Thirty-Five Years of Soil Testing

Trente Cinq Années d'Essais de Sols

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INTRODUCTION

When I gave the Rankine Lecture in 1966 I noted that I was the first lecturer to have spent the early years of his professional life on the design and construction of engineering works. Moreover, I had been to a University where my engineering degree involved the study of Civil, Mechanical and Electrical engineering simultaneously. Hence when I came to deal with soil mechanics the practical need for a sampler, shear box and triaxial apparatus was a challenge to go to the drawing board and workshop rather than to go to a catalogue, if one had existed in 1945.

In the present lecture I will examine, as far as time permits, my involvement in the development of laboratory and field equipment during the period 1945 to the present. Usually the apparatus was developed to meet a specific need - almost invariably it has subsequently been used, either in its original or modified form, to carry out a wide range of investigations. Many of the pieces of apparatus have been taken up by commercial firms and become standard pieces of equipment.

(a) (b)

Fig.1. Open drive sampler of 1945.

Fig. 1(a) shows the first sampler with which I became involved in 1945. It is an open drive sampler with a flap valve at the top to allow the upward flow of large quantities of water. There is a jarring link at the top and cutting edge at the bottom, both of which could be removed and caps screwed on for ease of transportation. Fig. 1(b) shows the jarring link which permits the drilling rods to be used to drive the sampler into the ground - a much more efficient method than hitting the rods at the top. The figure standing at the side appears to be myself in 1944 or 45.

The laboratory equipment which was more or less contemporary with the above sampling equipment was the shear box. Fig. 2 shows the model which I developed from the standard Building Research Station version which, though beautifully made, was not very strong. The particular model shown in the figure was built in 1945 and was not actually stripped down for a major overhaul for over 21 years - it seemed to be strong enough to take anything that was demanded of it. A special feature was that if we wanted to use very high vertical loads for overconsolidation we could replace the ball bearings with a cylindrical rod of high tensile steel.

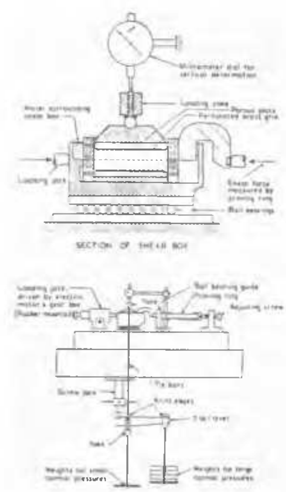

Fig.2. The 6 centimetre shear box. Layout of loading system.

At about that time I became involved in reservoir design and one of the construction materials was gravel. Nobody had measured the strength of gravel other than by its angle of repose which is rather crude particularly when it is well compacted. In order to carry out such measurements I developed a foot square shear box (Bishop 1948) which worked for many years both for research purposes and in producing practical results for the Metropolitan Water Board.

Previously I mentioned sampling in stiff clays but sampling in sands presented us with considerable difficulties. In an early paper in Geotechnique (Bishop 1948) I published details of a sand sampler the principles of which are shown in Fig. 3. The thin walled sampler lives inside a bell; the whole assembly is lowered with the boring rods. When in position the sampler is pushed into the sand using the lining tubes for the reaction. The boring rods are then withdrawn, water in the diving bell is blown out with compressed air and the sampler is pulled into the air space in the bell. The sand sample is now held in the sampling tube by a meniscus effect which is sufficient to retain the sample in the tube during retrieval.

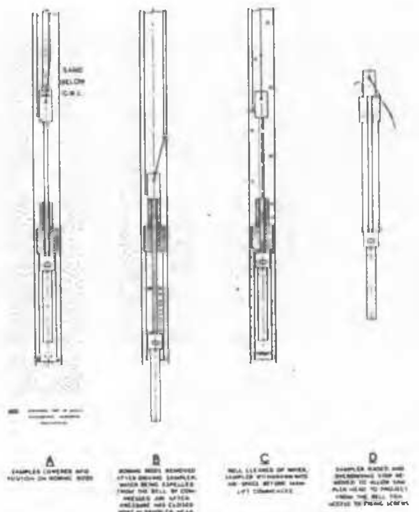

Fig. 3. Method of sampling sand in a lined borehole.

