Triaxial Testing at the Norwegian Geotechnical Institute

By
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SYNOPSIS

The equipment and the procedures for triaxial tests used at the Norwegian Geotechnical Institute today are described in detail. The use of the test results in connection with the stress path method for stability analysis is briefly outlined. Cyclic loading procedures are also included.

INTRODUCTION

Originally, triaxial tests at NGI were used mainly to determine shear strength parameters for the case where the vertical stress increases and the horizontal stress is kept constant, Andresen and Simons (1960). In the following years it was gradually realized that laboratory specimens ought to be subjected, as closely as possible, to the same stresses and stress changes as in the field. Equipment and procedures were then developed so that any combination of vertical and horizontal stresses, including cyclic loading, can be applied. Readings, and to some extent stress or strain regulations during the test, were automated.

DESCRIPTION OF EQUIPMENT

General lay-out

Figure 1 presents the lay-out of a typical triaxial test unit. The specimen is enclosed in a rubber membrane

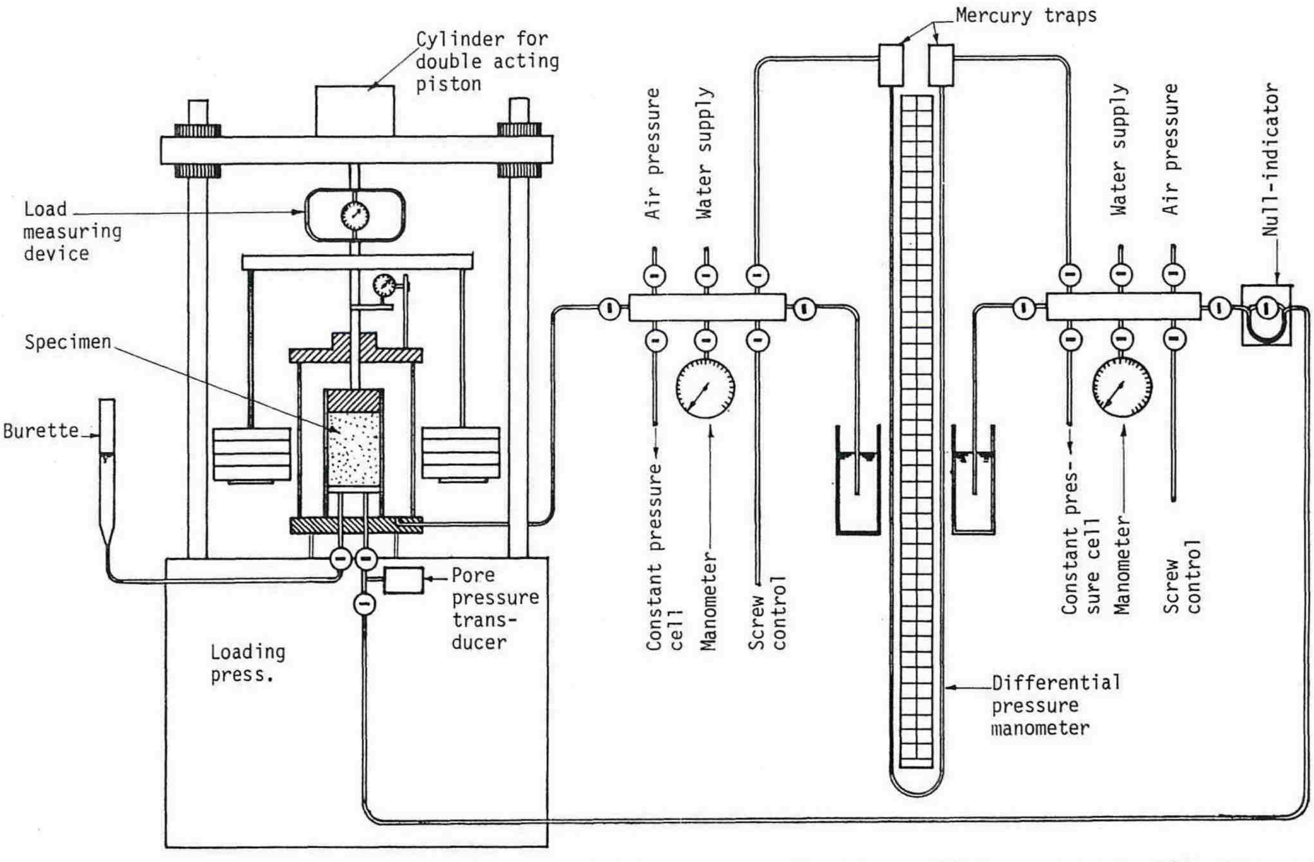

Fig. 1. General layout of a typical triaxial test unit. (The two extra cells with consolidation equipment, which also may be included in one unit, are not shown on the figure.)

inside the triaxial cell. The piston through the top of the cell acts on the top of the specimen. It can be loaded in three ways: by the motordriven press, by deadweights on the hanger and by the air-operated double acting piston on the top of the loading frame.

