New Oedometer and New Triaxial Apparatus for Firm Soils

Jacobsen , Moust

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A New Oedometer

The normal oedometer consists in principle of a ring containing the specimen and two pistons with filter-discs allowing water to escape. During the test the pistons are pressed towards each other by vertical loadings alternating in steps, and time-deformation curves are obtained. This version of the oedometer gives errors in the measurement of the applied stress, due to friction between the specimen and the oedometer ring and between the pistons and the ring. By using a so-called floating ring, the latter friction is reduced to the smaller of the two piston frictions.

For settlement calculation purposes this apparatus is used very often, on account of the cheapness and quickness of the test and because experience shows that this method gives reasonable results on normally consolidated clays. However, in this way we calculate settlements of structures on moraine clay which are two to four times larger than observed. In the following it is shown that this is to a great extent due to deformation of the apparatus itself and to the so-called bedding effect.

Investigation of Apparatus

Under a loading increment the different parts of the oedometer become deformed, and in the oedometers normally used some of these deformations will be measured by the dial gauges as a vertical deformation of the specimen. These movements are of course small, but of the same order of magnitude as the deformation of a firm soil specimen.

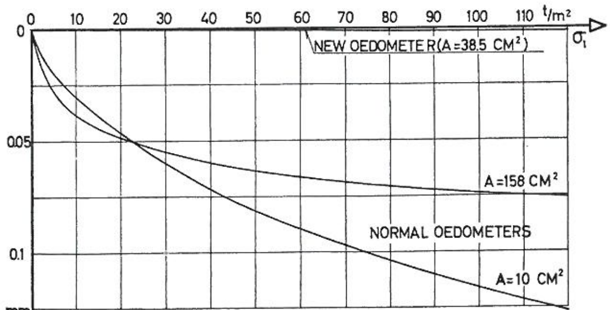

Fig. 1.1 Calibration curves for vertical deformations of the apparatus itself by loading.

An investigation of the "elasticity" of the apparatus itself consists of tests carried out on brass cylinders instead of samples and with only one filter-disc. In that way there are two surfaces of filter-discs against brass surfaces as a normal test. Fig. 1.1 shows such calibration curves for the oedometers normally used with a sample area of 10 cm² and for a bigger one with a sample area of 158 cm². These curves cover the normal stress interval in which the deformations of the apparatus itself can be seen to be smaller than 0.1 mm. The most important factors causing these deformations are

1. crushing of grains situated between two parts of the apparatus.
2. closing of gaps between different parts of the apparatus because the surface is not perfectly plane or due to faults in the arrangement of the apparatus.
3. deformations in threads or bending of the support.

It is impossible to get the same calibration curve from one test to another; effects 1 and 2 in particular can vary very much, and it is therefore in fact impossible to correct these errors. This is the main reason for constructing the new oedometer cell.

The New Oedometer Cell

The problem to be solved in the new oedometer cell is thus the measurement of the vertical deformations of the sample itself. If it were attempted to eliminate frictions totally the apparatus would become very complicated and expensive (and very much like the new triaxial cell). The new oedometer cell is therefore a normal one, but without the above-mentioned sources of error.

A sketch of the new oedometer cell is shown in fig. 1.2.

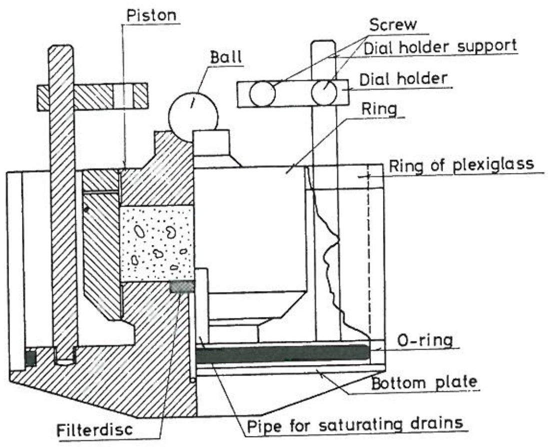

Fig. 1.2 The new oedometer.

The specimens have normally a height of 30 mm and a diameter of 60 mm. A sampler at the D.G.I. has a diameter of 70 mm, and when preparing the specimen the outer 5 mm are cut off in order to eliminate disturbance in the surface of the sample.

The lower part of the cell serves three purposes:

1. to act as the lower pressure head
2. to hold the rods for the dial gauges
3. to hold a plexiglass ring containing water.

It is constructed as one rigid unit in order to avoid the above-mentioned deformations. The dial gauges measure directly at the upper pressure head. There are two of them situated near the edge. In the center of the upper pressure head the load is applied through a ball. It will be seen that the dials indicate the deformation between the two pressure heads only. The deformation between the specimen and the pressure heads consists of an adaptation of the specimen to the filter-discs (bedding effect) and penetration of the grains of the filter-discs into the surface of the pressure heads. In order to minimize these deformations only one filter-disc in the centre of the lower pressure head is used, having a diameter of $\frac{1}{3}$ of that of the specimen. For the same reason the specimen is cast against the pressure heads by means of gypsum, with the exception of the small area of the filter-disc only.

The oedometer ring is very thick, and high vertical pressures (up to 3000 t/m²) can be applied without causing significant vertical deformations through horizontal expansion of the ring.

To measure the deformations of this apparatus itself, a sample of gypsum was cast directly in the cell, having a height of 1 cm. A calibration curve also including the gypsum sample is shown in fig. 1.1 (called new oedometer). The best calibration curve shows no deformation at all, indicating that the deformation of this system was less than 0.001 mm for a load increment of 120 t/m². This shows first that the "elasticity" of the apparatus itself is negligible even for very firm soils such as e.g. heavily preconsolidated boulder clays and also that the deformations of gypsum are negligible. In fact it is possible to make gypsum with nearly constant volume.

Finally, it should be mentioned that the deformations of the plate supporting the cell in the loading arrangement can give some errors. This plate is therefore very thick (the dimensions are 250 × 250 × 50 mm³). The influence of this plate is already reduced by giving the lower pressure head smaller dimensions on the underside.

The influence of the apparatus is illustrated in fig. 1.3, showing the results of tests carried out on the same kind of moraine clay (Kratbjerg) and in the same way, but with different apparatus. If it is assum-

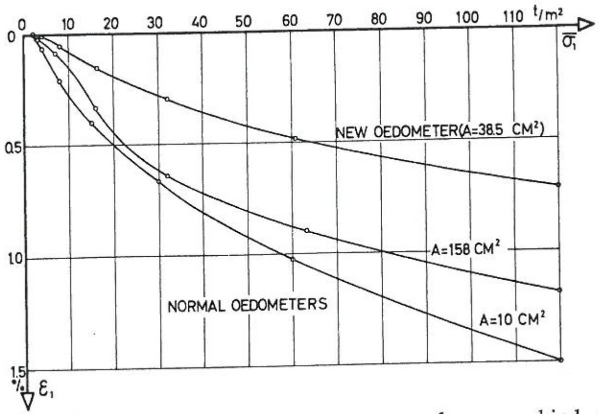

Fig. 1.3 Results of tests carried out on the same kind of moraine clay in the same way, but in different oedometers. Kratbjerg moraine clay.

ed that the new oedometer gives correct measurements, it will be seen that the influence of the "elasticity" of the previous apparatus itself is for this soil more than 100 %. Compared with this the friction effect would appear to be of minor importance.

When making tests on sand it is impossible to cast out with gypsum and to avoid rotation of sand grains at the end of the specimen and penetration of sand grains into the brass surfaces of the pressure heads, but here consistent calibration curves can be made.

Drainage of the Sample

The drainage is not monoaxial, because the filter-disc covers part of the end of the specimen only. It is thus not possible to calculate the permeability by applying Terzaghi's theory. It is, however, possible to calculate the drainage by numerical network analysis on an electronic computer. If this curve is plotted in a $\sqrt{t}$, log t diagram as proposed by Brinch Hansen, we can find the time of consolidation t_c and define an equivalent drainage path H_q, which when using the normal equation gives the permeability:

$$k = \frac{\pi}{4} \cdot \frac{\gamma_w H_q^2}{K \cdot t_c} \cdot \qquad (1.1)$$

Two curves were calculated. One with drainage to the filter-disc only, and one with drainage to the filter-disc and the gap between ring and pressure heads. These curves can be seen in fig. 1.4. For $D = 2H = 3d$, the average H_q is found to be $0.7D$. (D is the diameter, H the height of the sample and d the diameter of the filter-disc). It will be seen that by using this formula we can calculate the permeability except for a factor which may have values between 0.5 and 2.

