G. Sandbaekken,[1] *T. Berre,* [1] *and S. Lacasse*[1]

Oedometer Testing at the Norwegian Geotechnical Institute

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ABSTRACT: The paper describes the test equipment, the testing procedures, and the interpretation of the results from oedometer tests as practiced today by the Norwegian Geotechnical Institute. Both the incremental loading and the constant-rate-of-strain methods are used. The test procedures and the interpretation include steps to account for the effects of sample disturbance. A new method for determination of the coefficient of consolidation is presented.

KEY WORDS: oedometer test, clay, sample disturbance, procedures, coefficient of consolidation

Oedometer tests were originally performed with an incremental loading procedure. Continuous loading tests were introduced and reported by Wissa and Heiberg [*1*], Wissa et al [*2*], Lowe et al [*3*], Smith and Wahls [*4*], Aboshi et al [*5*], and Janbu et al [*6*] among others. The continuous loading method includes constant rate of strain, controlled gradient, and constant rate of loading. In 1980 the Norwegian Geotechnical Institute (NGI) developed a fully automated continuous loading oedometer test device. The constant-rate-of-strain loading method was preferred to a controlled gradient because it was found mechanically simpler and easier to run.

Oedometer testing at NGI includes special trimming and mounting procedures and an unloading-reloading loop to correct the stress-strain curve for the sample disturbance affecting the behavior of a soil, especially at stresses lower than the preconsolidation stress.

This paper describes the oedometer cells, the specimen preparation techniques, the test procedures, and the interpretation of the tests as done at NGI. Typical results and the soil parameters inferred from the test are given.

[1] Norwegian Geotechnical Institute, Oslo, Norway.

Oedometer Cells

Three oedometer cells with soil specimen cross-sections of 20, 35, and 50 cm^2 are in use (Figs. 1 and 2). The height of the specimens is typically 20 mm, but 30-mm-high specimens are sometimes used with 50-cm^2 cross sections. The stainless steel oedometer ring has a highly polished inner surface. The 20-cm^2 ring has its own cutting edge. With the 35- and 50-cm^2 rings, an additional cutting ring is used to trim and mount the specimen. The top cap and the base plate, both made of chromed brass, are provided with 5-mm-thick porous stones to which two drainage tubes are connected. The diameter of the top cap is 0.15 to 0.25 mm less than the inner diameter of the oedometer ring. This type of oedometer allows one to:

1. Flush the porous stones with water after mounting of the specimen. In addition, evaporation from the specimen is prevented before flushing of the stones, which is important in the case of specimens mounted with dry filter stones.
2. Perform permeability tests and, in constant-rate-of-strain tests, measure pore pressure at the bottom stone.

The oedometer cell has also the possibility for back-pressuring if the drainage tubes from the top cap are removed and a chamber is placed around the specimen instead of the Perspex guiding ring (Figs. 3 and 4). The back-pressuring capacity of the chamber is 700 kN/m^2. A bellofram seals the chamber around the piston.

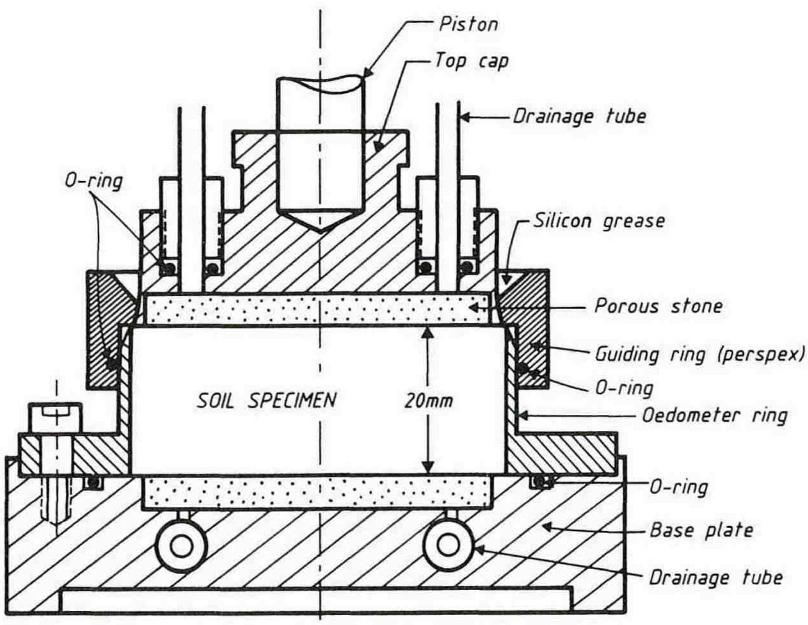


FIG. 1—*Schematic drawing of 20-cm² oedometer cell.*

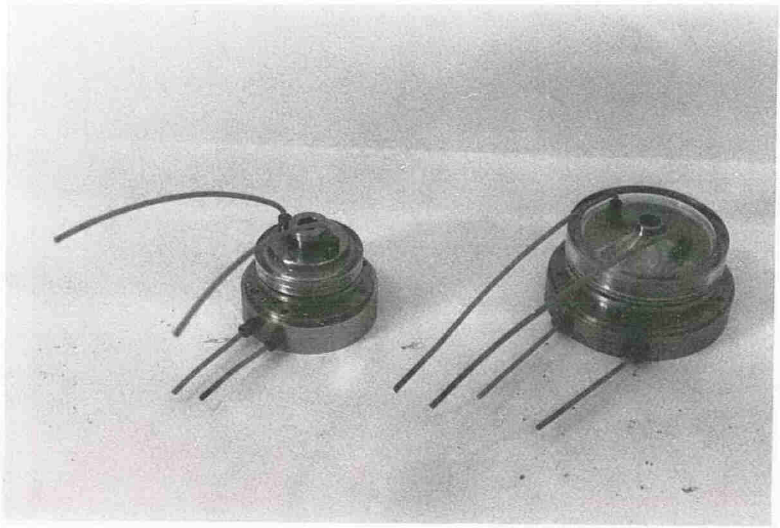


FIG. 2—*20- and 50-cm² oedometer cells.*

Trimming Equipment and Procedure

Two different methods of mounting the specimen into the oedometer ring exist. For very soft clays (undrained shear strength less than about 12 kN/m^2), the soil is pushed vertically from the sample tube directly into the oedometer ring. In this case, the extrusion is done continuously and at a rate of about 5 mm/min. For stiffer clay, the sample is first extruded and trimmed down to a diameter