DEVELOPMENTS IN THE TRIAXIAL APPARATUS

The triaxial machine had of course already taken its place in testing and I will outline a few of the developements that I was able to introduce. The measurement of volume change of partly saturated soils requires the measurement of water passing into or out of the cell and this entails inaccuracies due to non-linear and irreversible volume changes of the cell. The device shown in Fig. 4 is used for studying all-round compressibility. The only error is in the volume change of the perspex itself due to its bulk compressibility and a correction can be applied for this.

The problem of measuring pore pressure with no change in volume had been with us for many years and the form of apparatus which we

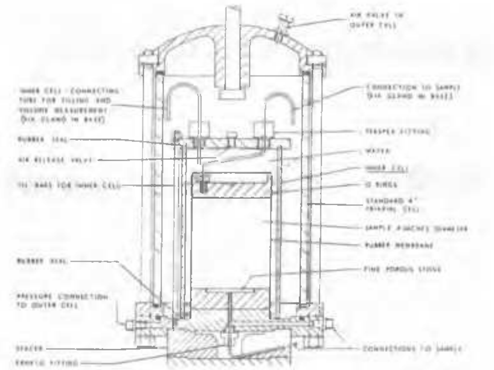

Fig. 4. Triaxial apparatus. Inner cell for accurate volume measurement (after Matyas, 1963).

ultimately developed was a very thick walled capillary tube containing a thread of mercury in contact with a reservoir of mercury at the base (Fig. 5). The water above the mercury was connected to the sample and the pressure was controlled so as to maintain a constant length of mercury thread. This system operated for many years and had many other uses because, being a small bore capillary tube, it could be used for fine volume measurements as well as for checking compressibility and other such purposes. I show this as an example of a piece of apparatus which was a common feature of our laboratories for probably a decade and a half.

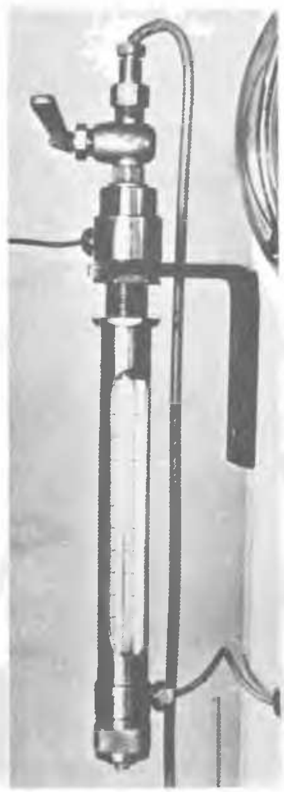

Fig. 5. Null indicator for pore pressure measurement.

An interesting question was how to measure volumechange in a dry sample since you are faced with the problem of a compressible fluid. We solved this problem by using mercury in the tube connecting through to the air in the sample (see Fig. 6). If any air were displaced from the sample then, to keep the mercury at atmospheric pressure, it was necessary to move the mercury interface by an equal volume. An oil manometer in the air line enabled us to keep atmospheric pressure very accurately. The tests had to be carried out relatively rapidly as air can in fact pass through the natural rubber membrane surrounding the sample into the water in the cell.

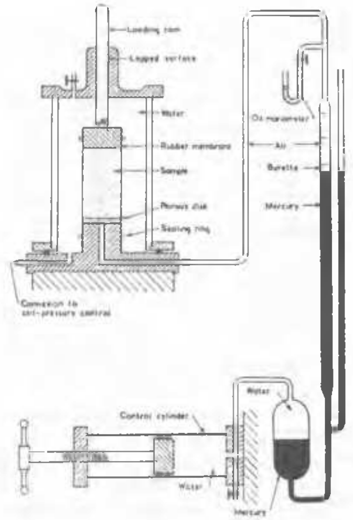

Fig. 6. Layout of triaxial apparatus for measuring volume changes in dry sand samples.

One of the problems in the laboratory was the application of constant pressure in the triaxial apparatus. Dr. Henkel and I thought that it would be advisable to develop a servo-mechanism to give a more constant pressure. While we were developing such a mechanism we found that the mercury manometer that was to be used as part of it could do the job on its own. Fig. 7 shows the well known principle of the system which incorporates a calibrated self compensating suspension for the upper mercury pot. I still find that this is the most fool-proof arrangement and it is one of the cheapest too.

