dry, cohesionless sands, the sample density can be regulated by vibrating the sand during filling. After filling the lower ring (T) of the top cap assembly is placed on top of the sample, and the protruding part of the outside membrane is pulled up over the ring and coated with vacuum grease. A thin compression ring (X) with a wedge shaped cross section is slipped between the inside membrane and the mandrel. This ring seals the upper end of the inside membrane against the bottom ring (T) of the top cap assembly when the upper plate (Y) is screwed down on the ring.

The vacuum on the outside membrane can now be released; it must then be applied to the interior of the sample. An internal vacuum is equivalent to a confining pressure of approximately one atmosphere. If there is no leakage the sample becomes stable enough so that it can stand without the aid of the inside mandrel or the outside mold. The mandrel can then be unbolted and removed. The two halves of the outside mold are unclasped and also removed.

Before the upper plate (Y) of the top cap is screwed onto the bottom ring (T), the inside diameter of the sample must be measured if an exact void ratio determination is desired. When both parts of the top cap assembly are in place, two O-rings are fitted over the sample, one at the base, the other at the upper end in order to provide additional sealing. The outside diameter of the sample can also be determined. The sample (still under vacuum) is now ready for testing.

TEST PROCEDURE

There are several options for confining the hollow-cylinder samples under pressure. Differential, external fluid pressures can be applied or a test can be run with the sample under internal vacuum while the inside and outside fluid pressures are both atmospheric. Another possibility is to apply an outside fluid pressure greater than one atmosphere and maintain the inside (annular) pressure at one atmosphere. If the inside pressure is to be produced by a liquid, the annular volume of the hollow sample must be filled with the liquid before the upper part of the top cap is screwed on in such a way that no air is trapped inside.

The Plexiglas loading cap is placed on the top cap of the sample and the Plexiglas cylinder with the top plate of the triaxial cell is carefully put over the sample and fastened to the base plate by means of the four bolts and wing nuts. The cell can then be filled by opening the valves to the oil reservoir. Filling can be speeded by pouring the oil directly into the cell through the bushing in the top plate. The air outlet in the top plate has to be opened during this procedure.

When the cell is filled, the piston is inserted and the proving ring with dial gages is placed into position under the loading yoke. Contact between the loading piston and the proving ring is made by raising the loading table very carefully by hand. Weights are then put on the loading yokes of the constant pressure units to produce the desired inside and outside confining pressures on the sample. This is accomplished with the aid of the screw control; the triaxial cell meanwhile is still isolated from this pressuring system. The constant pressure cells are next coupled to the triaxial cell by closing the valves to the reservoirs and opening those to the triaxial cell.

The readings on all four channels of the strain recorder are set to zero. The test is now ready to start.

The driving motor is switched on; this raises the table at a constant, predetermined rate. Two people are required to run a test: one reads the load and displacement dial, the other monitors the corresponding output from the load cells in the pedestal unit which in turn is fed into a multichannel strain gage recorder. The test is terminated when the load starts decreasing under increasing strain.

EVALUATION OF APPARATUS AND RECOMMENDATIONS FOR FUTURE TESTS

One of the major problems encountered when preparing a sample for testing was leakage. Unfortunately, a leak can be detected only after a vacuum is applied to the sample interior. Even then it is not always possible to locate the source of the leak which might be caused, for example, by a pinhole in one of the membranes. If a leak does occur at this point, there is no alternative but to discard the sample and start over again.

Another problem, already mentioned earlier, is the friction of the loading piston against the O-ring in the bushing. It was observed that the magnitude of this friction amounts to about 5-10 percent of the total applied force. This O-ring should be replaced by a frictionless seal such as a Quad-ring.

Slow leakage of cell fluid under pressure through the vinyl conduit enclosing the strain gage wires was also a problem. Attempts to stop this leak with epoxy and rubber cement were not entirely satisfactory. The mineral oil has the disadvantage that the rubber membranes begin to swell after prolonged contact with the oil. Glycerin was also tried as a cell fluid; it did not affect the membranes, however, this caused electrical shorting in the strain gage circuits.

The following modifications and improvements in the pressuring system are also suggested:

1. A domed inlet to the air bleed valve in the top plate of the triaxial cell would facilitate the removal of air.

2. Air bleed valves should also be provided in the oil-water interface cells.

The lead wire connections to the strain gages mounted on the "pressure sensitive" pedestal unit are fragile; they should be handled with extreme care lest the soldered connections break.