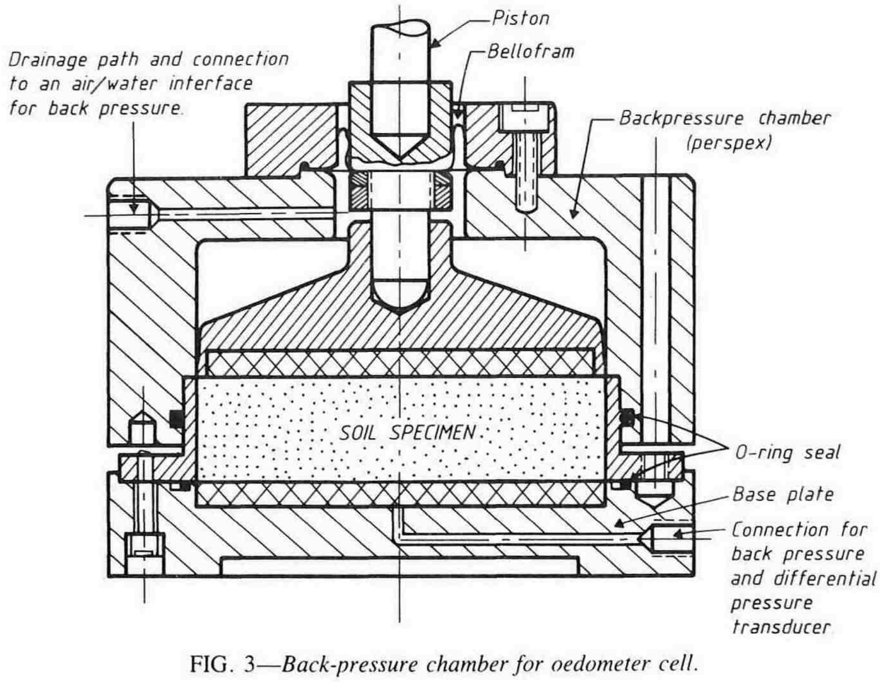


FIG. 3—*Back-pressure chamber for oedometer cell.*

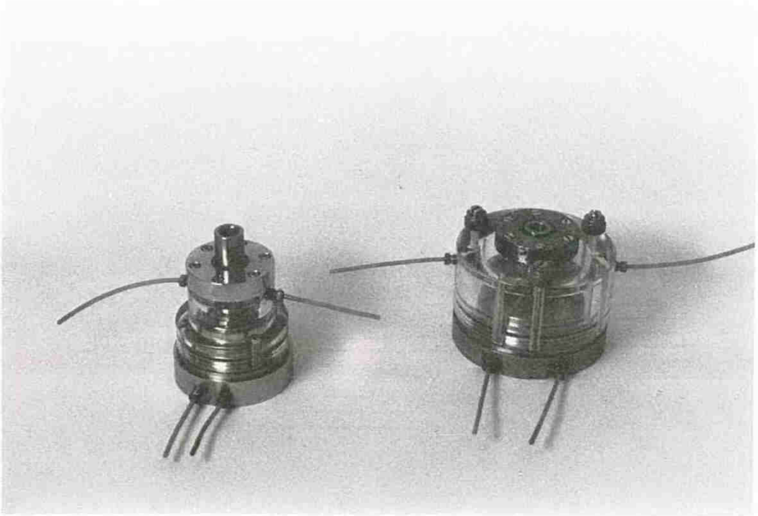


FIG. 4—*20- and 50-cm² oedometer cells with back-pressure chamber.*

slightly larger than the oedometer ring, and then pushed into the ring. To minimize evaporation from the soil specimen, the samples are trimmed and mounted in a room with humidity around 90%.

Very Soft Clay

Figure 5 illustrates the vertical extrusion of a sample directly into the oedometer ring. The oedometer ring is fastened upside down onto a yoke which is fixed to two guiding rods. The ring is coated with liquid paraffin oil to minimize wall friction. To provide the clay with as much lateral support as possible during the trimming operation, the distance between the top of the sample tube and the cutting ring is kept at a minimum (less than 10 mm). The extrusion rate is kept constant and slow enough to allow cutting away of the excess material with a spatula. Extrusion is stopped when the soil specimen protrudes 5 to 10 mm above the oedometer ring.

A wire is used to cut the clay several times under the edge of the cutting ring. Two very thin bronze plates are pushed into the cut previously made by the wire. The plates penetrate from each side of the specimen. A single bronze plate may also be used, but the clay above the plate may then tilt due to the insertion of the plate. The clay is cut several times below the brass plates with a wire, and while the wire is drawn quickly through the clay, the yoke holding the oedometer ring and the bronze plates is raised. The clay inside the oedometer ring is now completely separated from the rest of the sample in the tube.

The clay protruding from the top of the oedometer ring is cut away by means of a wire saw and a steel straight-edge before the base plate is mounted. The yoke is unfastened from the guide rods and rotated so that the cutting plates come on top. The cutting plates are removed and the top of the specimen is trimmed level.

For 35- and 50-cm^2 cells, the cutting ring on top of the oedometer ring is removed before a final trimming of the top surface of the specimen is done. The Perspex guiding ring and top cap are then put in place. The groove between the top cap and the Perspex guiding ring is filled with silicon grease to prevent evaporation from the specimen.

Medium-to-Stiff Clay

A 40- to 50-mm-high sample is extruded from the tube and trimmed down to a diameter about 5 mm larger than the inner diameter of the oedometer ring. The ring is coated with paraffin. The sample is pushed incrementally into the ring held by the yoke which is fixed to the two guiding rods. The excess material is cut away by means of a spatula. The remaining steps in the procedure are the same as described earlier for very soft clay except that the plate on which the specimen is placed replaces the two bronze cutting plates.

Mounting with Dry Filter Stones

At NGI, oedometer specimens are always mounted with dry filter stones to prevent swelling of the unloaded specimen. Figure 6 illustrates the difference observed in the behavior of a stiff clay mounted with dry and saturated filters. The main reason for the difference between the two curves is believed to be that the specimen with wet stones absorbs water from the stones and thereby softens. One may argue that dry stones may absorb water from the specimen and thereby cause an extra compression, which again could explain the higher p'_c-value for this specimen. However, when clay specimens are left overnight at a vertical stress equal to 0.25 p'_0, almost no compression is observed.

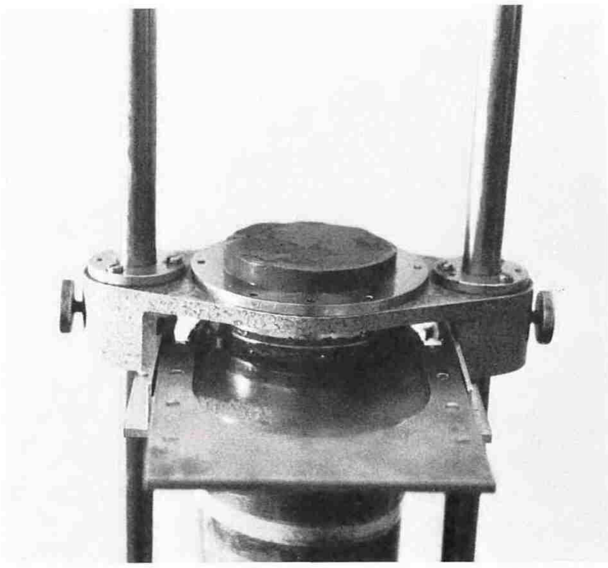


FIG. 5—*Specimen extruded from sample tube directly into the oedometer ring.*

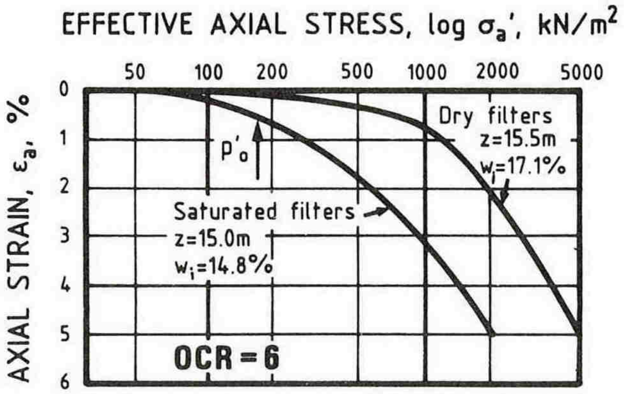


FIG. 6—*Results of incremental loading oedometer tests on stiff clay specimens mounted with dry and saturated filters* [7].

For quick clays, a wet filter paper (Whatman No. 54) is placed on the top surface of the specimen to prevent squeezing of the soil up in between the top cap and the oedometer ring. Otherwise filter paper is not used.

Incremental Loading (IL)

Apparatus

The loading apparatus (Fig. 7) consists of a standard Geonor loading frame with capacity of 10 kN and a 10:1 lever arm. The vertical compression of the specimen is measured by a dial gage with divisions in 0.01 mm.

Loading Procedure

Figure 8 illustrates the incremental loading procedure. The first load increment is usually equal to 25% of the *in situ* vertical effective stress, p'_0. For heavily overconsolidated clays, one may apply p'_0. A load increment ratio, $\Delta p/p$, equal to 1.0 (i.e., doubling the load for each increment) is used for loading up to p'_0. The stress at which unloading starts (called p'_1) is equal to either once or twice the preconsolidation stress p'_c (see later section on Sample Disturbance). When loading from p'_0 to p'_1, the load increment ratio is reduced to 0.5 to better define the stress-strain (load-compression) curve around the preconsolidation stress. The increment duration is usually 2.5 h (three increments in a workday). For most clays tested at NGI, this duration allows the specimen to reach end-of-primary consolidation. However, if the time compression curves (with Taylor's method) indicate that more time is required to reach end-of-primary, the increment duration is increased.