Two valve selector blocks, respectively for cell pressure and pore pressure are connected to the triaxial cell. Each block has outlets to a screw control, a Bourdon gauge, a constant pressure cell and an air pressure supply. (The constant pressure cell is a high precision pressure source, used on both the cell and the pore pressure sides.)

Between the two blocks a mercury differential pressure manometer can measure the difference between the cell and pore pressures very accurately, independently of the magnitude of the back pressure. Since both blocks have an outlet to the atmosphere, the manometer can also measure low absolute cell pressures or low absolute pore pressures. Two traps effectively prevent the mercury from escaping into the valve blocks. In addition to the traditional measuring devices, the triaxial test unit is also equipped with electronic transducers for automatic data logging. The air pressure supply, coming into each of the valve blocks, together with the electronic transducers, enable automatic regulations of stresses or strains.

For maximum utilization of a loading press and its auxiliary equipment two extra consolidation units can be included in the triaxial test unit. A consolidation unit consists of a triaxial cell where the piston can be locked, a cell pressure unit and hangers for application of deadweights on the piston. After completion of consolidation, the piston is locked in position and the cell moved to the loading press.

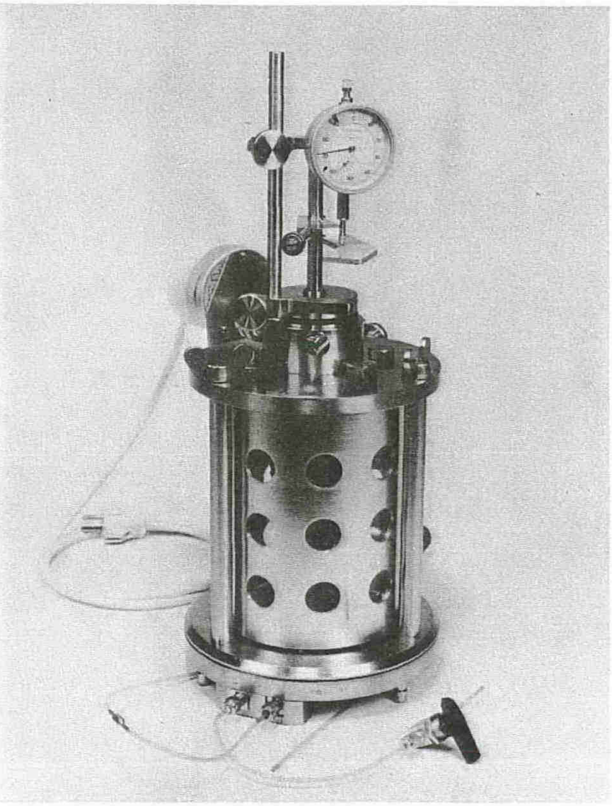

Fig. 2. Triaxial cell for tests with static loading. (The lucite cylinder is reinforced by an outer steel cylinder with big holes.)