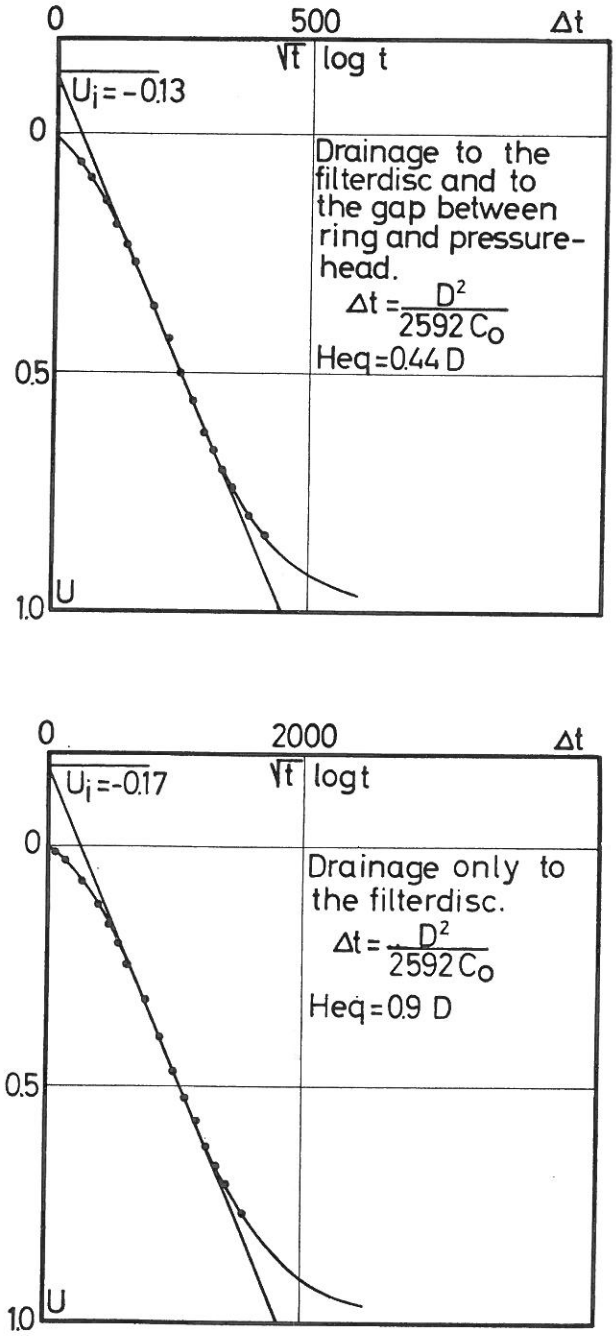

Fig. 1.4 Numerical calculation of the drainage.

Test Procedures

A moraine clay is normally preconsolidated like many of the other Danish clays. From experience we know that when using the first loading curve the settlement will be considerably overestimated, even when testing the soil in the new rigid oedometer. Therefore we first reconstruct the "stress history" by loading up to a maximum pressure σ_{max}, so near the preconsolidation pressure σ_{pc} as possible, and unloading to the in-situ pressure σ_o as proposed by H. Lundgren. If the settlement is calculated by means of the following reloading curve correspondence with the observed settlement is obtained.

Preparation of the Sample

By sampling, the effective overburden pressure will partly be transferred into suction in the pore water. In the laboratory the first loading is increased very quickly to avoid swelling of the specimen.

When casting gypsum to the ends of the specimen some of the water will make it swell and the suction will decrease. This is an effect of only minor importance for moraine clay, because the capillarity is normally smaller than the overburden pressure.

The Primary Curve

Moraine clay contains stones, some of which are located at the surface of the sample, and when preparing the specimen it is necessary to remove stones from the surface and to fill the holes with gypsum to avoid fatigue of the specimen. In this way we get a specimen with a somewhat smaller diameter than that of the oedometer ring. This means that the first loading curve does not represent an oedometer test with no lateral deformation, but rather a kind of compression test. Further, this makes it impossible to determine the preconsolidation pressure σ_{pc} on this curve with any accuracy even if the in-situ preconsolidation pressure is exceeded ten times. This effect is dependent on the size of the sample. In fig. 1.5 some primary curves are shown for tests under the same conditions and on the same soil but with different diameters in the apparatus. If Poissons ratio μ is 0.33, it can be shown that a diameter 0.5–1 mm less than the correct one gives an error of the same magnitude as indicated in fig. 1.5.

The shape of the primary curve is thus influenced very much by the precision of the preparation of the sample. Furthermore, tests have been carried out in the same apparatus on the same soil but with different diameters of the specimens. Fig. 1.6 shows the different shapes of the primary curves. Such curves are sometimes published and indicate – in the author's opinion – sample diameters smaller than that of the oedometer ring.

Finally a test was carried out without a ring and compared with another test on the same material

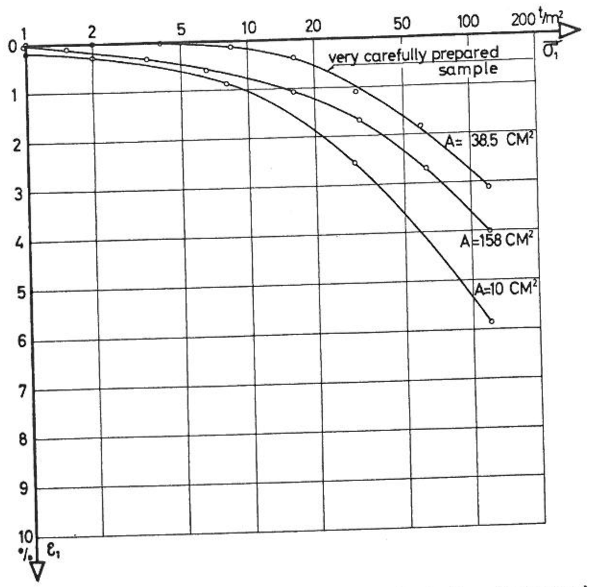

Fig. 1.7. A primary curve showing an adaptation deformation for the same kind of moraine clay. Kratbjerg moraine clay.

(fig. 1.6). This shows that the oedometer ring does not begin to function until the point of maximum change of inclination is reached. Unfortunately this point and the preconsolidation point seem to be so near to each other that it is very difficult to distinguish between them.

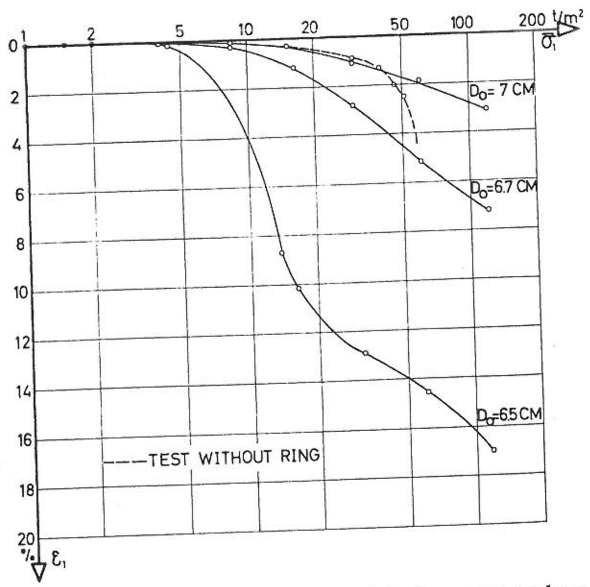

Fig. 1.6 Some primary curves found in the same oedometer for the same kind of moraine clay, but with different diameters of the samples. The diameter of the ring is seven cm. Kratbjerg moraine clay.

If the preconsolidation pressure is exceeded up to ten times it is possible to get an idea of the virgin curve and this pressure. Fig. 1.7 shows an example. Taking into account the adaptation deformations, we get in this case $\sigma_{pc} \sim 180$ t/m².

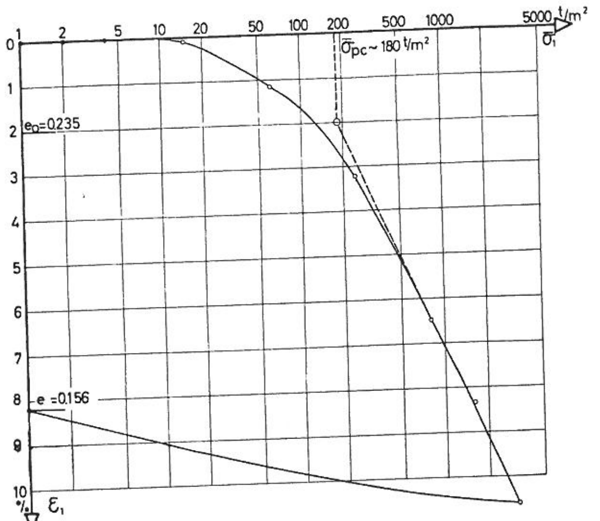

Fig. 1.7 A primary curve showing an adaptation deformation at about 2 %. The void ratios are calculated by means of bulk densities as determined by submerging in trichlorethylene. Carlsberg moraine clay.

Loading Cycles

After unloading from the maximum pressure a reloading curve, starting at the pressure σ_u, is produced. σ_u should correspond to the effective overburden pressure at the beginning of the construction period. If one sample should be representative for a homogeneous stratum the test is carried out with several unloading and reloading cycles. This may also be done for statistical reasons. A normal test can be seen in fig. 1.8.