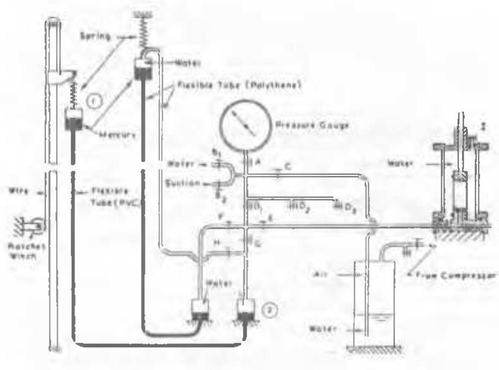

Fig. 7. Layout of pressure system.

It was becoming clear to us that sample size was important for evaluating the strength of stiff fissured clays. Moreoever we were wanting to test representative samples of rock fill. We decided to build as large a triaxial machine as possible which would still enable us to handle the samples ourselves without heavy equipment. We chose a sample size of one foot diameter and two feet in height. This is about the biggest undisturbed sample that can reasonably be handled. Fig. 8 shows a general assembly of the machine which is designed to apply a hundred ton thrust.

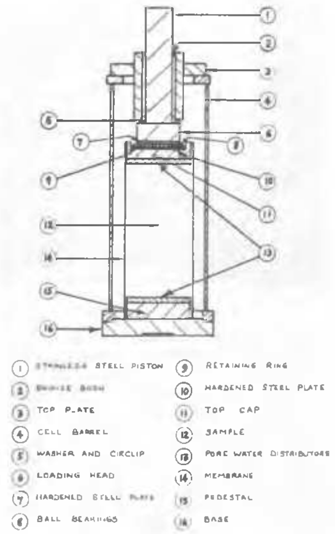

Fig. 8. Large triaxial cell general assembly.

Fig. 9 is a photograph of the apparatus itself showing the cell, electrical controls, the pressure vessels giving either air or water control and the head of the machine which runs up and down with a motor to position itself on two screws which were left over from old testing machines going back generations.

Fig. 9. Photo of the large triaxial apparatus.

Fig. 10 shows a sample of London clay after failure and it should be noted how smooth the failure surfaces appear to be and it has relatively low strength. We took it to a large strain to see what would happen and it is interesting that the rubber membrane did not rupture showing that natural rubber is an extremely useful material for membranes.

Fig. 10. Sample of London clay after failure.

We wanted to do some triaxial tests at very high pressures and one of the problems is that the uplift against the ram can be very large compared with the strength of the sample. Fig. 11 shows a method of balancing out the cell pressure on the ram by duplicating the ram at the base of the apparatus. Rotating bushes at each end cut down that ram friction to virtually zero. It makes a very efficient form of cell and the axial load is a direct measure of the deviator stress acting on the sample.

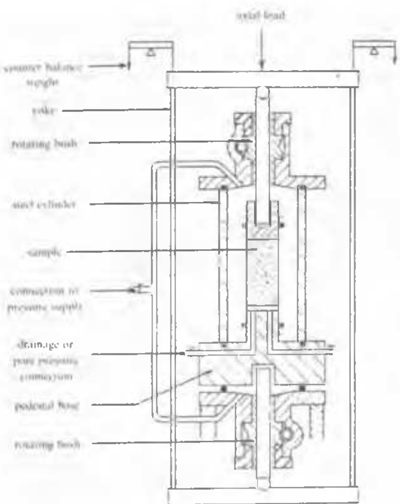

Fig. 11. Method of balancing out cell pressure.

A 10,000 psi version of this apparatus was built to examine the validity of the principle of effective stress at very high pressures. A typical result is shown in Fig. 12. We kept the difference between the cell pressure and back pressure constant but varied both pressures by some 4000 psi at various stages during a test. Since there are no kinks in the stress-strain curves at each change it appears that Terzaghi's original equation is completely vindicated even at very high pressures.

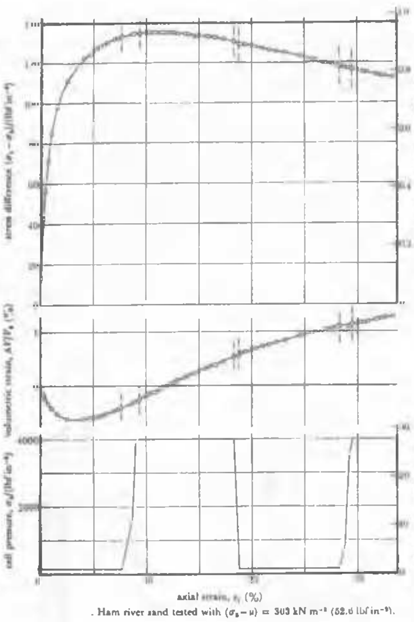

Fig. 12. Typical results from high pressure tests.