Triaxial cell

Two types of triaxial cells are in use, one for static loading and one for cyclic loading. The one for conventional static loading is basically the same as the one described by Andresen and Simons (1960) (see Fig. 2) but with the following improvements:

1. The surface of the piston through the top of the cell is hardchromed, and the rotating bushing is nitrid-hardened. The use of these materials leads to fewer friction problems, and makes it possible to reduce the clearance between piston and bushing so much that the oil leakage from the cell is greatly reduced. This type of piston/bushing can also be used for cyclic loading.
2. A wheel on the dial gauge arm prevents rotation of the piston and therefore ensures that no torque is applied to the specimen by the rotating bushing. As shown in Fig. 2 the wheel bears against a rod at the top of the cell.
3. The pedestal is made as one single unit, so that the whole pedestal is shifted when the specimen diameter is changed. (In the original cell, rings of different diameters were placed on a permanently mounted 10 cm^2 pedestal). The cell can easily be adapted to specimens with heights up to 160 mm by placing aluminium rings between the base plate and the lucite (plexiglass) cylinder. An 0-ring seal is used between the aluminium ring and the lucite cylinder.
4. When the lucite cylinder is reinforced, as shown in Fig. 2, or replaced by a steel cylinder, the cell pressure capacity increases to 20 bars.
5. The connection between piston and top cap can take both compression and tension forces (see Fig. 3). A sphere-segment ensures this. During mounting of a specimen the segment is pushed through a rectangular hole in a brass plate fixed to the top cap. Then the piston is turned 90 degrees,*) so that the sphere-segment is locked to the top cap. (The allowable amount of tilting of the top cap can be adjusted by a nut as illustrated in Fig. 3. This adjustment is done before mounting of the specimen). Normally the top cap is allowed to tilt ± 4 degrees.**) When the force on the piston changes

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*) Clearance between the sphere-segment and its seating in the top cap ensures that no twisting is applied to the specimen.

**) This is when low friction end plates are used, see fig. 14. When such plates are not used, the top cap is allowed to tilt ±6.5°.

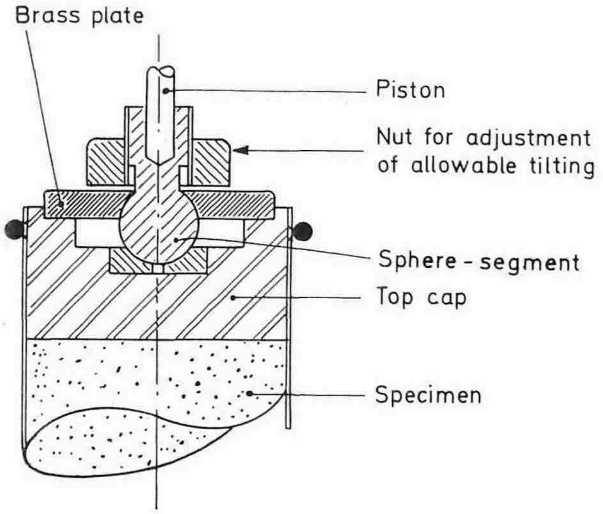

Fig. 3. Details of connection between piston and top cap for static loading cells.

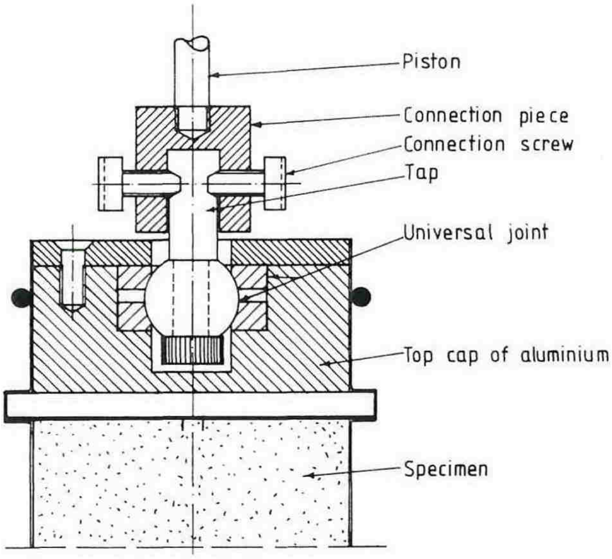

Fig. 5. Details of connection between piston and top cap for cyclic loading cells.

from positive to negative, or from negative to positive, a dead movement of about 0.06 to 0.15 mm was measured in the connection. This is acceptable for static loading but not for two-way cyclic loading tests.