The deformations of the reloaded sample might be thought to depend on the preparation of the sample,

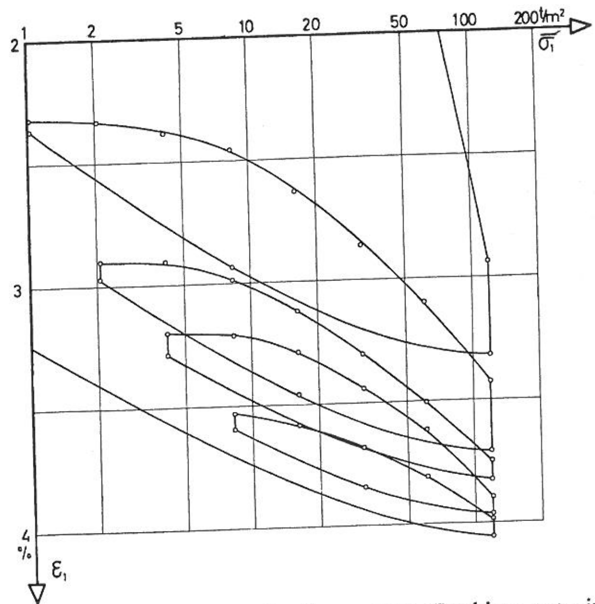

Fig. 1.8 Unloading and reloading curves. Kratbjerg moraine clay.

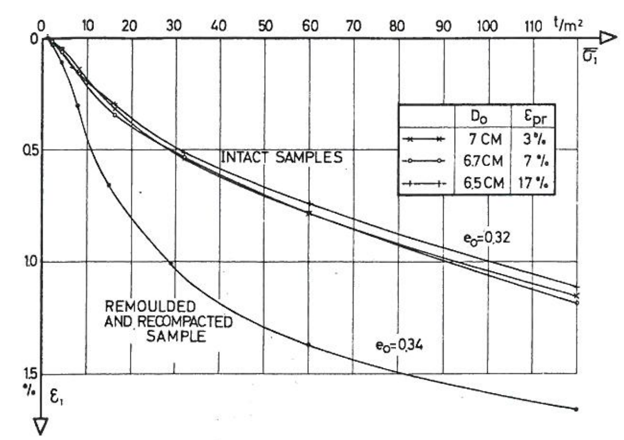

Fig. 1.9 The effect of the preparation of the sample on the reloading curves. Kratbjerg moraine clay.

i.e. the diameter of it. Fig. 1.9 shows reloading curves for the same three tests as mentioned above (fig. 1.6). The differences are very small and the variation is random. This means that for this kind of moraine clay any effects of the adaptation of the sample to the ring will be negligible at the reloading curve. This indicates that the large deformations at the primary loading have no remoulding effect on the sample.

The reason why no influence is found could be that the effect of remoulding is of minor importance. A remoulded sample of the same materiale is prepared with the same water content and a test with the same procedure is made. This result is also shown in fig. 1.9 and shows that complete remoulding has a definite effect on the reloading curve.

This very surprising result is perhaps not valid for other clays because the dilatancy properties of the sample may be of importance. But the influence of the deformations in the primary curves is at any rate small on the reloading curves.

In this case the preconsolidation pressure has not been exceeded and therefore only small volume changes have occurred. This means that the void ratios of the three samples under reloading are nearly equal.

If the preconsolidation pressure is exceeded the void ratio decreases, and therefore the maximum pressure influences the deformations in the reloading curves.

Some tests have been performed by varying the maximum pressure while using the same unloading pressure σ_u at the unloading and reloading cycles. The duration of the maximum loads was normally one day, when the consolidation time was about half an hour. By comparing the reloading curves, it can be seen that the sample has increasing deformations for increasing values of the maximum load.

This effect was not observed during the adaptation of the sample to the ring even at a deformation of about 20 %, but here it is quite obvious. It is therefore clear that volume changes cause this effect. This agrees with the fact that unconfined compression tests show no peak stresses but have "vertical tangent", i.e. that this effect do not occur under constant volume conditions (fig. 2.15).

This effect is probably caused by destruction of the electrical interaction between pore water and clay flakes. After some time these bindings may be reestablished. Two tests were carried out to investigate the time effect when the preconsolidation pressure is exceeded. Only one test was completed. Calcareous deposits between the pistons and the ring spoiled the other test.

The first maximum load was $\sigma_{max} \sim \sigma_{pc} = 16$ t/m², the later ones 240 t/m². The minimum load was $\sigma_u = 1$ t/m². The duration of the first maximum load was 120 min. Fig. 1.10 shows that the mentioned effect gives deformations for $\sigma_{max} = 240$ t/m² twice as big as for $\sigma_{max} = 16$ t/m². The next maximum load was applied for 44000 min. and the last one for 135000 min. By comparing the reloading curves directly the influence of ageing is seen.

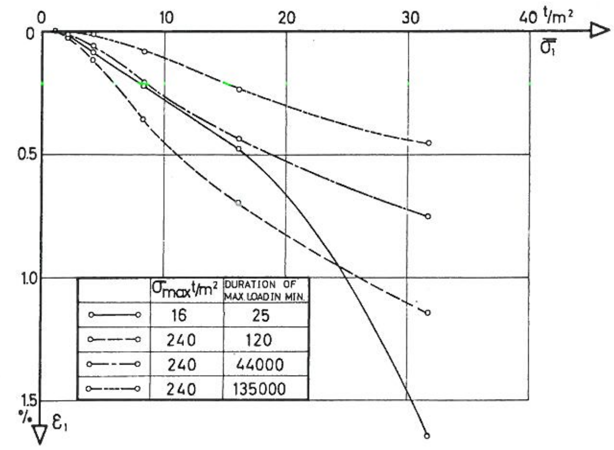

Fig. 1.10 Remoulding and ageing effects. Sabro moraine clay.

During the test the void ratio changed from 0.52 to 0.31. Another moraine clay (Kratbjerg) had nearly a natural void ratio of 0.31 and the same grain distribution. By comparing reloading curves from a normal test performed on this soil with $\sigma_u = 1$ t/m² (fig. 1.9) with the last curve in the ageing test it can be seen that the deformations are nearly equal. This means that in this case the electrical bindings were almost reestablished within four months.

A New Triaxial Apparatus

In a triaxial apparatus the cylindrical soil specimen is placed between two pressure heads and surrounded by a thin rubber membrane separating the pore water and the water in the cell. It is possible to vary the cell pressure and the vertical load independently and to measure the volume changes and the vertical deformations. The tests can be carried out under drained or undrained conditions.

This apparatus is very suitable for determining the strength properties of a soil by a series of tests with different cell pressures, increasing in each test the vertical load until failure and considering the maximum vertical load as a function of the cell pressure. The strength properties are defined by using Coulomb's failure condition:

$$(\sigma_1 - \sigma_3)_f = (\sigma_1 + \sigma_3)_f \sin \varphi + 2c \cos \varphi \qquad (1.2)$$

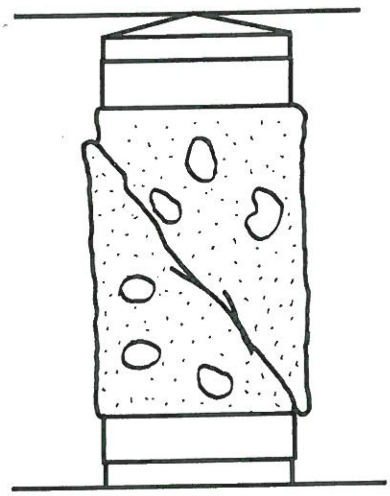

Fig. 1.11 Unconfined compression test with fixed ends shown after rupture. Line – rupture.

Investigation of Apparatus

The condition for the use of equation (1.2) is that the material is continuous and that the sample deforms as a cylinder with uniform stress and strain distributions and with no shear stresses at the surfaces of the cylinder.

However, the end platens are normally filter-discs and thus rough and the rupture zone is normally very narrow. According to Taylor (1941) the influence of these "fixed" ends on the measurements of the drained strength properties is negligible, when using samples with heights twice the size of the diameter.

But when estimating the undrained shear strength of a firm soil in this kind of triaxial test, the formation of a distinct rupture surface causes in some cases a grave error. This point is demonstrated later.

In the standardized triaxial apparatus the most important sources of error are

1. Non-uniform deformation of the sample.
2. "Elasticity" of the apparatus itself.
3. Friction influence on the axial load.
4. Premature collapse of the sample.
5. Membrane effects, including diffusion of air in the cell water and compression of water-filled cavities between the membrane and the surface of the sample.
6. Measurement of pore water pressures.