MEASUREMENT OF STRENGTH IN THE FIELD

In my introduction I mentioned that we would not stay wholly in the laboratory. The vane test has a long history of development particularly in Sweden. The vane shown in Fig. 13 is for laboratory purposes and is made very sensitive by fitting it on the end of a rod and measuring the twist in the rod optically as a measure of the torque. The apparatus can be used to measure the strength at the liquid limit to an accuracy of about 10 percent.

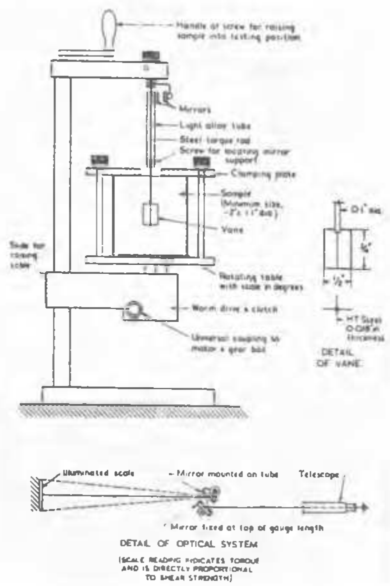

Fig. 13. Laboratory vane apparatus.

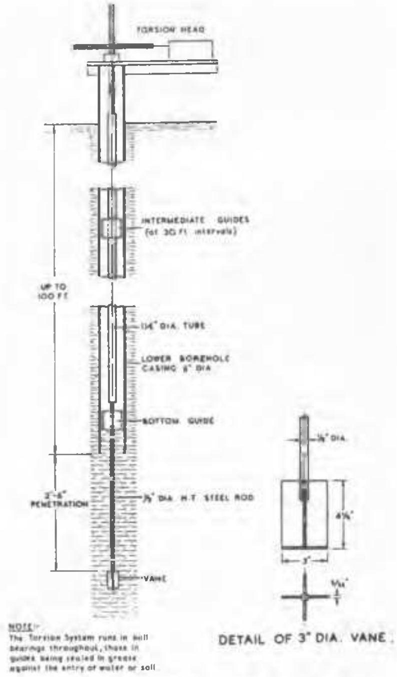

Fig. 14. Field vane apparatus.

At about the same time we developed a field vane. The equipment is shown in Fig. 14 and was made in a great hurry for a consulting job. The leading edges of the vane were slightly 'set up' to minimise disturbance during insertion. It was bored into the ground and then pushed ahead a distance of 1 to 1½ metres. The top of the vane was rotated by a wheel with a wire round it which was driven by a tennis net winder. The apparatus had a long and useful life.

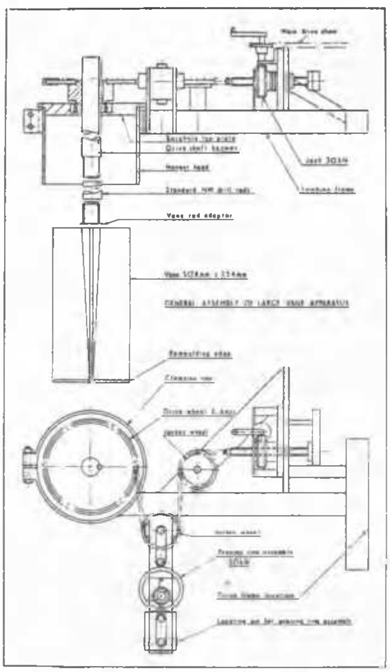

Fig. 15. Improved field vane apparatus.

More recently we have become suspicious about size and we made the vane shown in Fig. 15. It is roughly ten inches in diameter by twenty inches long and again the edges are 'set up'. This vane was used exhaustively on the Thames Barrier scheme in the marshes at a place called Stanford le Hope locally known as Mucking - a more apt description. The interesting thing that we found was that the big vane gave about 30 percent lower strength than the standard NGI vane testing at the same rate and in the same clay which was normally consolidated. I am still not satisfied as to the cause of this but we think that the NGI vane may suffer from consolidation during installation and testing. The clay has an extrememly high coefficient of consolidation under low loads and this drops several orders of magnitude when it is loaded. Therefore it may be that the lower strength is the more correct value.