The triaxial cell is designed for tests on short samples (i.e., height to diameter ratio less than two). In order to use the results of such tests for the theoretical analysis originally intended, it is necessary that the sample ends be "lubricated," i.e., unconstrained radially. If this condition is satisfied, then the stress-boundary conditions will be known at both ends. The top end of the sample will be subjected to a uniform pressure distribution. The pressure distribution at the lower end, on the other hand, should be nonuniform; it is measured by the concentric rings of the pedestal unit, each acting as an independent load cell. This measured stress distribution at the lower end in turn can be compared with the theoretically predicted stress distribution based on an assumed yield criteria for the material in question. "Lubricated" ends are made possible by inserting two rubber membranes with silicon grease in between them at both ends of the sample. For hollow-cylinder samples these membranes should have an annular shape.

During compression testing the samples not only deform but also tend to change volume. Sample volume change will be reflected by a movement of confining fluid into or out of the triaxial cell. In order to evaluate these volume changes, from which conclusions can be drawn about sample deformations, two volumeters should be inserted into the pressure lines leading to the triaxial cell. Further testing with the apparatus for this purpose will require the design and installation of these volumeters.

If the aforementioned suggestions and guidelines for future testing are followed, the hollow-cylinder apparatus should work quite satisfactorily and be a useful tool for studying the mechanics of granular media.