1. Non-Uniform Deformation of the Sample

The normal shape of the triaxial specimen of a firm soil after testing shows failure as a narrow rupture zone inclined nearly $45° - \bar{\varphi}/2$ to the vertical (fig.1.11). In this zone the main shear deformations and volume changes are located, and the soil properties measured do not refer to the total specimen, as normally assumed.

This means that the vertical deformation corresponds to movements in this zone, and it can be shown that even the small deformations at the beginning of the test are overestimated when they are interpreted as uniform deformations of the whole sample under uniform stresses (fig. 1.26). When measuring the distribution of the pore water after the test it is observed that the water content in the failure zone is greater than in the other parts of the sample, even in undrained tests.

The narrow rupture zone is formed if the soil expands under rupture conditions. When a locally weak zone in the specimen is near failure, its water content will increase and the zone becomes still weaker. The shear plane, which is subsequently formed, starts developing here. The zone is very narrow and needs only a little water to expand. Therefore the changes of volume here may be considerable even in undrained tests, and the resulting undrained shear strength corresponds to a higher water content than that measured, and it is therefore smaller than the actual strength. In drained tests the effective cohesion is measured too small, whereas the effective angle is nearly correct determined.

The undrained shear strength is measured in the field by vane tests or plate tests. Plate tests give of course the most correct value because the tests are made on really undisturbed soil surfaces, but the vane test gives nearly the same result in unfissured firm soil, only 10 % higher, due to the enforced rupture

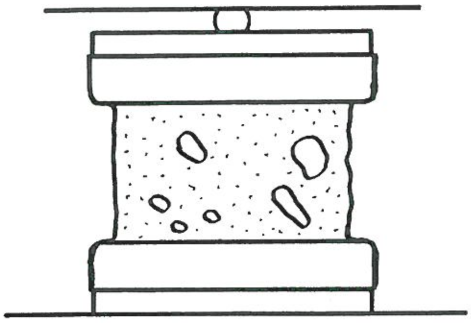

Fig. 1.12 Unconfined compression test with free ends shown after rupture. Zone – rupture.

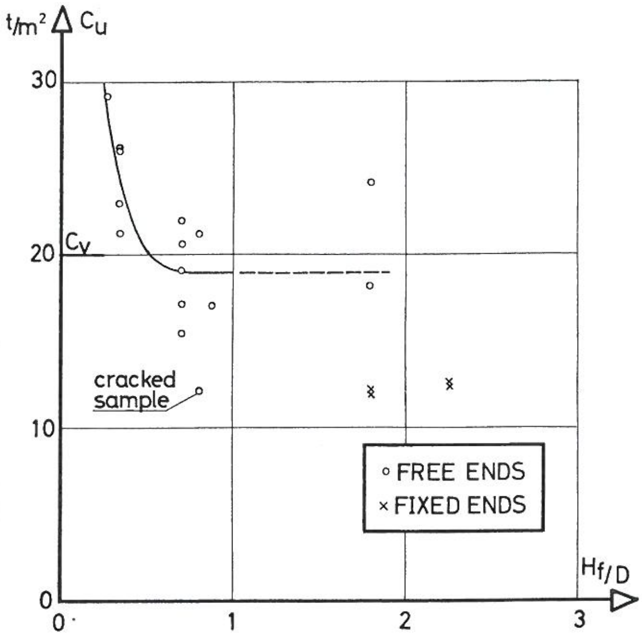

Fig. 1.14 The effect of the sample height on the undrained shear strength in tests with free ends. H_f is the sample height at failure and D the sample diameter. Kratbjerg moraine clay.

surface. The vane test is carried out so fast that the water content in this surface is nearly constant during the test. The unconfined compression tests give only as an average 40 % of the correct result; very carefully performed tests up to 60 %. So the formation of a rupture surface is a very important factor in testing firm soils.

The solution of this problem is to enforce uniform deformation conditions at failure. By giving the specimen a height equal to the diameter the creation of a single shear plane is prevented (fig. 1.12). By using "smooth" pressure heads the shear stress at the ends of the sample can be minimized. Thus we get a nearly uniform plastic zone and uniformity in stress and strain distribution is obtained.

The smooth pressure heads consist of a glass plate with silicone grease and thin rubber membranes as proposed by Rowe and Barden (1964) (fig. 1.13). The proposed system is naturally not quite frictionless, but it is sufficient if the roughness is negligible.

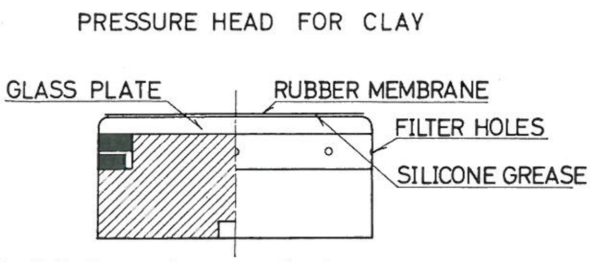

Fig. 1.13 A smooth pressure head.

When testing clays it is only necessary to use one membrane. The surface of these soils can become very smooth during preparation perhaps after the removal of some stones. But when testing sand it is necessary to use more membrance because the sand grains penetrate the rubber membrane and rub against the glass plate.

For moraine clay some unconfined compression tests have been carried out to check on the effect of the pressure heads. The cross-section area was 10 cm² and the following heights were used: $H = 2D$ (2 tests), $H = D$ (8 tests), $H = 0.5D$ (4 tests), $H = 0.4D$ (1 test). The two tests with $H = 2D$ had a peak point corresponding to the increasing water content in a rupture plane. Three of the tests with $H = D$ had a similar maximum value of the deviator stress. Radial cracks transformed the specimen into a series of smaller specimens with $H >$ "D". The other 11 tests had uncracked cross-sections. The test results are shown in fig. 1.14 and a curve has been drawn through the average values. This curve gives the influence of the smooth pressure head. By comparing this result with vane tests made in situ one gets on an average:

$$c_u \sim 0.93\, c_v \text{ if } H_o \sim D_o$$

and fig. 1.14 shows that using $H_o = D_o$ the influence of the pressure heads is negligible. The test curves with $H_o \sim 0.5\, D_o$ show no maximum stress or vertical tangent, but have ever increasing values of the stress according to the increasing influence of the pressure head. Tests with $H_o \sim D$ show vertical tangents at failure, confirming that the influence is very small (fig. 1.15).

When testing sand the height of the sample is also equal to the diameter to prevent the formation of rupture surfaces. But it is necessary to use more membrane to get a smooth pressure head. Therefore tests have been performed with a varying number of membranes. The results of a test series are shown in fig. 1.16 and it will be seen that when using more

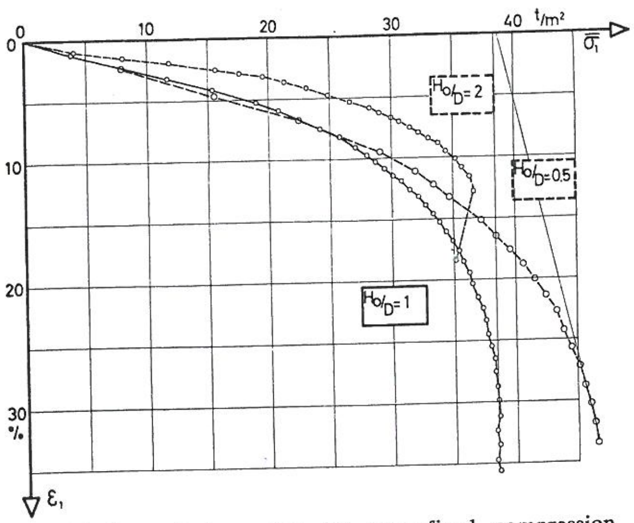

Fig. 1.15 Stress-strain curves for unconfined compression tests with free ends. H_0 is the initial height of the sample and D the sample diameter. Kratbjerg moraine clay.

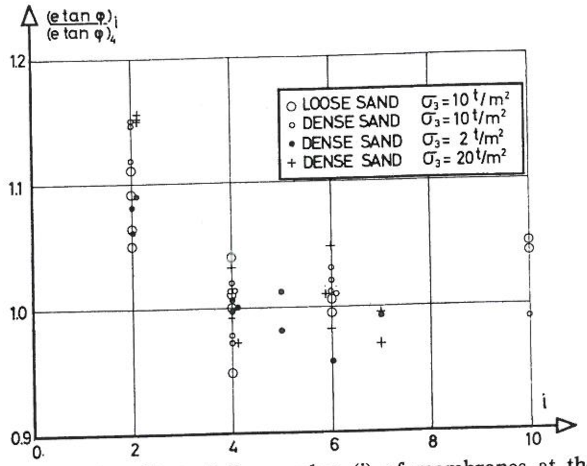

Fig. 1.16 The effect of the number (i) of membranes at the free ends by testing of sand. The results show that four membranes on each pressure head is minimum. G-12 sand.

than four membranes similar results are obtained. In this case four membranes were used.

Fig. 1.17 shows a sample of moraine clay after a test with a deformation of about 15 %. It is obvious that all parts of the specimen have been in a state of failure and that the strain distribution is rather uniform.