Figure 4 shows the triaxial cell used for cyclic loading tests. The top plate of the cell is divided into two parts, one fixed to the lucite wall, and the other, with the piston, mounted on two columns. When the cell is assembled, the part with the piston is mounted first and the connection between piston and top cap is fastened. Thereafter the lucite cylinder with its top plate is mounted. This type of cell assembly is not new. Cells of this type have been used for several years at MIT and have been described for example by Franke (1978).

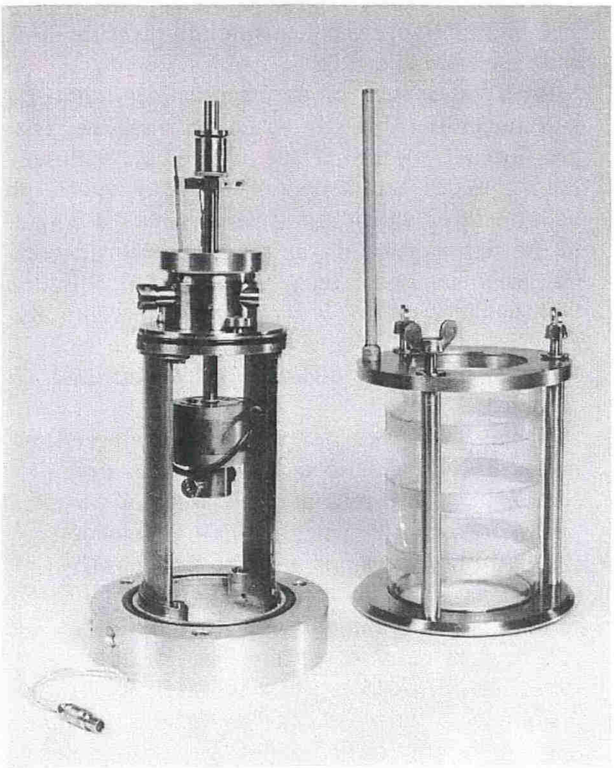

Fig. 4. Triaxial cell for cyclic loading tests. (An internal load cell is fixed to the lower end of the piston.)

The reason for making the cell in this way is to facilitate the connection process between the piston and the top cap. This connection is more complicated for cyclic than for static loading tests, because no dead movement can be tolerated in cyclic loading tests. The connection is shown in Fig. 5. During mounting of a specimen, the piston with a connection piece at its bottom end, is lowered over a tap sticking up from the top cap. Then the two connection screws are fastened. The top cap is now fixed to the piston. The universal joint, which is modified to give a minimum of false deformation, allows some tilting of the top cap. The gap between the top cap and the connection piece limits the tilting to ± 4 degrees.

Loading systems

Loading of a triaxial specimen is done by applying a force on the piston through the top of the triaxial cell. Three loading systems are used:

1. Dead weights on the hanger. If a negative (pulling) force is going to be applied, the hanger is replaced by two loading arms, one at each side of the piston. Dead weights are convenient for anisotropic consolidation where the required piston force is less than about 600 N. (This limit, which applies both for positive and negative forces, is due to the hangers and the loading arms. If the dimensions of those are increased, the piston force can also be increased).

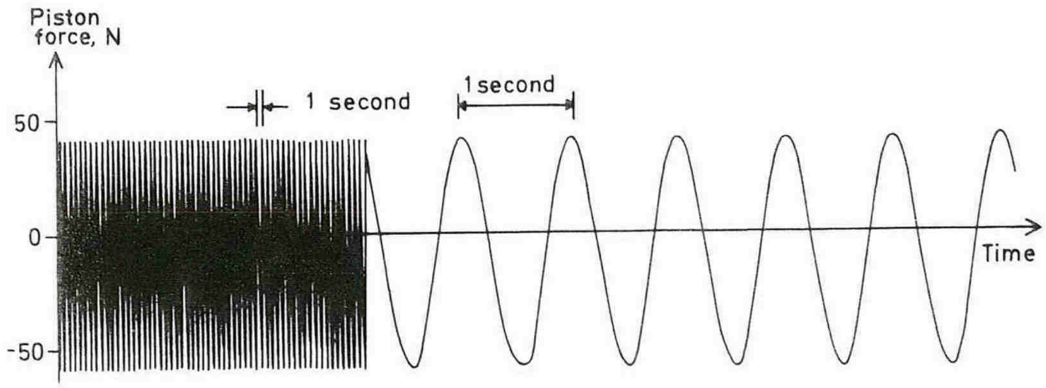

Fig. 6. Example of load pulses created by the cyclic loading system. (Printout from strip chart recorder.)