At p'_1, the stress is kept constant overnight. The compression reading after one night with constant stress is assumed to come close to the virgin curve for a test where all the increments have lasted 24 h. If it is assumed that the 2.5-h and the overnight virgin curves are parallel on a semilogarithmic plot [*8*], the overnight reading may be used to estimate the 24-h virgin curve and the 24-h p'_c. For tests where oedometer creep parameters are required, the stress may be held constant a week or even longer. At the end of the p'_1-increment, the porous stones are saturated with water of the same salinity as the pore water of the clay, and a constant-head permeability test is carried out (described below). The specimen is unloaded to p'_0, usually in two steps, and the stress is again kept constant overnight.

From p'_0 to $(p'_0 + p'_1)/2$ on the reloading curve, the load increment ratio is 1.0. Thereafter the load increment ratio is 0.5 until the stress has reached the virgin curve. The rest of the oedometer test is performed with a load increment ratio of 1.0. The specimen is loaded to about 9 p'_c or to the loading capacity of the apparatus. The maximum load is kept constant overnight (16 to 24 h) before a second constant head permeability test is performed. The whole loading procedure is performed with free drainage from the top and bottom filter stones.

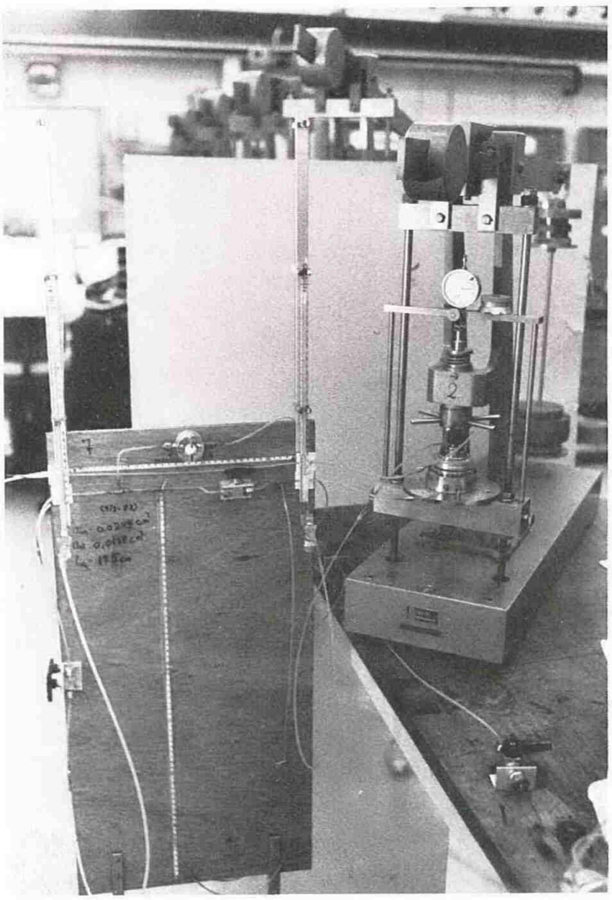


FIG. 7—*Incremental loading apparatus and constant-head permeability test setup.*

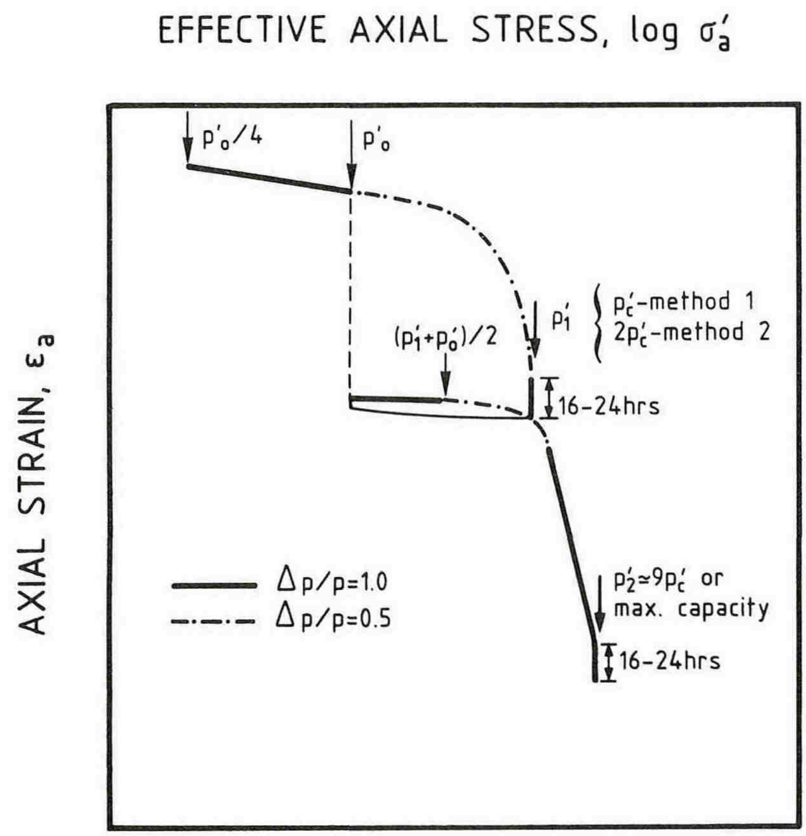


FIG. 8—*Incremental loading procedure.*

Correction for False Deformation

The initial deformation, as determined from a plot of deformation versus square root of time for the first load increment, is considered as false (although this is not quite true). For the rest of the test, false deformation is found from a calibration curve which has been determined with a steel dummy specimen between the porous stones.

Determination of Coefficient of Consolidation

The coefficient of consolidation, c_v, is computed from the coefficient of permeability, k, and the tangent constrained modulus, M (see later section on Determination of c_v). The relationship between k and axial strain, ϵ_a, called the k-line, is determined from time compression plots and from the two constant-head permeability tests run at p'_1 and p'_2. Axial strain and the logarithm of the permeability coefficient are assumed to plot on a straight line.

Time-Compression Plots and Coefficient of Permeability

From at least three load increments on the virgin stress-strain curve between p'_c and p'_2, the coefficient of permeability is calculated by means of Taylor's construction (Fig. 9).

Constant-Head Permeability Tests

The coefficient of permeability is measured twice during an incremental oedometer test. A schematic drawing of the portable apparatus used at NGI is shown on Fig. 10. Water of the same salinity as the pore water in the clay is pressed through the specimen, from bottom to top, by a mercury column in a U-shaped saran tubing. The amount of water flowing in and out of the specimen is measured separately. The test is continued until the water inflow and outflow are approximately equal. Almost no deformation of the specimen takes place during the permeability test, first because the test is carried out after the effective vertical stress has been kept constant overnight, and second because the applied gradient causes only a minor reduction in the effective stress from the stress on the virgin compression line.