Fig. 1.17 also shows a sample of sand after a test with a deformation of about 15 %.

2. *Deformations of the Apparatus Itself*

The deformations of the apparatus is tested by means of a brass cylinder with the same dimensions as those of the sample. Calibration curves for a standard triaxial apparatus with rough end platens are shown in fig. 1.18. The measurement of vertical deformations and loads takes place outside the cell. Variation of the vertical load causes bending of the bottom plate. When the cell pressure changes, bending in the top plate and deformations in threads and bolts also take place. The crushing of grains between

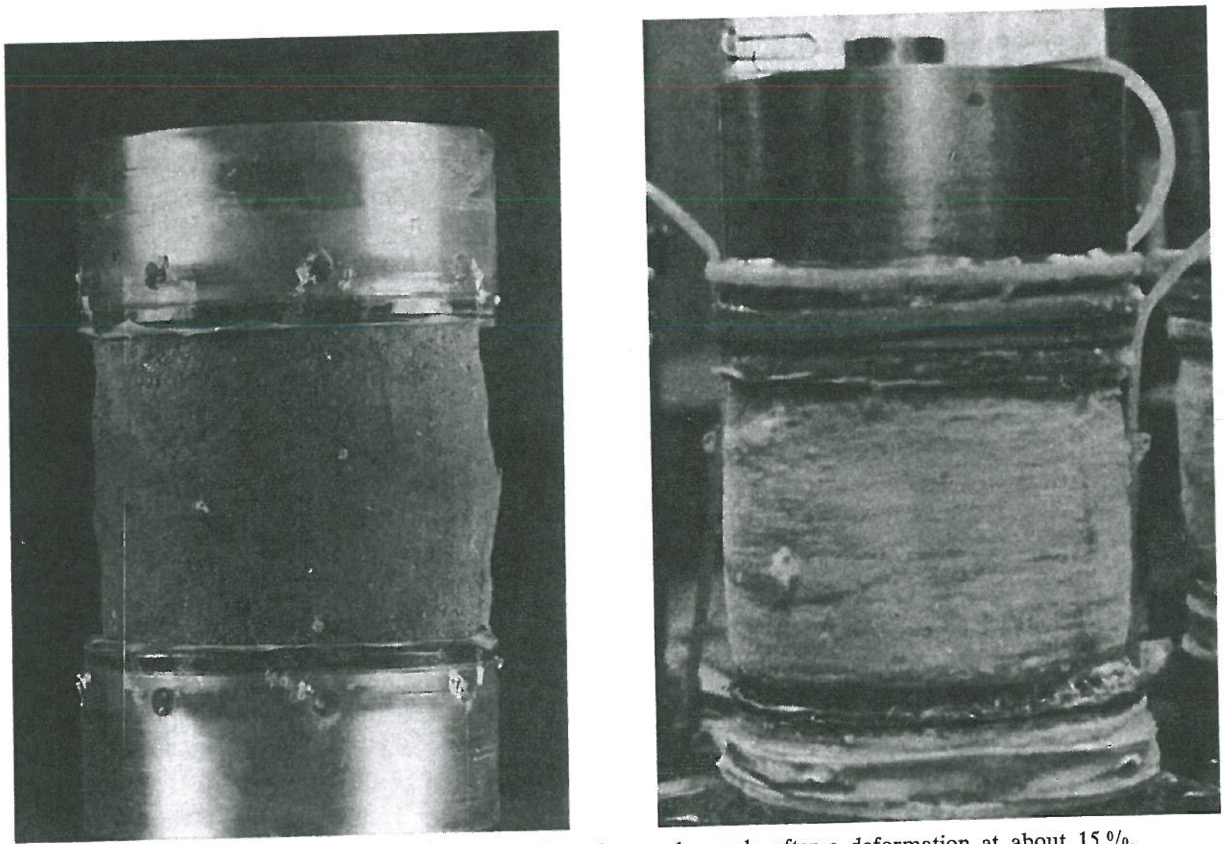

Fig. 1.17 Samples after rupture. A moraine clay sample and a sand sample after a deformation at about 15 %.

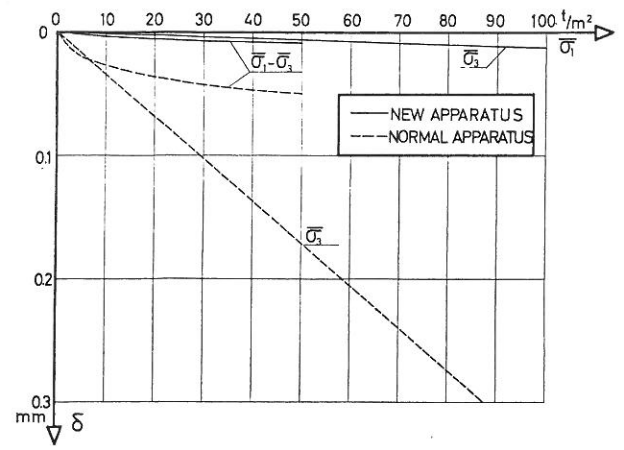

Fig. 1.18 Calibration curves for the measurement of vertical deformations. In the normal apparatus cylindrical brass samples are used with a cross-section area of 10 cm². In the new one the area is 38.5 cm².

two parts plays a large role too. Only some of these deformations are reproducible. Therefore even carefully calibrated apparatus is not suitable for measuring vertical deformations on firm soils. The influence of the apparatus can exceed the deformation of the sample proper.

By placing the dial gauges inside the cell it is possible to measure directly from the lower pressure head to the upper. This gives the further advantage that it is possible to measure the deformations directly also under isotropic conditions without moving the piston and without giving the specimen some vertical load.

Dial gauges are still used, but it is necessary to have oil in the upper part of the cell. Dial gauges work well in oil, but it is necessary to store them in oil between tests. Otherwise the oil will coagulate.

In this way the elasticity of the apparatus is reduced essentially (fig. 1.18). The last deformations are caused by the thin rubber membrane and silicone layer situated at the pressure head. When making the

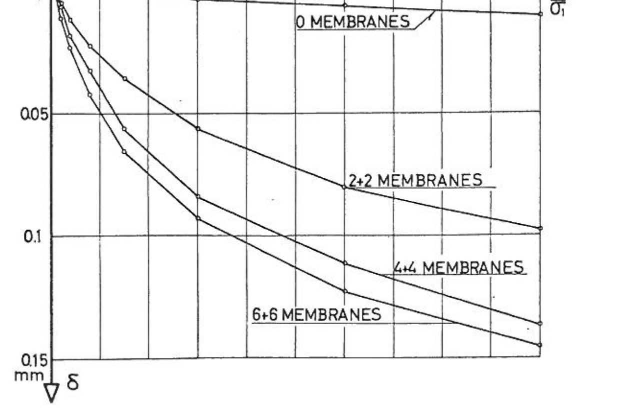

Fig. 1.19 The additional effect of the number of membranes on the measurement of vertical deformation. (Sand).

tests as accurately as possible, it is necessary to make calibration curves for each soil, especially if sand is used, because the grains will penetrate into the rubber. This effect is of great importance for small deviator stresses.

Fig. 1.19 shows calibration curves for sand. A 2 mm high sample is tested under isotropic compression and the curves give only the penetration deformations. It will be seen that the first membrane has the biggest effect. This means that the penetration gives greater deformations than the compression of the rubber itself.

It may be seen that these new deformations are of the same order of magnitude as those in the normal apparatus. The advantages of the new device are that smooth pressure heads can be used, measurements under triaxial compression can be carried out and the deformations caused by the rubber membrane can be calibrated.

3. Piston friction

The influence of friction along the piston may be avoided by measuring the vertical load inside the cell. Therefore a rather small loading frame is constructed.

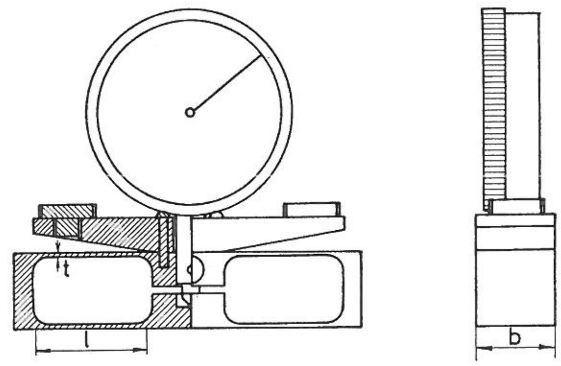

Fig. 1.20 A new proving frame.

The proving frame is shown in fig. 1.20. It consists of a loading frame and a beam. The dial gauge is placed directly in the frame. The frame is made in one single piece and the calibration is thus constant. It functions as four fixed beams, and the deformation and stress is given here:

$$\delta = \frac{l^3}{Ebt^3} P \qquad \sigma = \frac{3Pl}{2bt^2}$$

The symbols are shown in the figure. The gap in the middle closes under maximum loads to avoid destruction of the frame.