2. An air-operated double-acting piston on the top of the loading frame. The force can be either positive or negative. This system is used for anisotropic consolidation, especially if the required piston force is greater than about 600 N, and when the consolidation load should be applied continuously and automatically.

   The double-acting piston is also used for cyclic loading. The piston is then driven by a sinusoidally varying air pressure which is created by a mechanically driven plunger valve. The load period can be as short as one second and the shape of the loading pulse is almost sinusoidal. (See Fig. 6).*)
3. A motordriven loading press, which is used to deform the specimen at a constant rate. This is the same press as described by Andresen and Simons (1960), with some later modifications. The toothwheel combinations for the most usual speeds have been photographed. The time needed to change from one to another speed is thereby reduced. The press is also equipped with two electrical switches; one can stop the press after a certain displacement, and the other can stop the press after a certain time. The vertical columns in the loading frame have been reinforced so that a maximum load of 3.5 tons can be applied.

Cell pressure and pore pressure systems

The cell and the pore pressures are usually applied by bleeding air pressure valves. The system includes two valves, respectively connected to the low and high pressure supplies (see Fig. 7). The low pressure valve, maximum pressure 4 bars, is of the Nordgren type. The high pressure valve, maximum pressure 20 bars, is of the Fairchild type.

Both valves can be adjusted, either manually or automatically, through small DC-motors. The air pressure acts on the surface of glycerine enclosed in a brass cylinder. Submerged in the glycerine is a rubber balloon filled with deaired water which is connected to the cell pressure or the pore pressure valve block. Glycerine is used, since, according to Winter and Goldscheider (1978), it has almost no solubility for air. The idea of using glycerine in an air-water interface cell was put forward by Winter and Goldscheider.

The air pressure systems have replaced the constant pressure cells described by Andresen and Simons (1960), but these cells are still used for certain purposes, for example when a small difference between cell and pore pressures must be kept constant at the same time as the back pressure is very high or for calibrating pressure manometers. Pressures up to 20 bars can be kept constant within limits of about ±0.005 bars. The required pressure is obtained by applying loads to a piston acting into a chamber filled with oil and water. The constant pressure cells have been considerably improved since 1960. The volume capacity has been doubled by increasing the length of the

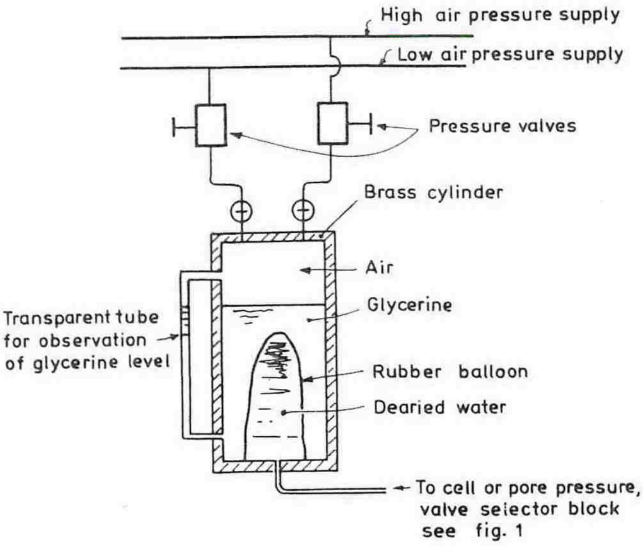

Fig. 7. Details of air pressure system. (Principal sketch.)

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*) A similar device has been described by Chan (1976).