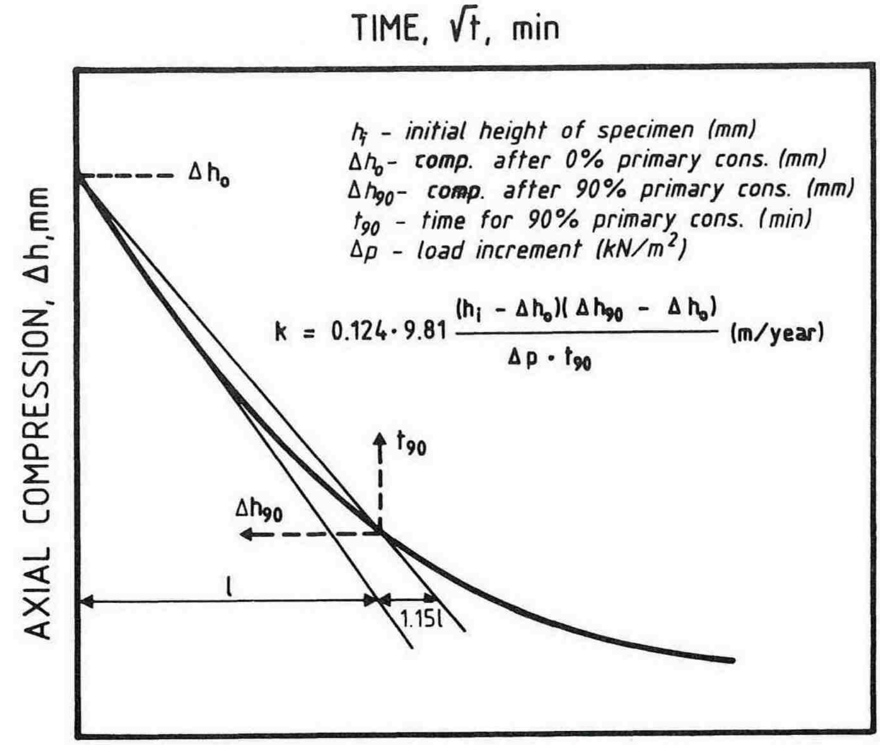


FIG. 9—*Coefficient of permeability* k *from time-compression curve.*

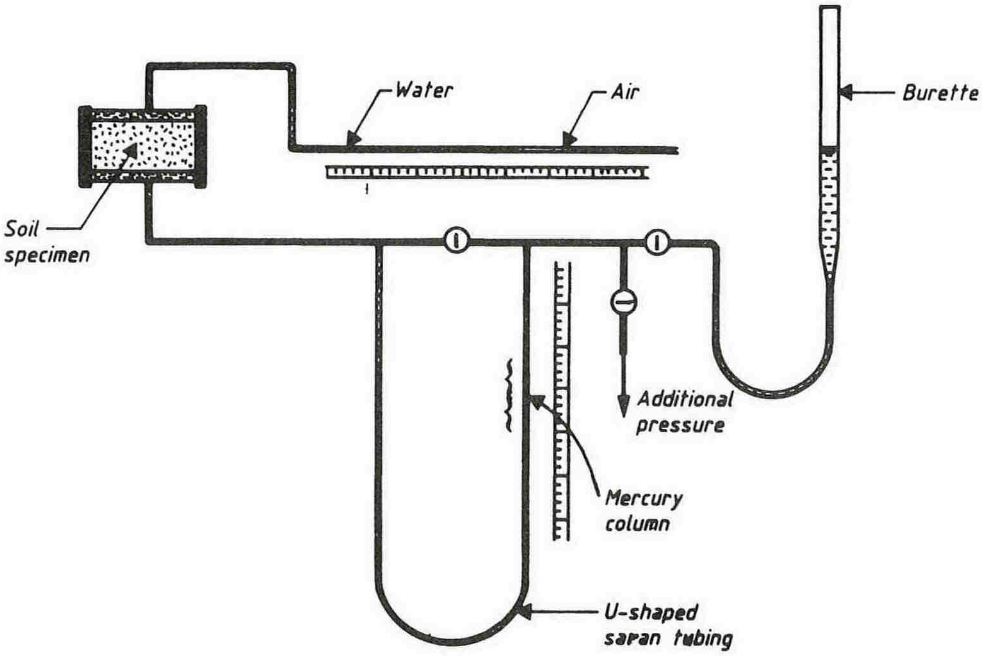


FIG. 10—*Sketch of apparatus for constant-head permeability test.*

A 100-mm-long mercury column provides a gradient sufficient to complete a permeability test in about two hours for a 20-mm-high clay specimen with a permeability coefficient of about 10^{-7}cm/s. For clays with lower permeability, the burette in Fig. 10 is replaced by a pressure source which acts in series with the mercury column. The excess pore pressure in the bottom porous stone is always kept less than about 10% of the vertical effective stress acting on the top of the specimen.

The permeability test may also be carried out with back pressure. Only the amount of water flowing into the specimen is measured. The test is then continued until the rate of flow has become approximately constant with time.

Continuous Loading (CRS)

Apparatus

Two different apparatuses for constant-rate-of-strain loading have been developed at NGI: an older type, which is a modification of the incremental loading device, and a new apparatus developed in 1984 especially for testing on board the drilling ships in the difficult North Sea environment (Figs. 11 and 12).

The onshore apparatus consists of a modified Geonor loading apparatus. The loading frame has a capacity of 10 kN and a 10:1 lever arm. A rectangular proving ring or a load cell for measuring vertical load is mounted in the vertical deadweight hanger which can be secured to a screw-thread jack (Fig. 11). The motor (12 V dc), placed on the front of the apparatus, drives a shaft connected to the screw-thread jack. The standard motor can apply a constant axial strain rate between almost 0 and 4% per hour on a 20-mm-high specimen.

The offshore apparatus consists of a loading frame and a ball screw assembly controlled by a stepping motor (24 V dc) (Fig. 12). The load capacity for the apparatus is 10 kN. An initial load up to 100 N can be applied on the specimen by dead weights. This new apparatus facilitates mounting of the oedometer cell into the loading apparatus under storm conditions, and minimizes the effects on the test from sea waves and vibrations in the ship. The new apparatus has proved much better than the older offshore CRS device in both respects (see next section).

For both apparatuses, the vertical load is measured with electronic load measuring devices. Vertical displacement is measured by a linear variable differential transducer (LVDT) mounted on the back side of a dial gage. Pore pressure is usually measured with a total pressure transducer. If back pressure is used, the difference between the pore pressure at the bottom of the specimen and the back pressure at the top is measured with a differential pressure transducer.

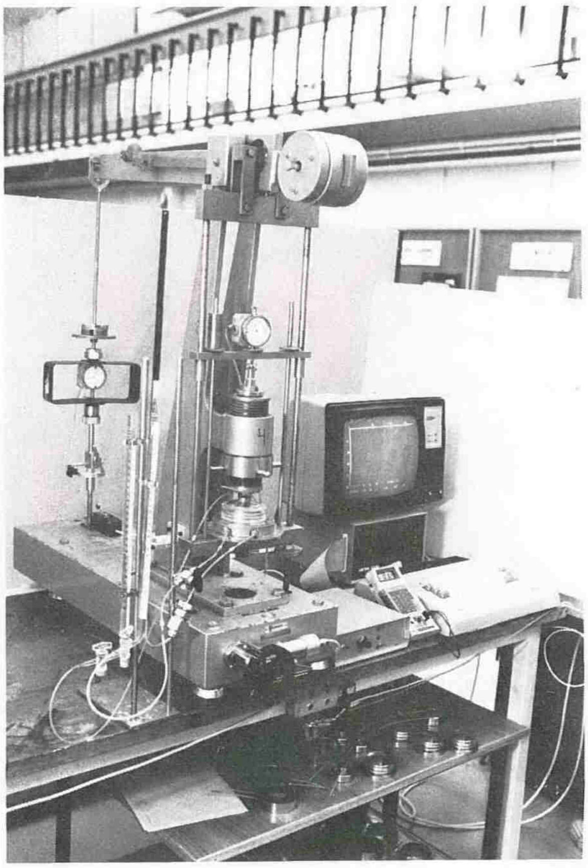


FIG. 11—*Constant-rate-of-strain oedometer used onshore.*

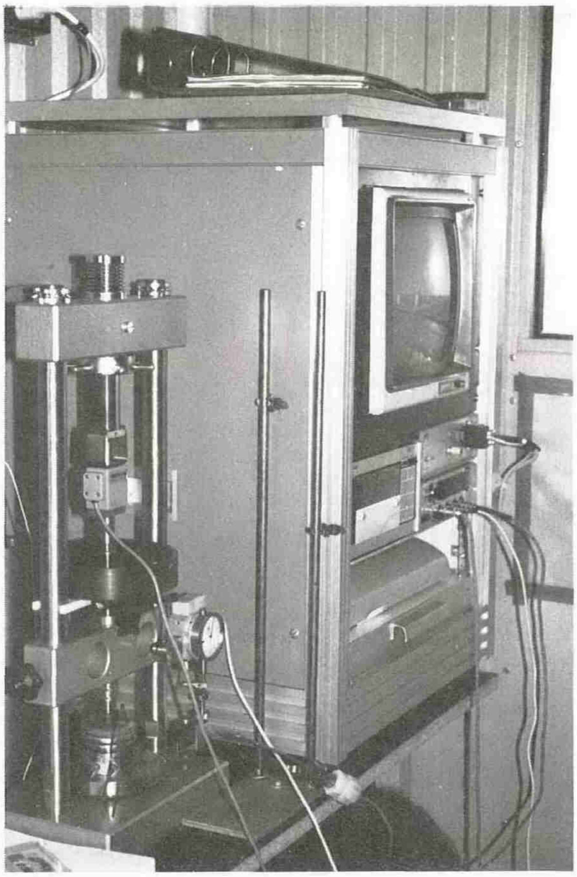


FIG. 12—*Constant-rate-of-strain oedometer used offshore.*

Data Acquisition and Regulation System

A microcomputer logs the test data at preselected time intervals. The data are recorded on a magnetic disk and then transferred to the main NGI computer for storage, computations, and plotting of standard diagrams. Offshore, the test data are stored on tapes or floppy disks and the test results are processed by the microcomputer. The interfacing box between the microcomputer and the loading apparatus was developed at NGI. The interfacing box provides the excitation voltage (6.0 V) to the transducers and the adjustable voltage to the motor. It also switches the motor on or off in one of two directions, depending on the orders from the computer.