The maximum stress in the frames is $\sigma_{max} = 10500$ kg/cm².

The interior profile of the frame is milled out and is standard for a series of frames. Only the thickness of the flabs varies from one frame to another and this makes a series of different frames quite as cheap as a series of identical frames.

4. Premature Collapse of the Sample

The deformations in the frame are very small and it is necessary to use very sensitive dials ($\delta < 1$ mm for max.load). By using these stiff proving frames it is possible to avoid premature collapse of the sample. This is a phenomenon which otherwise may occur in sands at low cell pressures.

5. Membrane Effects

Air dissolved in the water diffuses through the rubber membrane especially at high cell pressures. This gives errors in the measurement of volume changes or pore water pressures. By using de-aired water in the cell this effect is reduced.

By using smooth pressure heads with diameters larger than that of the specimen some cavities are formed in the corners when cylindrical membranes are used. Under increasing cell pressure the water in these cavities enters the sample or gets into the volume-measuring system. It is therefore necessary to make membranes with corners.

If tests are carried out with moraine clay this method is not sufficient. Moraine clay contains stones and some of these are located at the surface of the specimen. Removal of the stones and replacement by remoulded material gives locally weaker parts in the sample.

If the stones are situated at the ends, it is of course necessary to remove them. If not, it is better to let the stones remain. In order to avoid having water between the membrane and the sample around the stones a rubber fluid is painted directly onto the surface of the sample and after a drying period a rubber membrane is formed with ideal adaptation to the specimen.

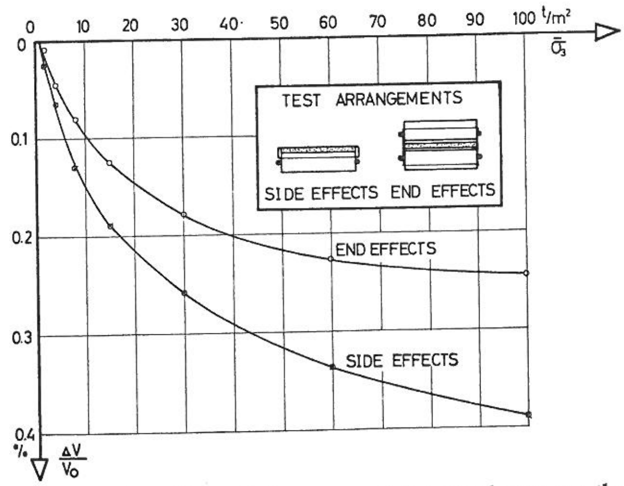

Fig. 1.21 The effect of the surrounding membrane on the measurement of volume changes. G-12 sand.

If filter papers are used to reduce the drainage period it is necessary to calibrate this effect.

Sand tests give rise to further problems. Under increasing vertical pressure the sandgrains will penetrate into the membranes on the pressure heads and as the cell pressure increases the surrounding membrane is pressed into the spaces between the grains. When calibrating the first effect a 2 mm high sand sample is placed between the pressure heads mounted with silicon grease and membranes. The second effect is calibrated by means of 2 mm of sand layered on the pressure head and with a rubber membrane embracing the sand surface. After correction for isotropic compression one gets the curves shown in fig. 1.21.

6. Measurement of Pore Water Pressure

The most important source of error is air bubbles situated in the connections between the pore water system and the measuring system, giving differences in the water pressures in the two systems.

When using filter-discs some air is always situated in the upper part of them after establishment of the specimen, even if water is washed through the filter-disc. By pressing water through the specimen, possibly by using back pressure, one may succeed in getting the air through the specimen – some of it dissolved in water. It is evidently a good method for sand samples, but for clay it is in fact impossible. The process takes too long and the binding between the clay particles is spoiled.

In the new triaxial equipment filter-discs are only used when testing sand. These have a diameter of 7 mm i.e. 10 % of that of the sample, and are placed in the center of the pressure head. When testing moraine clay the filter system consists only of four surface drains extending from the lower to the upper pressure head. The drain is made of filter paper with a small strip of sand and is rather incompressible. The water can be washed through this system outside the specimen and the air bubbles can be effectively removed. This ensures an effective connection between the pore water and the outer system (fig. 1.22).

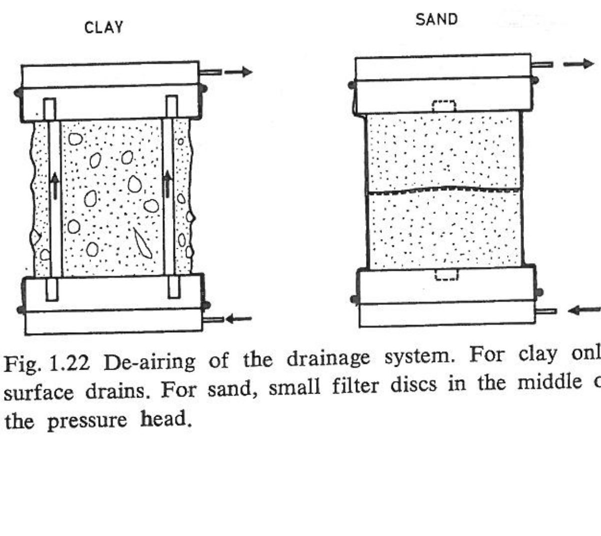

Fig. 1.22 De-airing of the drainage system. For clay only surface drains. For sand, small filter discs in the middle of the pressure head.

The New Triaxial Equipment

A drawing of the new triaxial cell is shown in fig. 1.23. In the top plate there is a spindle for the piston and an air valve. The upper part of the cell is filled with oil, in which the proving frame and the dials are placed. The oil enters through a tube from the bottom. The sample stands on a plate in the bottom of the cell. This plate is connected with the bottom through a ball and three screws, which can make the plate tilt. This makes it possible always to get the centre line of the proving frame and that of the upper pressure head to coincide. The connection between pressure head and proving frame is a ball situated between two plates having the same diameter as a small plate on the proving frame. When the first load is applied this system gives no horizontal stresses or displacements of the upper pressure head.

The rods for the deformation dials are placed on the plate in the bottom. The space between the lower pressure head and this plate is cast out with gypsum to avoid deformations here.

The cell pressure is controlled by Bishop's mercury pressure control.

The volume change is measured by watching the pore water flowing to or from the sample. The measurements take place in a horizontal capillary tube with an air bubble inside.

Fig. 1.24 shows a photo of the new equipment.

When using smooth pressure heads a special sand sample former is necessary, because the diameter of the pressure heads is greater than that of the sample (fig. 1.25).

When performing extension tests it is necessary to use other pressure heads and another connection between the proving frame and the pressure head. The

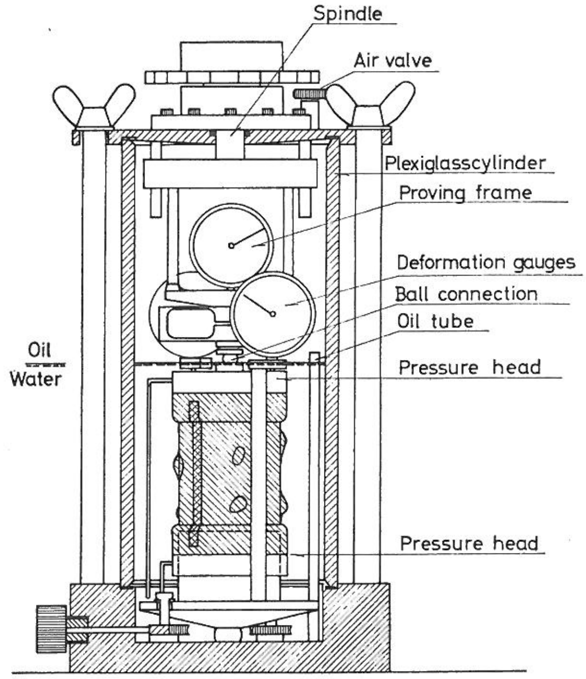

Fig. 1.23 The new triaxial cell.