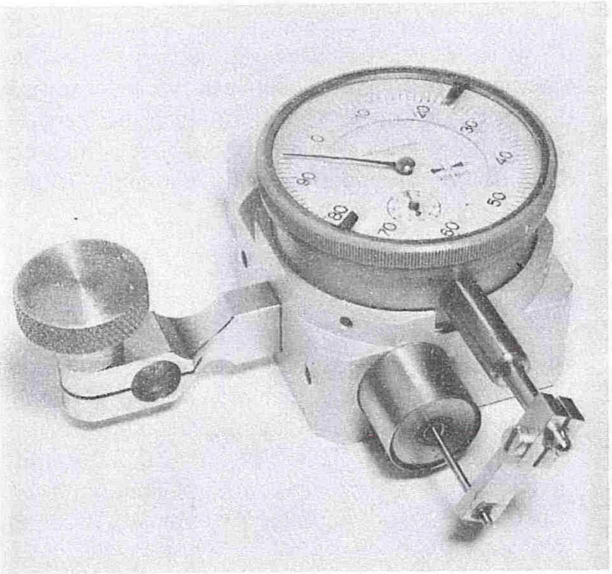

Fig. 8. Dial gauge with LVDT mounted on its backside. For measurement of vertical displacement of triaxial specimens.

piston. The piston has been hardchromed and the rotating bushing has been nitridhardened. This metal combination minimizes friction and allows to reduce the clearance between piston and bushing so much that the oil leakage is very small. The piston is rotated back and forth by a small electric motor. This removes almost all friction between piston and bushing.

Electronic measuring devices

The following parameters are measured by electronic devices: piston force, vertical displacement, pore pressure, cell pressure and volume change. Some details about these devices are given below.

Piston force is measured mostly by proving devices with linear variable differential transformers (LVDT's) mounted on the backside of the dial gauges. The LVDT's are produced by Hewlett-Packard. The proving devices now used are not ringshaped, but have a rectangular form. They are also made of better materials. As a result of these changes they have a more linear curve than the old proving rings. The main advantage with this type of load measuring device is that the electrical reading can be checked by the dial gauge. This has been done for each test at NGI in the last three years. Repeated calibrations show that the dial gauge readings are more reliable than the electrical ones. However, the disagreement between the two is usually less than 2 % of the measured load if this load is higher than 20 % of the maximum load for the ring.

Vertical displacement is also measured with a LVDT mounted on the backside of a dial gauge (see Fig. 8).

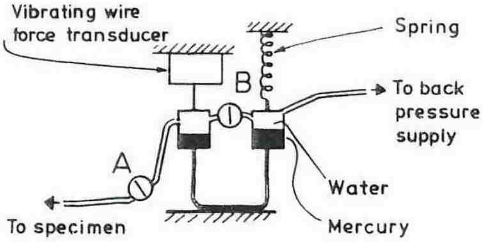

Fig. 9. Electronic device for measuring volume change where a mercury pot is weighed by a force transducer.

Pore and cell pressures are measured by Tyco pressure transducers. The zero readings for these transducers have been checked after each test during the two years they have been in use at NGI. The difference in zero readings before and after a test is normally less than 0.3 % of the reading at maximum load.*) The temperature in the laboratory is not controlled, but the variation over the period it takes to carry out one test is normally less than ± 1 °C.

Volume change is measured by two types of electronic transducers. In one case a vibrating wire force transducer is used to weigh a mercury pot connected to the specimen (see Fig. 9).

This device has been in use for about 5 years and has performed well. The accuracy is better than with