The computer program gives the operator a choice of loading procedures. The operator inputs the following parameters:

- Time interval between readings.
- Stress before unloading (p'_1).

- Maximum stress after reloading (p'_2).
- Time interval under constant stress at p'_1 and/or p'_2.
- Number of unload-reload loops.

The loading procedure calls for very little manual intervention. Except for the first loading to 0.25 p'_0, saturation of the porous stones, and connection of the pore pressure transducer to the base plate, the entire test is performed by the microcomputer.

Loading Procedure

The loading procedure is very similar to the incremental loading procedure except that the load is applied at a constant rate of strain. The rate is chosen manually such that the excess pore pressure at the undrained base of the specimen never exceeds 5 to 10% of the total vertical stress.

Prior to the start of the continuous loading, a vertical stress approximately equal to $p'_0/4$ is applied by dead weights in one step. The vertical stress is thereafter increased continuously at a constant rate of strain. Saturation of the porous stones is done at the overburden stress p'_0, or above the assumed initial negative pore pressure in the specimen, if higher than p'_0. The porous stones are flushed with CO_2 for 5 min before saturation with water of the same salt concentration as the pore water of the specimen. For a test with back pressure, the latter is applied immediately after saturation of the porous stones. If the specimen tends to swell after saturation of the stones, the load is manually increased to prevent swelling. The remainder of the test is completely automatic.

As previously described, the specimen is continuously loaded to p'_1, where the load is held constant overnight (16 to 24 h). The excess pore pressure and the vertical displacement are recorded during this period. The specimen is then unloaded to p'_0. Some negative pore pressures develop during this unloading, but they are allowed to dissipate before reloading. Finally, the specimen is loaded to the maximum stress p'_2. Constant-head permeability tests are sometimes carried out to check the values back-calculated from the measured pore pressures. The permeability tests are done in the same manner as for the incremental loading tests.

The procedure described above is used onshore. Offshore, the periods with constant stress are considerably reduced in order to increase the number of tests per apparatus.

For many clays tested at NGI a rate of axial strain of 0.5 to 1.0% per hour seems adequate and maintains the ratio of pore pressure to total axial stress between 2 and 7% throughout the test. Readings of total axial load, axial displacement, and excess pore pressure are taken every 5 to 10 min. The stress-strain curve is plotted simultaneously on the monitor of the microcomputer.

Correction for false deformation is done exactly as described earlier for the incremental loading tests.

Test Results

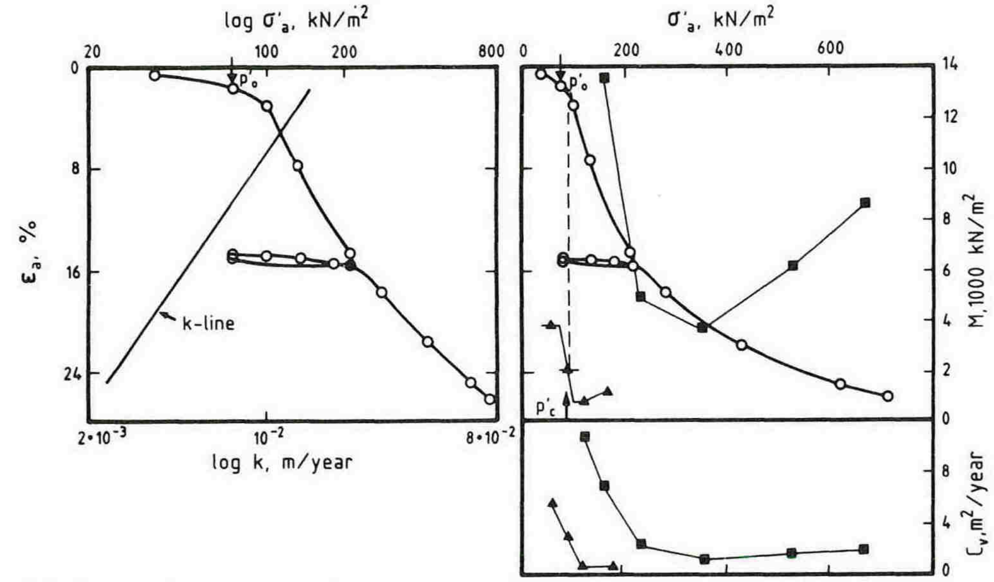
Incremental Loading

Figure 13 presents the stress-strain curve and permeability line (the *k*-line) from an incremental loading oedometer test on a lean North Sea clay. The data are generally plotted both on a semilog scale and on a natural scale (the latter recommended by Janbu [*9*] and Janbu et al [*6*]. In addition to the stress-strain curve, the plots provide coefficient of consolidation, coefficient of permeability, and constrained modulus. The interpretation of the test is discussed later.

Continuous Loading

Figure 14 gives an example of the results obtained from a CRS oedometer test on a soft plastic marine clay. The variation of the excess pore pressure during loading and reloading is also shown. Appendix I presents a few details of the method of interpretation used for the constant-rate-of-strain oedometer test.

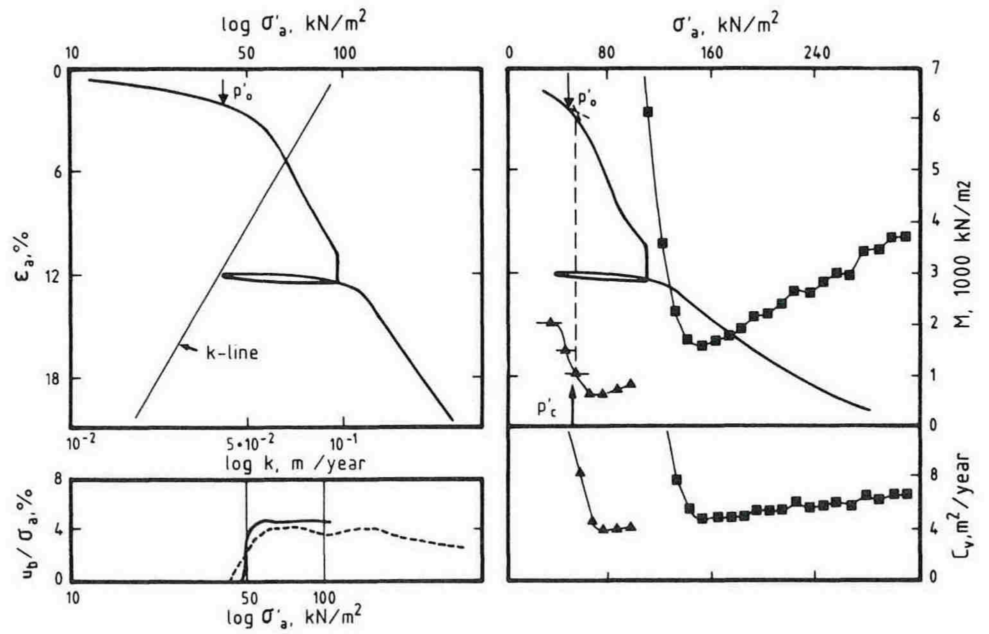
The first CRS oedometer tests carried out offshore (in 1983) were performed with the device shown in Fig. 11. Marginal weather conditions and vibrations on the ship resulted in wavy stress-strain curves as illustrated in Fig. 15*a*. The uniaxial type of loading frame now used offshore (Fig. 12) solved this difficulty, as shown by the comparative plots in Fig. 15*a*.