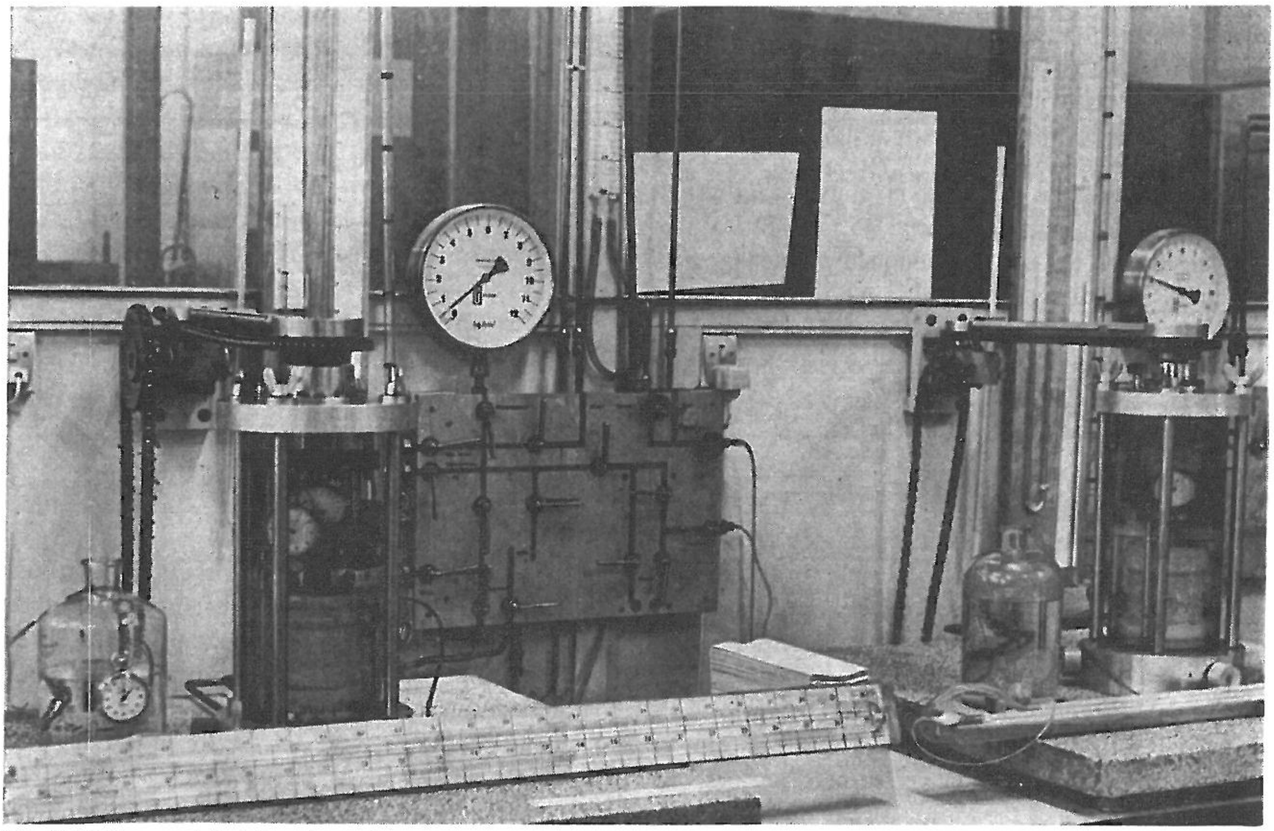

Fig. 1.24 The new triaxial equipment.

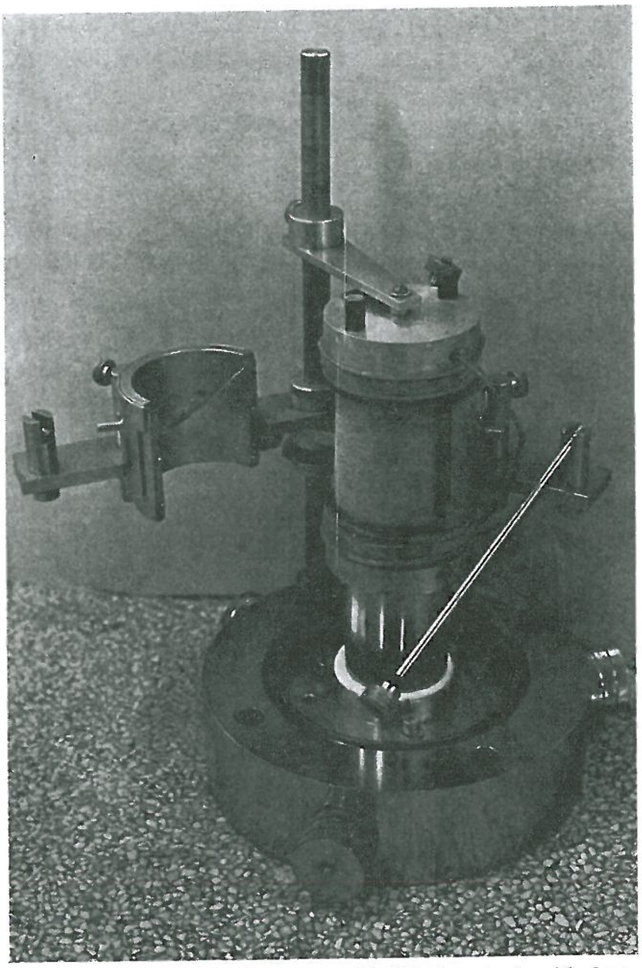

Fig. 1.25 A sand sample former. Used before tests with free ends.

pressure head can be screwed onto the plate and a ball connection fixed onto the frame. In the upper pressure head a piston is hydraulically moved into a hole in the ball connection.

Extension tests on firm soils give always a distinct rupture surface inclined nearly $45° + \bar{\varphi}/2$ to the vertical, and all the above-mentioned problems come up again. It is therefore actually impossible to make good extension tests on firm soils, and a comparison between compression and extension tests is not applicable.

Test Procedures

When preparing a sample of a firm clay such as for instance moraine clay, it is impossible to get the end surfaces smooth, and during the first part of a test this may give some bedding effects. It is therefore necessary to preload the sample. This is normally carried out under isotropic compression. Experience with oedometer tests shows that it is very important not to exceed the preconsolidation pressure. Therefore, we normally reconstruct the "mean stress"-history in the first isotropic part of the test.

When making rupture tests the vertical normal stress sometimes exceeds the maximum isotropic load, and some bedding effects will occur which will normally weaken the sample. This effect can be minimized by giving the sample an additional undrained vertical load. It is not possible to exceed the "mean preconsolidation pressure" in the undrained state.

The effect of the filters on the measurement of volume change is greatest during primary loadings. For reloading curves this effect is negligible.

Preparation of sand samples always consists of layering sand in a sand form and giving it its natural state. The "mean stress"-history is normally reconstructed.

Isotropic Compression

On a stiff, preconsolidated clay some tests are performed as isotropic recompression curves with unloading and reloading cycles. The influence of the filter may be very small and $\varepsilon_v/\varepsilon_1$ is near 3, as shown in table 1.1. It is not necessary to make corrections, because these are minor only.

TABLE 1.1

Isotropic compression test

$\varepsilon_v/\varepsilon_1$ measured on moraine clay

σ_3 t/m²	$\Delta\, \varepsilon_v/\varepsilon_1$	Mean value
99.3	3.06	
39.3	2.46	
9.65	3.90	3.50
19.3	2.86	
39.3	3.62	
99.3	2.71	3.00
19.3	3.16	
4.83	3.32	3.24
9.65	2.83	
19.3	2.75	
39.3	3.03	
99.3	2.68	2.78
9.65	2.96	
2.41	3.54	3.23

σ_3 t/m²	$\Delta\, \varepsilon_v/\varepsilon_1$	Mean value
4.83	2.87	
9.65	2.80	
19.30	2.70	
39.30	3.50	
99.30	2.26	2.81
9.65	2.96	
0.77	2.94	2.94
2.41	2.80	
4.83	2.65	
9.65	2.84	
19.30	2.78	
39.30	3.68	
99.30	2.70	2.93

The volume changes are very great in isotropic compression compared with the beginning of other kinds of tests. When performing a rupture test after isotropic compression cycles or after primary isotropic compression, it is necessary to let the latest isotropic stresses act on the sample for such a long time that the volume changes decrease very much.

When testing sand the membranes fit into the interstices between the surface grains giving an increase of the volume change. Normally "smooth" pressure heads are used, but without membranes and grease, in order to minimize the corrections in the vertical direction. After the test it is of course necessary to make these corrections. An example is given in table 1.2. $\varepsilon_v/\varepsilon_1$ is then near 3, but incorrected 5 to 12!

TABLE 1.2

Isotropic compression tests

Mean values of 2 × 5 tests on sand

		measured			corrected		
void ratio	σ_3 t/m²	ε_1 %	ε_v %	$\varepsilon_v/\varepsilon_1$	ε_1 %	ε_v %	$\varepsilon_v/\varepsilon_1$
	1	0	0				
	2	0.003	0.037	12.3	0.003	0.017	5.7
0.56	4	0.012	0.109	9.1	0.012	0.044	3.7
	8	0.029	0.205	7.0	0.029	0.076	2.6
	15	0.050	0.320	6.4	0.049	0.132	2.7
	30	0.083	0.483	5.8	0.080	0.226	2.8
	60	0.136	0.695	5.1	0.131	0.359	2.7
	100	0.191	0.900	4.7	0.197	0.512	2.6
	1						
	2	0.003	0.036	18.–	0.003	0.016	5.3
0.64	4	0.015	0.118	7.9	0.015	0.053	3.5
	8	0.035	0.247	7.1	0.034	0.118	3.5
	15	0.061	0.409	6.7	0.058	0.221	3.8
	30	0.105	0.619	5.9	0.099	0.362	3.6
	60	0.168	0.906	5.4	0.158	0.570	3.6
	100	0.231	1.168	5.1	0.216	0.780	3.6

Drained Tests with Constant Cell Pressure

There is no influence from the surrounding membrane in this type of test.