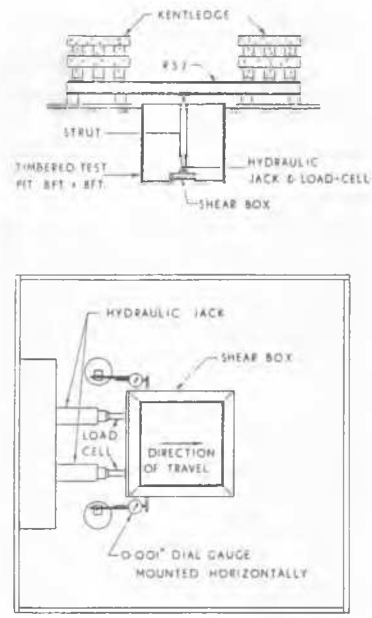

Fig. 16. Layout of direct shear test on 2 ft.x 2 ft. samples in the field.

Remaining in the field for the moment Fig. 16 shows the apparatus I used for some in situ shear box tests on the site of the potential reservoir in Maldon, Essex. The tests were carried out at the base of a test pit and the box was two feet square. Vertical load was provided through a long strut reacting against kentledge. The same set up was used for plate loading tests. The shear box tests raise the interesting question of anisotropy. My impression is that if there had not been anisotropy we would have had great difficulty in getting a reasonable shear zone underneath the box as it would have dug much more deeply into the ground.

PLANE STRAIN AND 3 x D

We first made a plane strain apparatus in, I think, about 1956. Clive Wood (1958) was working with me at that time and we made it first of all to take compacted soils for dams and subsequently Dr. Cornforth used it for sands. Fig. 17 is taken from some results obtained in 1961 and shows that for dense materials the value of ϕ' in plane strain can be as much as 4^{o} higher than in cylindrical compression.

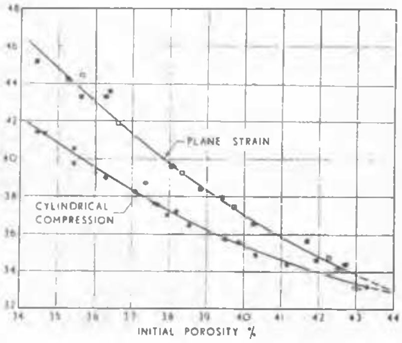

Fig. 17. Comparison of results of drained plane strain and cylindrical compression tests on Brasted sand (Cornforth, 1961).

Fig. 18 shows the most recent plane strain apparatus in use at Imperial College. The hydraulic loading ram is probably the key to the successful operation of the apparatus (Atkinson 1973). Note the internal load cell at the top and the wedge in the right hand end platten. When the sample has been assembled and put under pressure there is nearly always a gap between it and the end plattens. By operating a little piston by oil the wedge can be brought up against the sample watching the load cell at the other end to ensure that the sample is not significantly loaded. This form of the apparatus was developed by Atkinson (1973) for use with stiff clays but it has also been used for soft clays by Wesley (1975). The hydraulic loading ram has also been utilised in the hydraulic triaxial stress path cell (Bishop and Wesley, 1975).

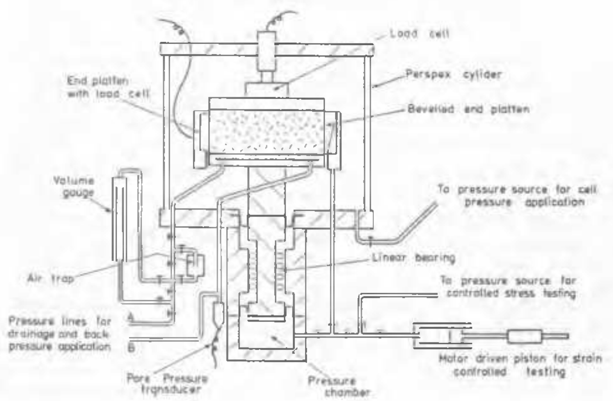

Fig. 18. The plane strain apparatus.