(a) Stress-strain curve and k-line in semi-log plot

(b) Stress-strain curve, constrained modulus and coefficient of consolidation (natural scale)

FIG. 13—*Results of incremental loading oedometer test on lean North Sea clay.*



(a) Stress-strain curve, k-line and excess pore pressure in semi-log plot

(b) Stress-strain curve, constrained modulus and coefficient of consolidation (natural scale)

FIG. 14—*Results of constant-rate-of-strain oedometer test on soft plastic clay.*

Sample Disturbance and Correction of Stress-Strain Curve

Figure 15*b* shows the stress-strain curves for (1) a slightly disturbed clay specimen, and (2) a perfect specimen of the same clay. Both specimens of undisturbed plastic clay from Drammen were initially artificially preconsolidated in oedometer cells. (This part of the loading is not shown in Fig. 15*b*.) One of the specimens was completed unloaded, mounted into a new oedometer cell with a smaller diameter and reloaded. This reloading curve is the "slightly disturbed specimen" curve in Fig. 15*b*. The other specimen was reloaded without doing anything which could disturb it. This reloading curve is the "perfect specimen" curve in Fig. 15*b*. The shape of the curve for the "slightly disturbed specimen" is not too bad with respect to disturbance. In fact, if the curve for the perfect specimen had not been there, the test would have been classified as very good. Still, the difference between the two curves is quite important. The curve for the slightly disturbed specimen has been corrected for disturbance according to the method proposed by Schmertmann [9]. It is seen that the corrected curve agrees very well with the curve for the perfect specimen.

When an oedometer curve is corrected for sample disturbance, the corrected curve usually deviates quite a lot from the uncorrected one as demonstrated in Fig. 15*b*. Therefore, correcting properly for sampling disturbance seems to be much more important than whether the load increments should be large or small,

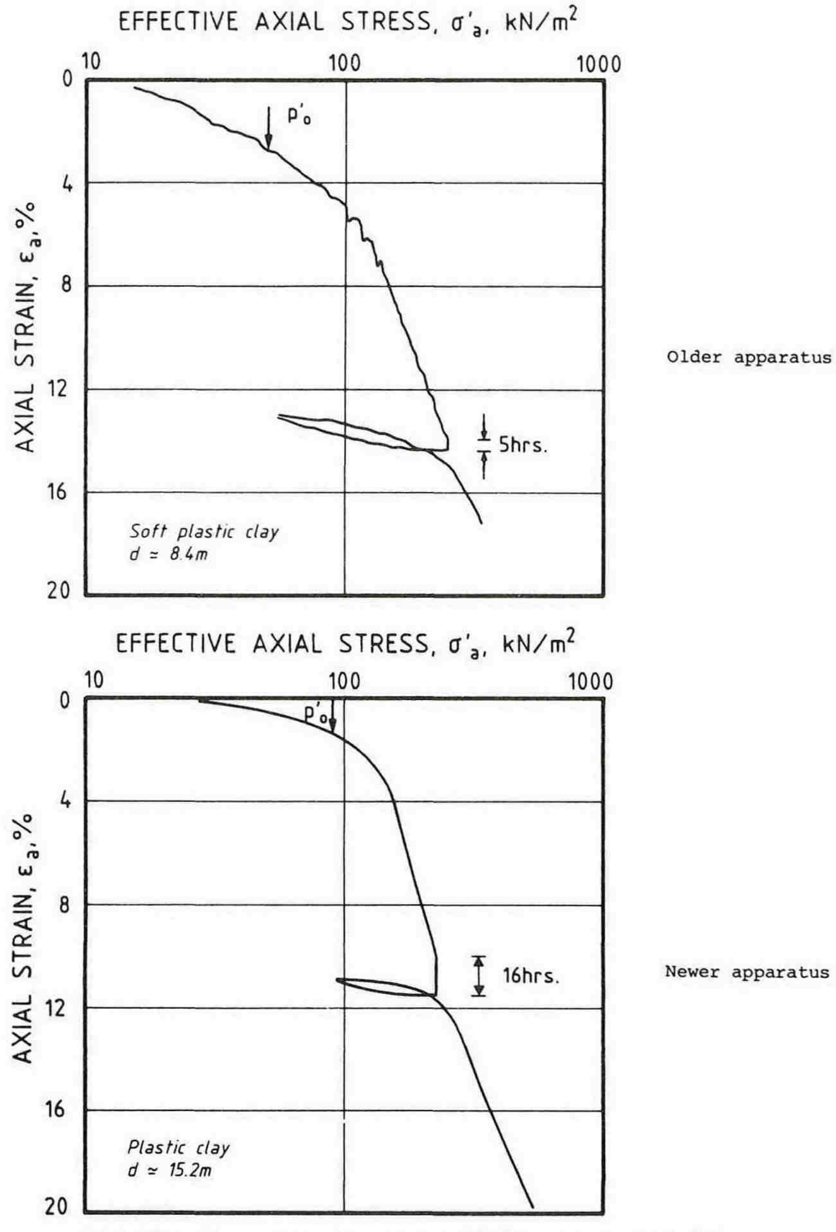


FIG. 15*a—Comparison of two types of CRS apparatus used offshore.*

whether the increment duration should be short or long, or whether the loading should be incremental or continuous. Consequently, extreme care should be taken:

- To obtain samples of high quality.
- To avoid, as much as possible, mechanical disturbance during extrusion, trimming, and mounting of the specimen into the oedometer cell.
- To avoid gaps between the specimen and the oedometer ring during mounting.

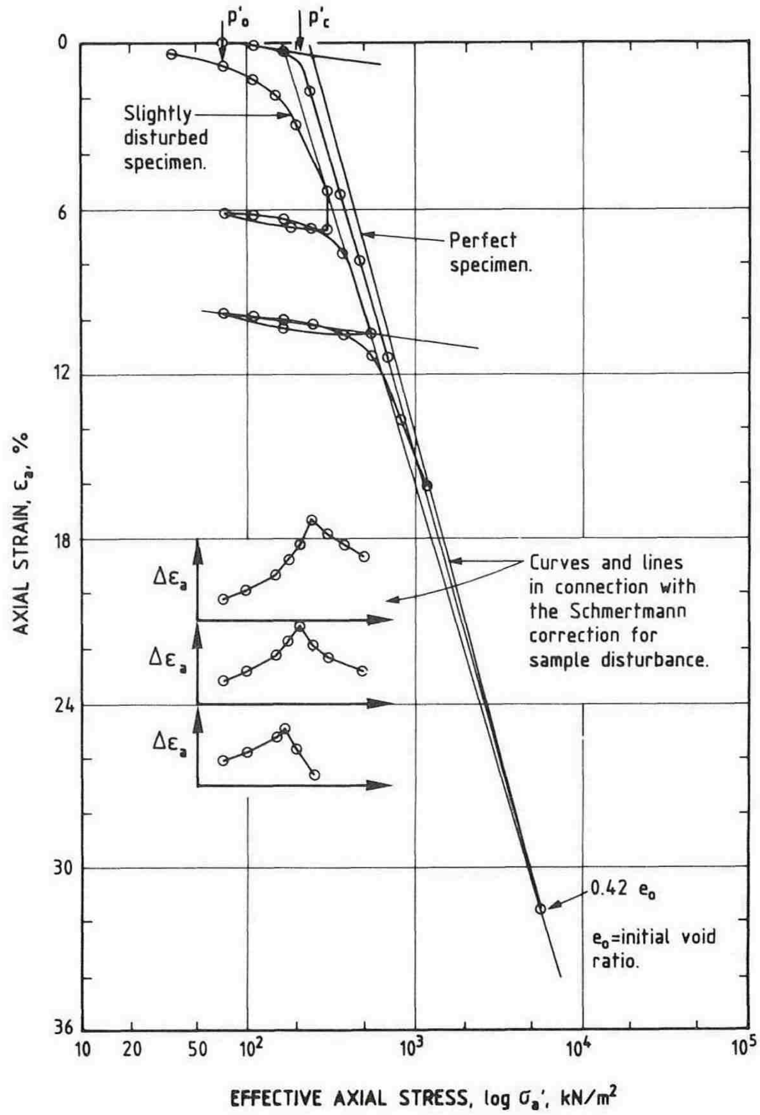


FIG. 15*b—Effect of sampling disturbance on stress-strain curve.*

- To prevent swelling of the specimen in the early stages of the test by using initially dry porous stones.