In the new apparatus there is nearly uniform stress and strain distribution even at failure. It gives from the very beginning of the test vertical deformations smaller than those measured in the normal way, as is shown in fig. 1.26. It also gives greater volume changes than normally measured. Consequently the drainage period continues for a longer time.

This kind of test is therefore only suitable for sand.

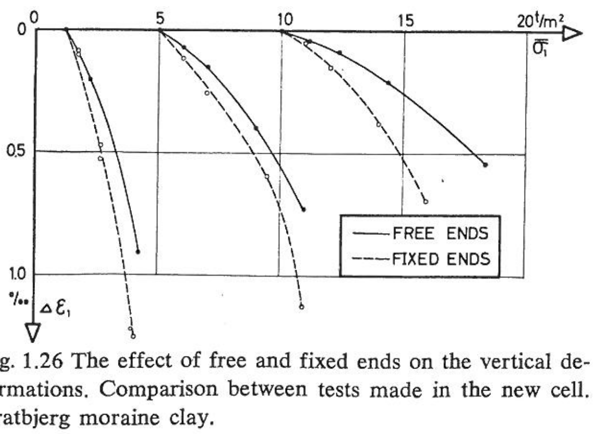

Fig. 1.26 The effect of free and fixed ends on the vertical deformations. Comparison between tests made in the new cell. Kratbjerg moraine clay.

Undrained Tests

At the D.G.I. these tests are normally performed as drained tests with constant volume and open drains. A thin capillary tube is connected with the pore water and during the test the cell pressure is varied so that no volume changes occur. The pore water pressure is zero and the measured stresses are the effective ones.

The stress path can be influenced by elasticity in the filter drains and by air diffusing through the membrane at high cell pressure.

These tests are normally used to estimate the undrained shear strength parameters for a clay and to give both drained and undrained parameters for a preconsolidated clay.

The Improvement Obtained in Test Results

Finally some tests made on the same soil, but in different apparatus, should be mentioned in order to illustrate the influence of the apparatus and the test procedures.

First we will compare tests in which the stress history is reconstructed.

Fig. 1.27 shows the results of two undrained tests performed with Kratbjerg moraine clay. It can be seen that in the normal apparatus the vertical deformation is overestimated at least by a factor of 2.

The stress paths for undrained tests on a heavily preconsolidated moraine clay with $c_u \sim 70$ t/m² are compared in fig. 1.28. Three tests in the normal apparatus are carried out from an initial isotropic pressure of 10, 25 and 60 t/m². Here peak values of $\sigma_1 - \sigma_3$ are observed. In the new apparatus the initial isotropic pressure is only 0.8 t/m², but this test gives nevertheless a greater undrained shear strength than those found in the normal apparatus. It may also be seen that the two test types give the same angle of internal friction, but different effective cohesion.

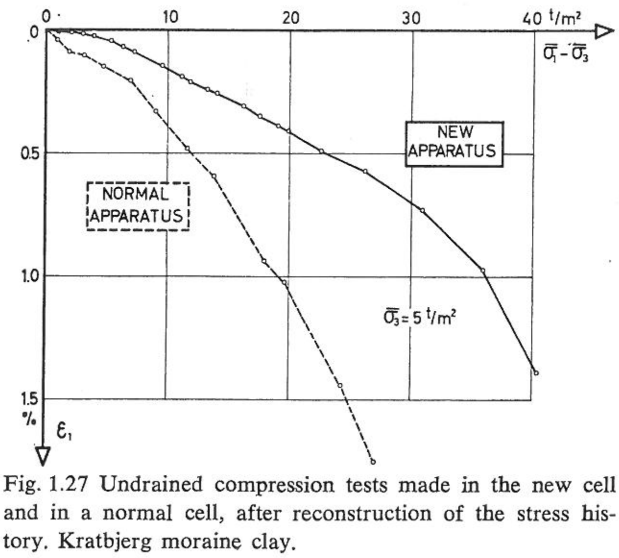

Fig. 1.27 Undrained compression tests made in the new cell and in a normal cell, after reconstruction of the stress history. Kratbjerg moraine clay.

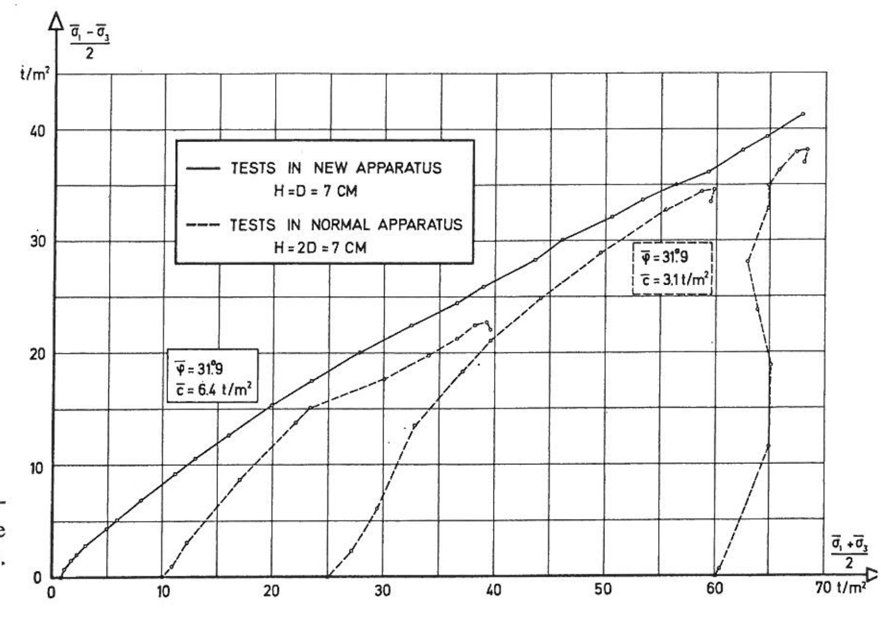

Fig. 1.28 Stress path in undrained compression test showing the influence of the formation of a distinct rupture plane. Carlsberg moraine clay.

In fig. 1.29 are shown the effects of the reconstruction of the stress history. Two tests are performed on a moraine clay with a preconsolidation pressure of only $\sigma_{pc} \sim 10$ t/m² and $c_u \sim 5$ t/m². In the new apparatus the stress history is reconstructed, but not in the normal one. The vertical deformation is here overestimated ten times in the normal apparatus!

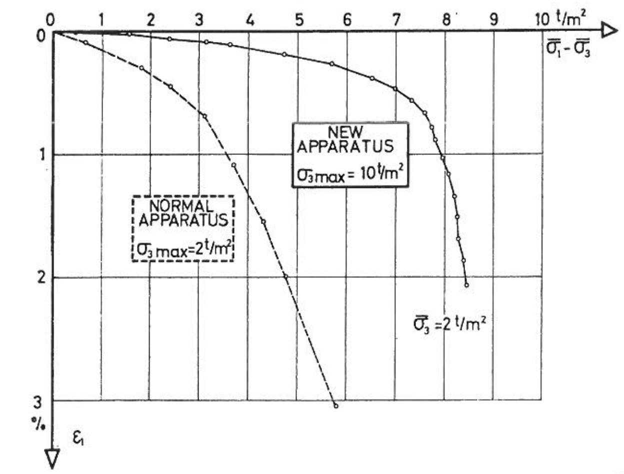

Fig. 1.29. Undrained compression tests made in the new cell and in a normal cell. The effect of the reconstruction of the stress history is also included. Sabro moraine clay.

Summary

When making laboratory tests with a preconsolidated moraine clay, it is important to reconstruct the "stress history" as closely as possibie. The reasons are that

1. It is necessary to adjust the sample as accurately as possible to the apparatus. This adjustment occurs at the primary curve, thus causing rather great deformations.
2. If the preconsolidation pressure is exceeded problems with remoulding and ageing effects arise and the void ratio changes too much.

After the primary curves, loading cycles should be carried out with varying unloading pressures according to the overburden effective pressures under the foundation.

When testing stiff soils such as preconsolidated clay or sand, it is absolutely necessary to have an "inelastic" apparatus which gives no deformation in itself. In normal apparatus the deformations may be overestimated 2 to 4 times!

In oedometer tests on moraine clay the bedding effect can be reduced by casting out with gypsum between sample and pressure heads.

When performing triaxial tests in the laboratory to get stress or strain parameters, it is very important to have a uniform stress and strain distribution. This is the case in oedometers, but in triaxial testing it is necessary to change the height of the sample from twice the diameter to the same as the diameter and to use smooth pressure heads. If the test is used to calculate deformations it is important to use "inelastic" apparatus.