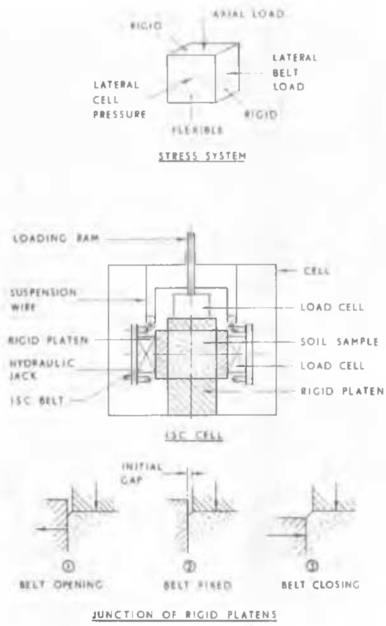

Fig. 19. Basic concepts of the true triaxial apparatus

Fig. 19 shows the version of the true triaxial apparatus which was developed by Dr. Green (1969). It consists of an approximately cubical sample between lubricated plattens. It has a belt operated by a small hydraulic jack with remote control and a load cell on the opposite side. The location of the belt relative to the top and bottom plattens is adjustable depending on whether the belt will move inwards or outwards (see lower half of Fig. 19). It is not a perfect system but it is relatively simple and had given some very interesting results. Usually the cell pressure is chosen to give the minor principal stress, the ram at the top giving the major principal stress and the belt providing the intermediate principal stress. However, there is freedom to vary the loading systems so that the major principal stress can be applied by any of the loading systems.

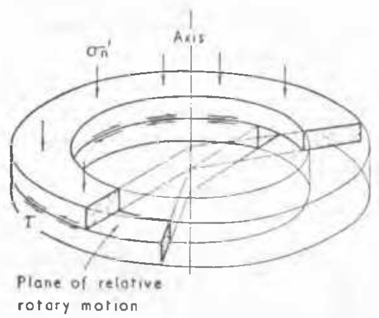

Fig. 20. Ring shear test sample.

The ring shear is another important piece of equipment and is shown schematically in Fig. 20. The lower half of the annular sample is rotated relative to the top half.

Fig. 21 shows the polished surface of London clay for which a residual angle of friction of 9.4° was measured. This figure was confirmed independently by La Gatta (1970) working under Casagrande at Harvard and it is comforting to get such close correlation of results using separate machines which were very different in detail.

Fig. 21. Polished surface of London clay after ring shear test.

ONE-DIMENSIONAL TESTING

The measurement of the coefficient of lateral pressure at rest is another interesting laboratory pursuit and it has also become a field pursuit now. The piece of apparatus shown in Fig. 22 goes back some time. It is a four inch diameter belt mounted on the sample and any change in its diameter causes a change in the position of a mercury thread. An electrical contact can be put on the mercury surface if need be. Fig. 23 shows one of our more interesting results for loading and unloading cycles on dry sand.

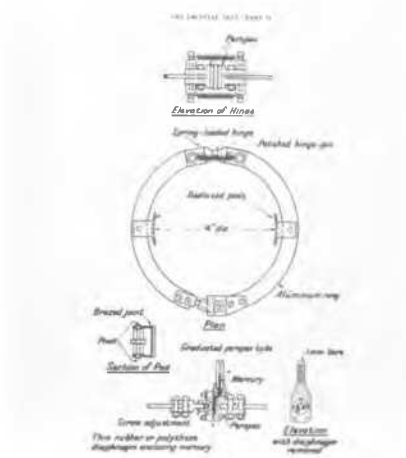

Fig. 22. Developed section of indicator for measurement of lateral pressure at rest.

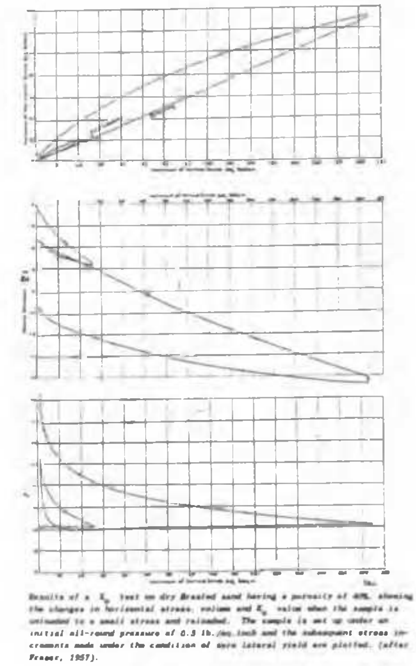

Fig. 23. Results of K_0 test for loading and unloading cycles on dry sand.