The disturbance is usually more severe for less-plastic materials. For disturbed samples, at stresses below the preconsolidation stress, the measured moduli tend to be too low, and at stresses above p'_c, the moduli tend to be too high (Fig. 15*b*).

The derived preconsolidation stress, p'_c, usually tends to become too low for disturbed specimens (Fig. 15*b*). However, p'_c may also be too high. The relative importance of sample disturbance is more pronounced at lower stresses.

To correct the stress-strain curve for the effects of sample disturbance at low stresses, an unloading-reloading loop is always included in the loading program (see Fig. 8). The stress at which unloading starts (p'_1) depends on which of two methods is used to correct p'_c for sample disturbance.

Method 1

The value of p'_1 is set equal to the preconsolidation stress (p'_c), where p'_c is estimated from the undrained shear strength, s_u, and the plasticity index, I_p [*11*].

The detailed procedure for this determination of p'_c is given in Appendix II. The oedometer reloading curve after unloading to p'_0 is then used *directly* for the settlement computations. This procedure has proved successful for the non-fissured heavily overconsolidated clays from the North Sea. The method should not be used for slightly overconsolidated clays. The s_u-values for the evaluation of p'_c are determined from unconfined compression and unconsolidated undrained triaxial tests. The p'_c-values obtained in this manner are usually considerably higher than the stress at the maximum curvature of the oedometer stress-strain curves. At least for uncemented clays, this may be due to the fact that the s_u-values for such clays are reached at very high axial strain values (10% or more) and are therefore less influenced by sample disturbance than the oedometer stress-strain curve around p'_c.

Method 2

The value of p'_1 is set equal to or slightly higher than twice the stress corresponding to the maximum curvature point on the oedometer stress-strain curve. The stress-strain curve may then be corrected for sample disturbance by Schmertmann's procedure [*10*], which requires an initial determination of p'_c. The value of p'_c is usually determined by Casagrande's [*12*], Janbu's [*13*], or Schmertmann's [*10*] methods, which all give approximately the same estimate. With Janbu's method, both the stress-strain and modulus-strain curves should be used to determine p'_c, as shown in Figs. 13 and 14. The Schmertmann method to correct the stress-strain curve includes using the unload-reload loop to account for disturbance effects during the initial loading to p'_c.

For the plastic, slightly overconsolidated Norwegian clays, the *in situ* p'_c-values may be considerably lower than even the 24-h oedometer p'_c. For plastic Drammen clay ($I_p \approx 30\%$) for example, the 100-year *in situ* p'_c seems to be about 25 to 30% lower than the 24-h oedometer p'_c. These figures have been estimated from data presented by Bjerrum [*14*] and Foss [*15*]. The indications are that the difference between the *in situ* p'_c and the oedometer p'_c increases with increasing plasticity.

Determination of c_v by the *k*-Line Method

For both incremental and continuous oedometer tests, the coefficient of consolidation c_v is computed from

$$c_v = k \cdot M \frac{1}{\gamma_w}$$

where k is the coefficient of permeability and M the tangent constrained modulus on the stress-strain curve.

For incremental tests, k is computed by the Taylor curve-fitting method for at least three load increments. Constant-head permeability tests are run at p'_1 and at the end of the test. The permeability values are plotted on a semilogarithmic scale versus vertical strain. For clays with a plasticity index below 20%, the two sets of k-values usually agree reasonably well, and plot on a straight line, the k-line. For more plastic clays, the k-values based on the time-compression curves tend to be lower than the directly measured values (see Fig. 16), more so for smaller load increments. In the case of such disagreement, the directly measured k-values are used to compute c_v. The k-values from the time-compression curves are believed to be too low because "delayed compression" in the soil skeleton retards the rate of compression. Delayed compression is a reduction in volume at unchanged effective stress if there were no water in the pores of the specimen (no hydrodynamic time lag) [*14*].

For sandy clays and silts, a difference between the two sets of k-values is also often seen (Fig. 17). The shape of the time-compression curve for this soil type is believed to be also largely governed by "delayed compression", because although the delayed compression in the soil skeleton is not as pronounced as for plastic clays, delayed compression still predominates the hydrodynamic time lag, because of the very high permeability of the material. In addition, one finds a large scatter in the permeability values back-figured from the time-compression curves because primary consolidation takes place so rapidly that it is difficult to

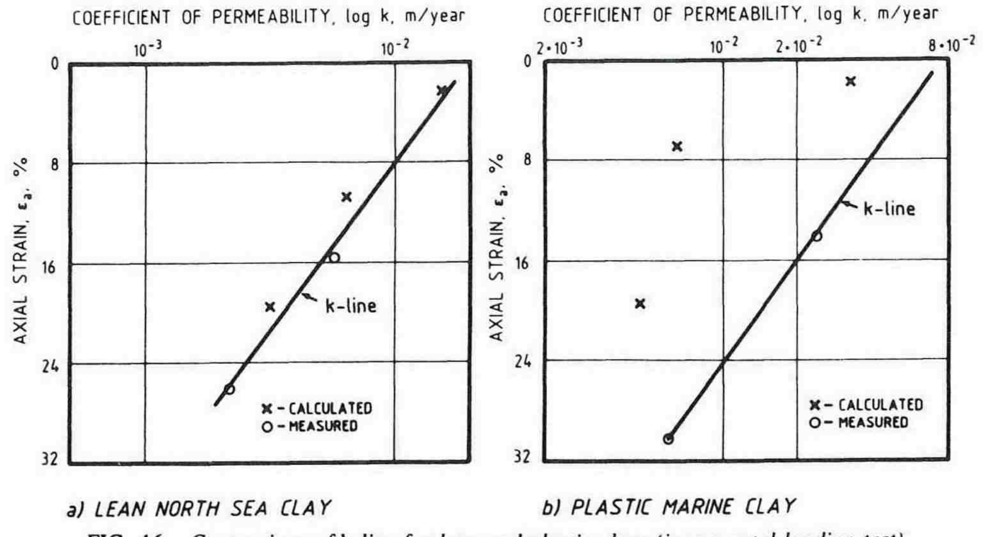


FIG. 16—*Comparison of* k-*line for lean and plastic clays (incremental loading test).*

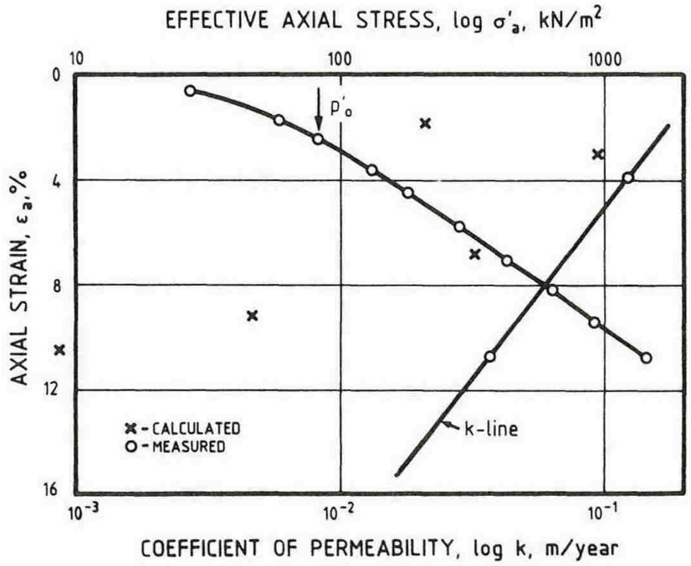


FIG. 17—*Oedometer curve for a clayey sandy silt (incremental loading test).*

interpret the time curves. For such soils, the directly measured *k*-values are also used to compute c_v.

For continuous tests, the value of the coefficient of permeability is computed from the excess pore pressure measured at the bottom of the specimen. The experience so far indicates that these *k*-values agree with constant-head test values over a wider range of soil types than the values back-calculated from time-compression curves in incremental tests. Constant-head permeability tests are carried out now and then to ensure that the *k*-values based on the excess pore pressure are realistic. As shown on Fig. 18, the *k*-values at the initial stage of the CRS test and during reloading (in the unloading-reloading loop) are much higher than the values corresponding to the virgin compression line. The latter are considered more reliable, and the *k*-line is drawn through these points.