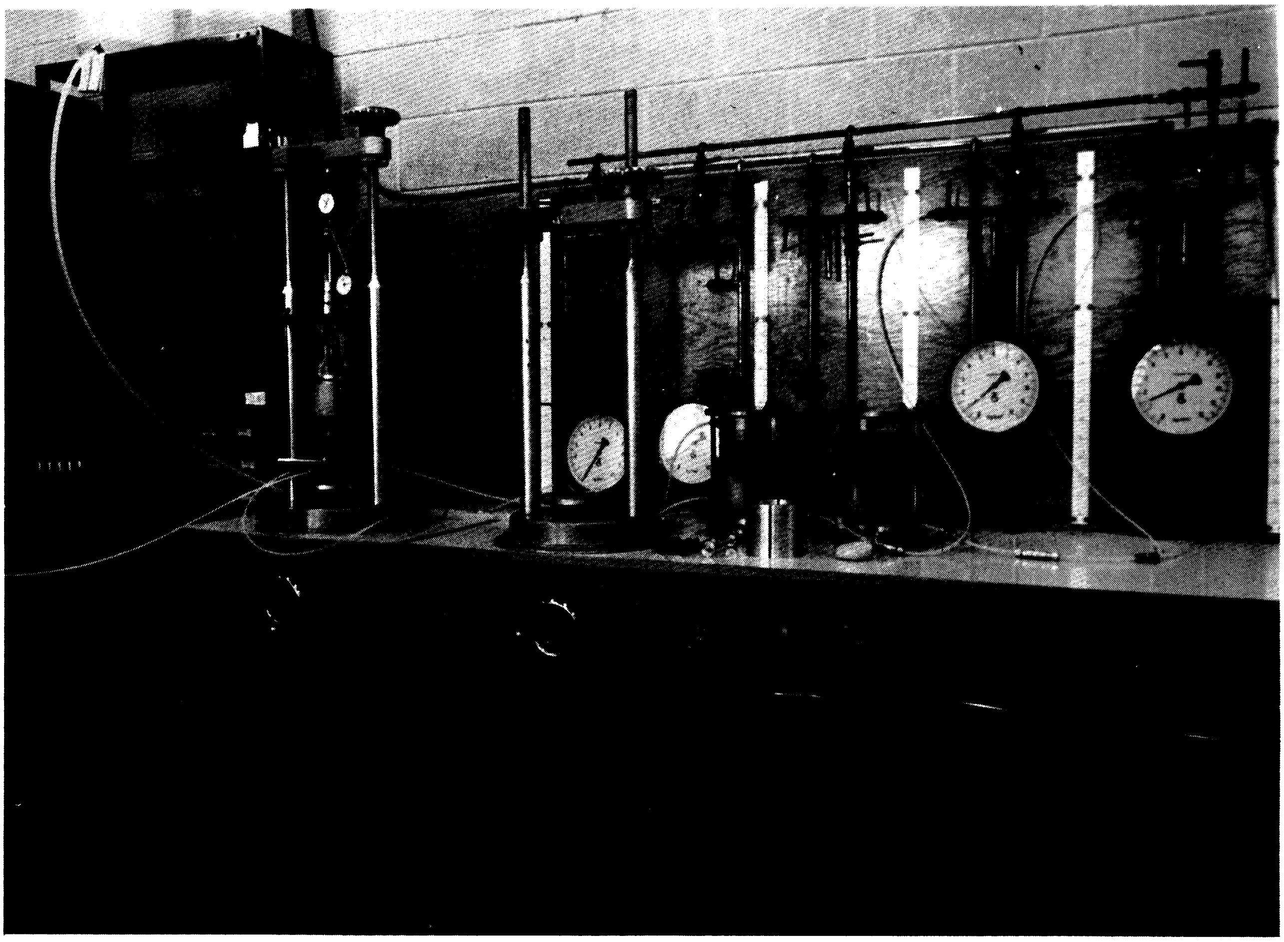

Figure 5. General view of triaxial cell and Geonor equipment.

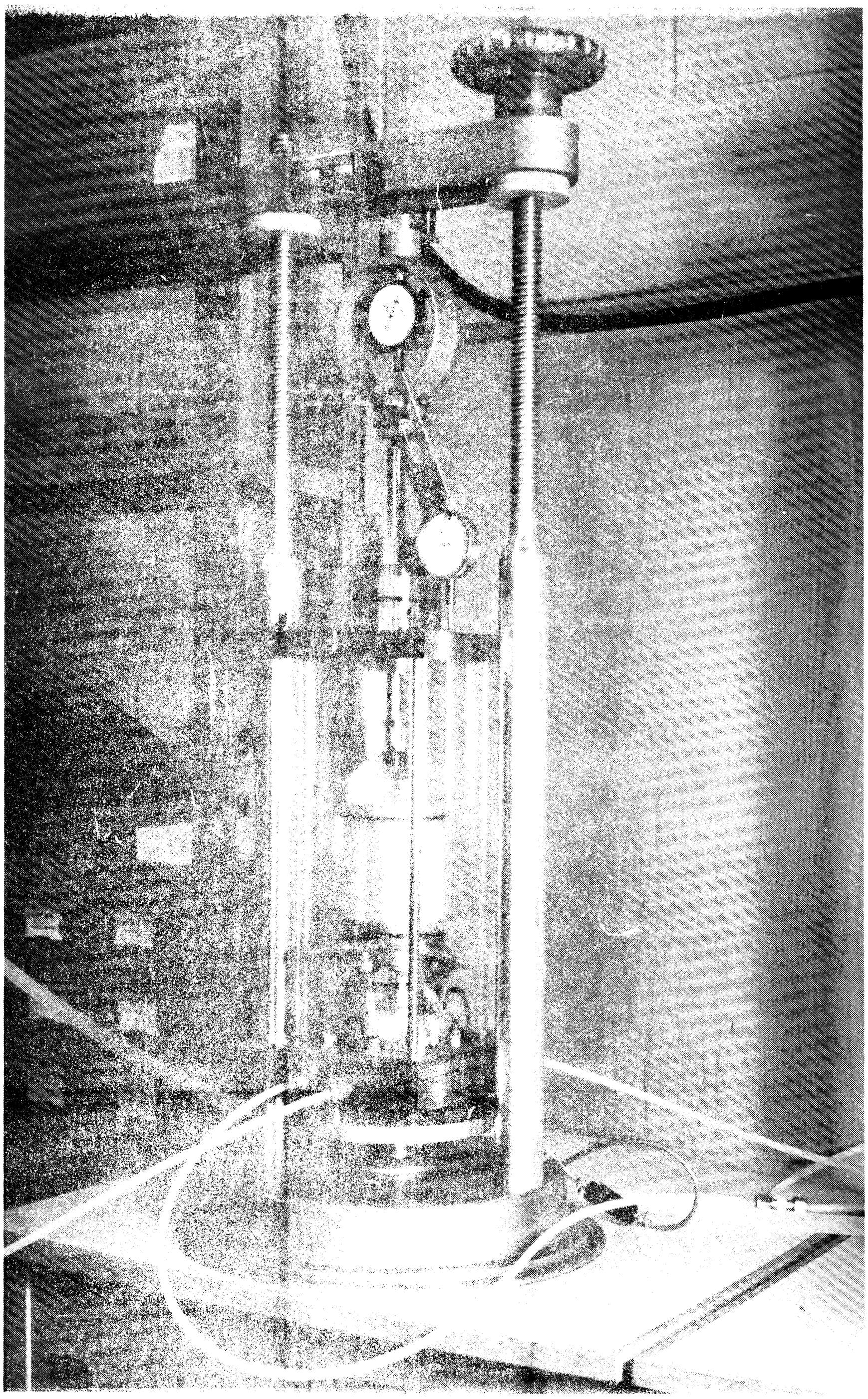

Figure [illegible]. Triaxial cell in loading frame.