The oedometer is a standard piece of equipment and at the time I first encountered it a variety of complex designs existed which made use of items such as bicycle wheels and wire. In about 1950 we wanted some additional units for the laboratory and also a commercial firm asked us if we would design one that was saleable. Fig. 24 shows the simple and compact device that we produced. The balance beam is of light alloy with high tensile strength and the frame is cast iron and therefore very rigid. This machine has remained a standard piece of equipment to this day in our laboratory.

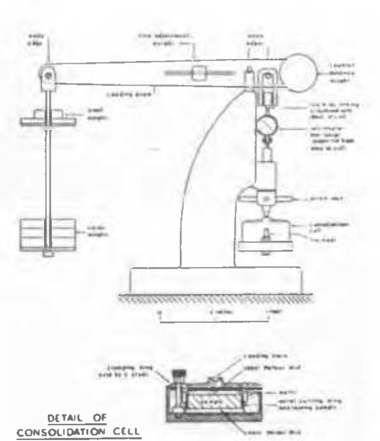

Fig. 24. Oedometer device.

The apparatus shown in Fig. 25 is a high pressure hydraulic oedometer containing a four inch diameter sample loaded through a rubber membrane. The displacement is measured by a transducer carried on legs which pass into the base on which the sample and porous stone are standing. Although designed for 10,000 psi, it is very accurate at small stresses. There is a facility for measuring pore pressure as well and we have found it a generally useful piece of apparatus.

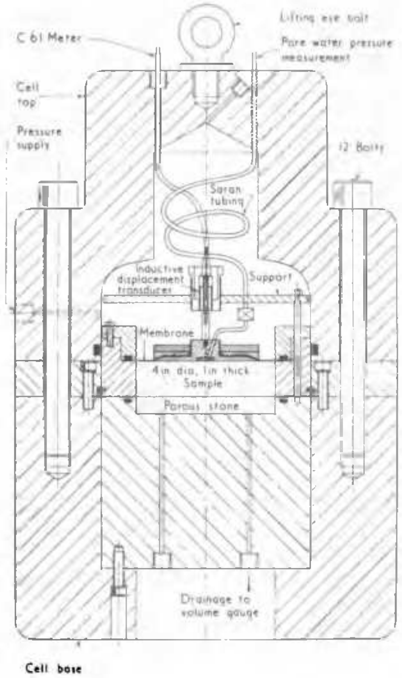

Fig. 25. Highpressure hydraulic oedometer.

TENSILE TESTING

It is seldom that true tension tests are carried out. We found a way of doing them using dumb-bell shaped samples and fluid pressure. Thus although there may be zero effective stress at the level of the platten (see Fig. 26) there

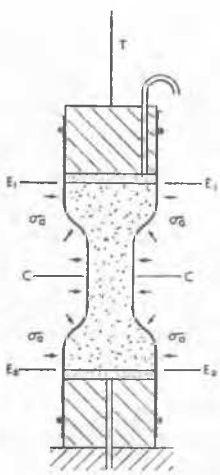

Fig. 26. Device for tensile test.

will be negative effective stress at the mid-height of the sample. Using this approach we were able to carry out drained tensile tests on materials like undisturbed London clay. Fig. 27 shows some test results. The undisturbed clay gave a tensile strength of about 5 psi whereas if the clay is remoulded it gives no tensile strength. I have not fully absorbed this result yet but I think the tensile strength is entirely in the pore water.

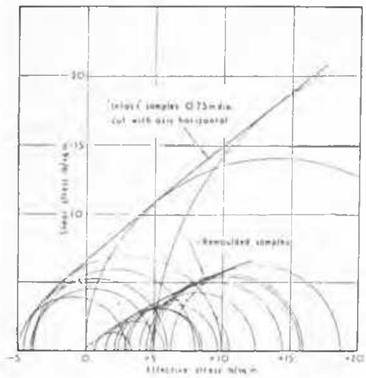

Fig. 27. Results of drained tension and compression tests on 'intact' blue London clay compared with the results of compression tests on remoulded samples.