The *k*-values corresponding to reloading approach the virgin compression values much more quickly when back pressure is used. This indicates that the deviations of the permeability coefficient during reloading are due, at least partly, to a lack of saturation of the bottom filter stone. Wissa et al [2] also pointed out that c_v-values from oedometer tests with back pressure were more reliable. For fully saturated soft clays, tests indicate little need for back pressure, whereas back-pressuring is preferable for stiff clays, even if practically fully saturated.

For both *incremental* and *CRS-tests,* one may argue that the tangent modulus, *M*, used to compute the total settlement in the field is not the correct value to use for obtaining the field c_v-value, since it implies that all settlement retardation in the field is due to hydrodynamic time lag. However, the approach is believed preferable to using c_v-values back-calculated directly from the time-compression curves, because these c_v-values can mean using very incorrect *k*- and *M*-values. The *M*-values may be incorrect because the ratio between primary and secondary compression may be much higher in the field than in the laboratory because of the usually much longer drainage path in the field. Another advantage with the *k*-line method is that the c_v-values may be based on modulus values corrected for sample disturbance and *k*-values from the *k*-line at the same void ratio as *in situ*. For loads between p'_0 and p'_c, this procedure can lead to c_v-values about three times larger than uncorrected c_v-values, which in turn may be two or three times higher than c_v-values derived directly from time-compression curves. The difference between the uncorrected c_v-values from the *k*-line method and those back-figured directly from the time-compression curves varies between 0 for clays with low secondary compression to as high as 3 for clays with pronounced secondary compression. The difference and scatter could well be more significant for clayey silts.

Summary

Both incremental and automatic continuous loading oedometer tests are run at the Norwegian Geotechnical Institute. Recently a special uniaxial automatic continuous oedometer has been developed for offshore use.

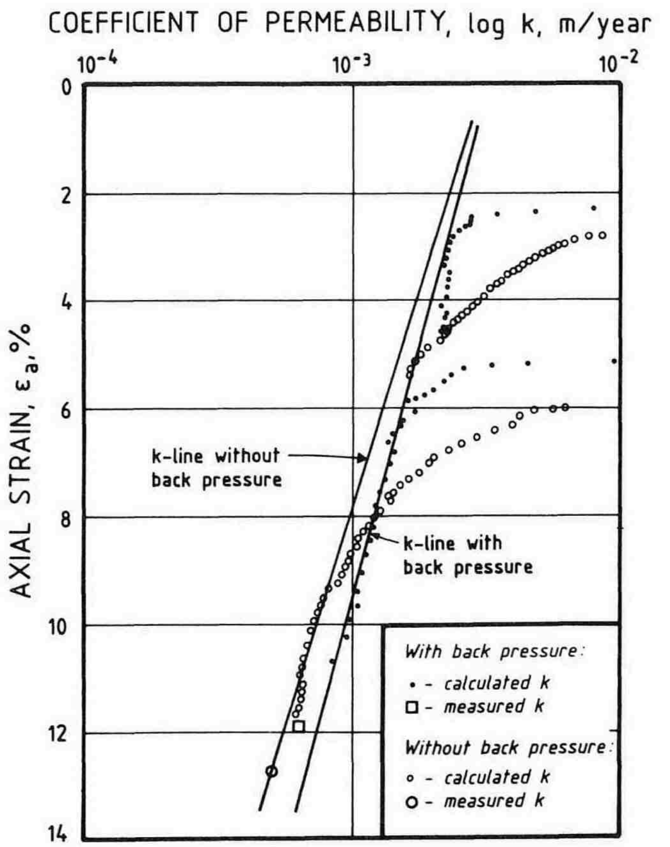


FIG. 18—*CRS oedometer test with and without back pressure.*

The commonly used test procedure includes an unload-reload loop to account for the effects of sampling disturbance, and two overnight loadings under constant effective stress to determine points on the 24-h virgin compression line and thereby the 24-h preconsolidation stress value. The durations of the other load increments are usually 2.5 h. Constant-head permeability tests are carried out before unloading, as a routine step of the incremental loading oedometer test. For constant-rate-of-strain tests, direct permeability measurements are made now and then to check the values back-calculated from the measured pore pressures.

The coefficient of consolidation is determined from the coefficient of permeability and the tangent constrained modulus on the stress-strain curve both for incremental and CRS tests. For incremental tests, the coefficient of permeability is based on direct measurements and the time compression curves.

It is essential in oedometer tests to correct properly for the effects of sampling disturbance. The procedures used to account for these are presented.

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APPENDIX I

Interpretation of CRS Oedometer Test

The theoretical solution for computing M, c_v, and k is based on the equations developed by Wissa et al [2]. The parameters M and c_v are assumed constant over an increment of time. The pore pressure distribution in the specimen is assumed parabolic (Fig. 19). The following test data are recorded:

- Δt time interval between readings,
- σ_a total stress at top of specimen (assumed uniform in specimen),
- u_b excess pore pressure at undrained specimen bottom,
- ϵ_a axial strain.

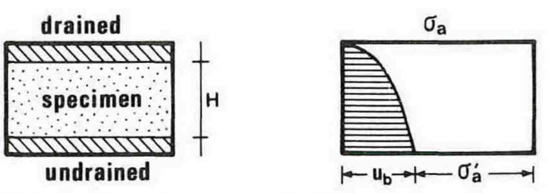

FIG. 19—*Stress distribution in CRS oedometer specimen.*

The test parameters are obtained as follows:

Average effective stress on the specimen:

$$\sigma'_{a_{av}} = \sigma_a - \frac{2}{3} u_b$$

Oedometer modulus:

$$M = \frac{\Delta \sigma'_a}{r \, \Delta t}$$

where r is the average rate of strain and $\Delta\sigma'_a$ the change in effective stress over an increment of Δt.

Modulus of compressibility:

$$m_v = \frac{1}{M}$$

Coefficient of permeability:

$$k = \frac{1}{2} \frac{r}{u_b} H^2 \cdot \gamma_w$$

where H is the height of the sample and γ_w the unit weight of water.

Coefficient of consolidation:

$$c_v = \frac{M \, k}{\gamma_w}$$

APPENDIX II

Determination of p'_c of Stiff Clay from Plasticity Index and Undrained Shear Strength

For very stiff clays, the value of p'_c is often estimated from the undrained shear strength, s_u, and the plasticity index, I_p, as previously described by Berre [*11*] and Andresen et al [*7*]. In this method, the value of s_u is determined from unconfined compression, unconsolidated undrained, or pocket penetrometer tests. The preconsolidation stress, p'_c, is obtained from

$$p'_c = s_u/(s_u/p'_c)$$

where the ratio (s_u/p'_c) is taken from the curve in Fig. 20 for an estimated value of p'_c/p'_0. If the first estimate of p'_c/p'_0 proves to be too far off, the computation of p'_c is repeated once or twice, with new values of p'_c/p'_0. This method has been used successfully for very stiff nonfissured North Sea clays.

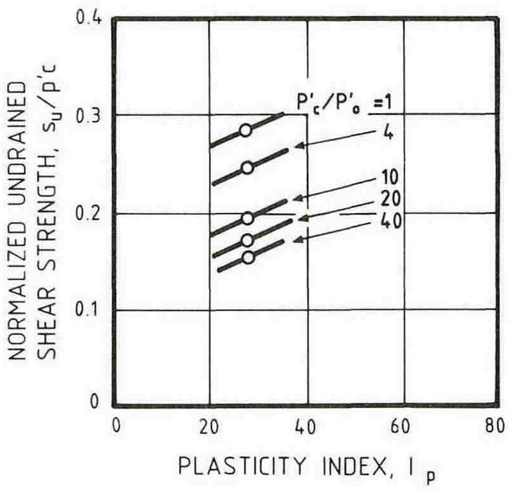

FIG. 20—*Normalized undrained shear strength as a function of* p'_c/p'_0 *ratio and plasticity index (data from Drammen clay).*

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