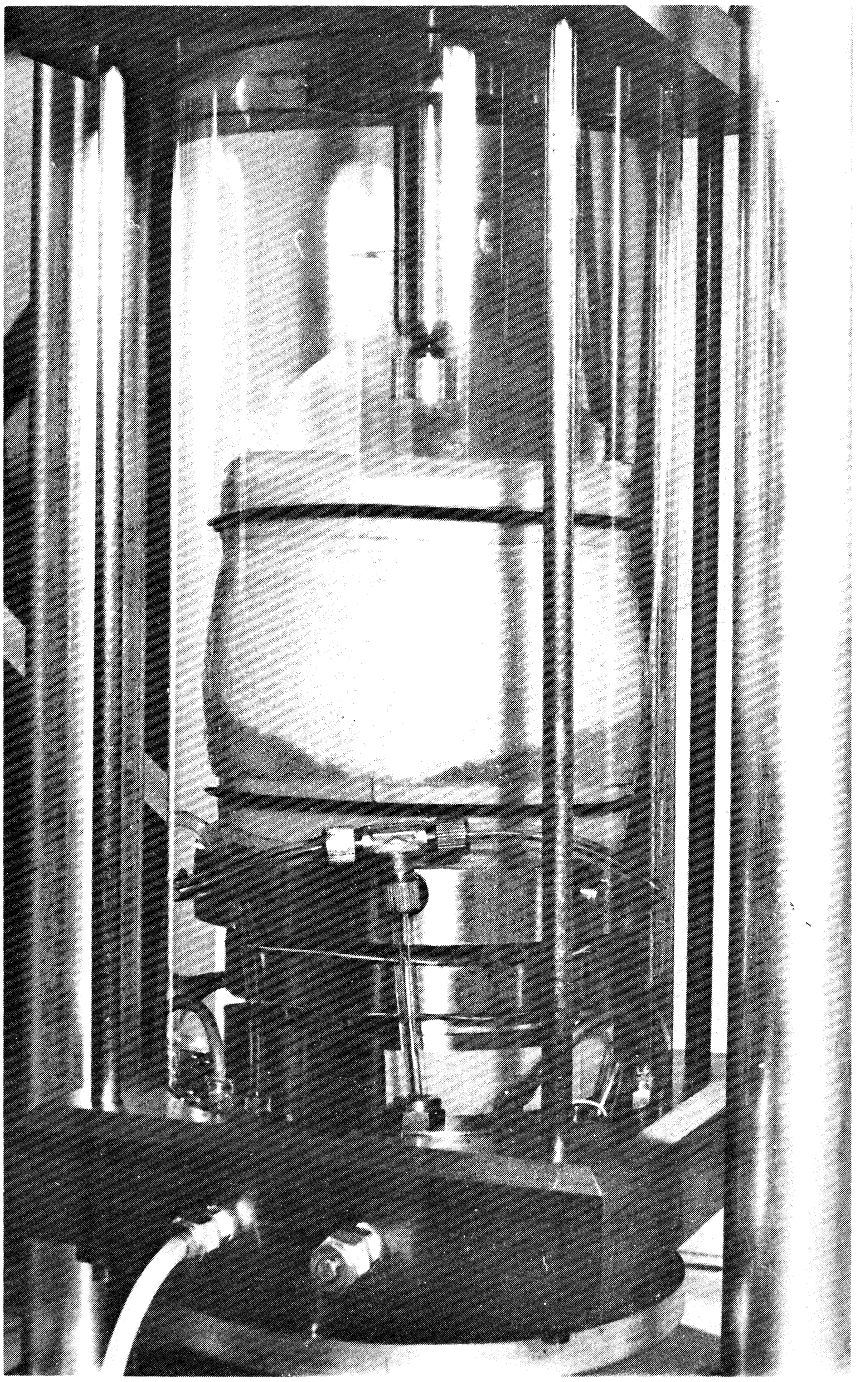

Figure 7. Close up of sample (after failure) and pedestal unit.

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