CREEP APPARATUS

Fig. 28 is a schematic diagram of a creep apparatus which I developed. Basically the sample is submerged in a mercury jacket and

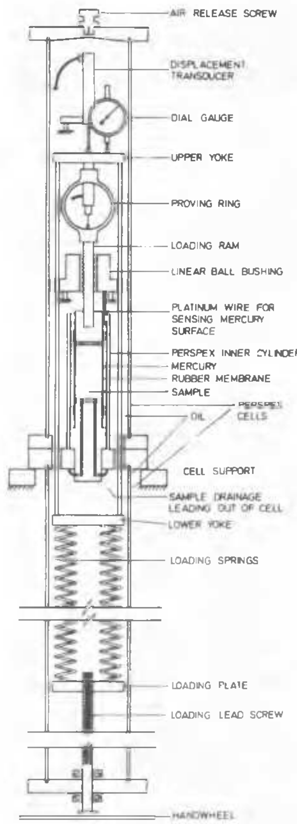

Fig. 28. Schematic diagram of spring loaded creep cell (after Lovenbury, 1966).

surrounded by oil in a perspex container. The load is applied by springs also submerged in oil so that there is no friction between the loading system and the sample. An inductive transducer is used to measure the strain and an ordinary dial gauge acts as a check. To tighten up the springs the handwheel at the base is turned. A number of creep tests ran for about 3½ years continuously. The results show that great care must be exercised in extrapolating results from tests lasting a few days to much longer periods as unexpected volume changes can occur after a hundred or more days.

HOLLOW CYLINDER APPARATUS

One of the limitations with all the pieces of apparatus which we have looked at so far is that you cannot control the rotation of the principal stress directions during the test. The hollow cylinder apparatus provides a reasonably satisfactory method of doing this. A decision has to be made over the thickness of the walls in order to limit pressure gradient across the sample but otherwise it is possible to control the direction of the principal stress very accurately.

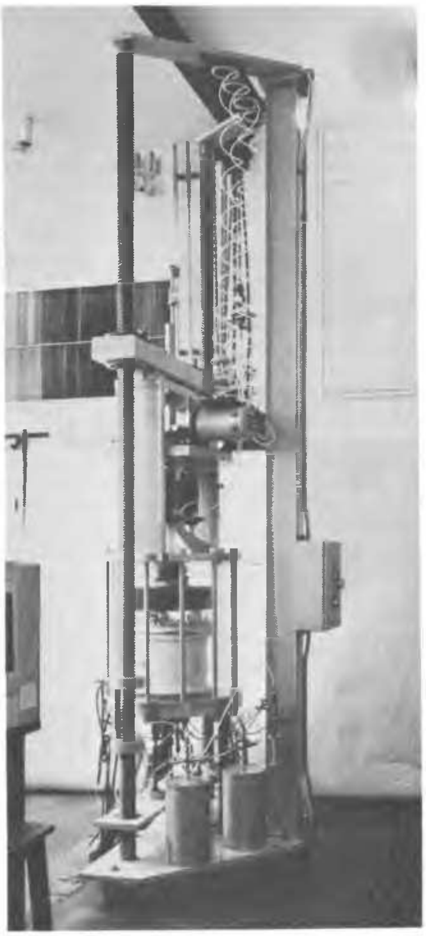

Fig. 29. The hollow cylinder device.

Fig. 29 is a photograph of the apparatus which has been developed at Imperial College. It has grown in size since its original conception. The sample is relatively small - ten inches high by ten inches in diameter. However, that must be housed in a cell together with the load cell for measuring axial force as well as torque. This leads to a cell weighing half a ton and since people have to work beneath it this leads to a screw operated machine for lifting it clear. That is why the apparatus looks rather formidable.

Fig. 29 also shows the compressed air cylinders for applying the torsion and separately those for applying the vertical load. Fig. 30 shows the hollow sample. A closer view of the assembled sample is shown in Fig. 31 with some of the instrumentation for measurements of local torsional and direct strain. One point to note is that the sample is flared at each end to avoid stress concentrations. This flaring appears to be satisfactory as the failure surfaces, which take the form of helices, form over the full length of the sample.

Fig. 30.

View of hollow cylindrical sample.

Fig. 31.

Assembled sample.

I shall not attempt to draw any special conclusions from the selection of pieces of equipment I have shown you. If I were to draw any moral from my talk it would be to avoid going to a catalogue when you have a special or unusual testing need. Unless you have strong evidence that other research workers have had success with a piece of commercial equipment be very cautious about buying things off the shelf. It is much better to try to make the apparatus if you can and you're more likely to have success.