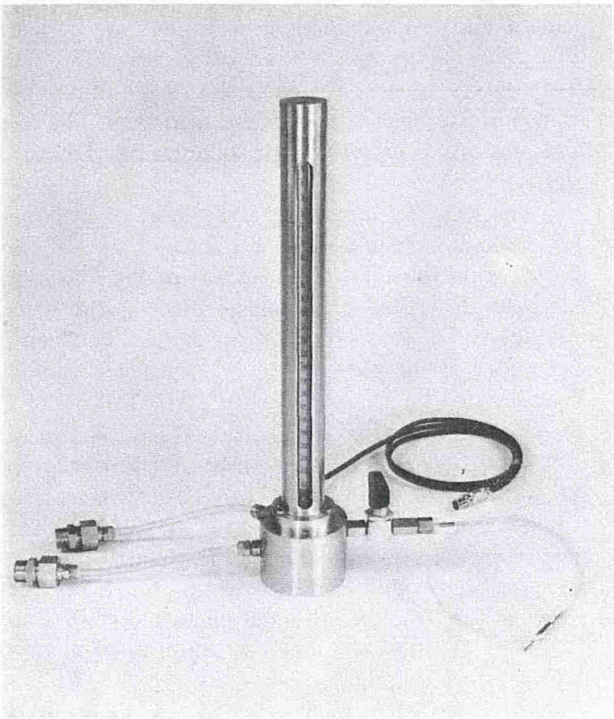

Fig. 10. Electronic device for measuring volume change where the height of water column in a burette is measured by a highly sensitive pressure transducer.

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*) Maximum load is the maximum stress the transducer can take.

burettes with 0.1 cm^3 divisions. If the volume change of the specimen becomes greater than 16 cm^3, valve A must be shut and valve B opened, so that the mercury level can be drawn back to its original position.

Figure 10 shows the second type of volume measuring device developed by the Central Institute for Industrial Research in Oslo. It consists of a burette enclosed by a cylinder filled with air. The burette is connected to the specimen. The height of the water column in the burette is measured by a very sensitive pressure transducer. Back pressure can be applied by increasing the air pressure both in the cylinder containing the burette and inside the pressure transducer. This device has been used for monitoring volume change in about 20 drained tests on sand. The accuracy is about the same as with the first type. The maximum volume change capacity is 25 cm^3.*) The electrical readings can be checked by manual readings on the burette. This device occupies less space, and is easier to move than the first apparatus. For slow drained tests on clay with back pressure there must be a long section with small diameter tubing between the volume change measuring device and the triaxial cell to avoid air diffusion into the specimen.

Automatic data logging and regulations

Except for the consolidation stage, all readings for continuously loaded static tests are taken automatically by an electronic data logger. The data are both printed out and punched on a paper tape by a teletype. The paper tape is read by a computer, which also collects all data for each test, does all computations and produces the standard drawings. The drawings are used directly as originals for laboratory reports.

Cyclic tests are logged by strip-chart recorders.

A special electronic box has been built for automatic regulations. The first version of this box, which has been described by Senneset and Grande (1977), was developed in a cooperation project between the Geotechnical Institute at the Technical University in Trondheim, the Central Institute for Industrial Research in Oslo and NGI. The box was later considerably modified at NGI to increase its accuracy. It is referred to as a two-channel box since two electronic transducers can be connected to it. In this box the signals from the two transducers are divided by adjustable voltage dividers and then compared. If the difference between the two divided signals differs from a preset value, the box starts a small electric motor. This motor is usually connected to an air valve which regulates the cell pressure or the piston force. The motor can operate in both directions. Each direction has its own adjustable current supply by which the motor speed can be adjusted manually. The box itself does not adjust the speed, it only switches the motor off or on in one of the two directions (depending on whether the difference between the two transducer signals is too low or too high). In principle this box should be able to regulate any process which can be described by an equation of the following form:

$$AX + BY + C = 0$$

where A and B correspond to the preset values of the two voltage dividers, C the preset value of the difference between the two divided signals, and X and Y the transducer signals. This box was originally built for performing K_0'-tests, where the specimen area is kept constant. When doing a K_0'-test, the box is connected to a vertical deformation LVDT and a volume change transducer. The voltage dividers are set so that the divided signals from the two transducers change with the same rate when the specimen area remains constant. The preset value of the difference is set equal to the initial difference between the two divided signals. If the specimen area comes outside the allowable limits, the box starts a motor which adjusts the piston force until the area again is correct. The cell pressure is increased at a constant rate. (The regulation motor may also be connected to the cell pressure valve. The piston force is then increased continuously). Fig. 11 shows the results of a K_0'-test performed with this box on a soft clay specimen. The stresses were at all times increased. It is doubtful if this system can be used for K_0'-tests, where the stresses decrease, because the strains connected with K_0'-unloading are extremely small. In the future the box probably will be used for tests where the vertical and the radial stress shall be increased continuously with a constant ratio between them, and for tests where the axial stress shall be kept constant and the radial stress either increased or decreased continuously. Up to now, NGI has had only limited practical experience with this box.

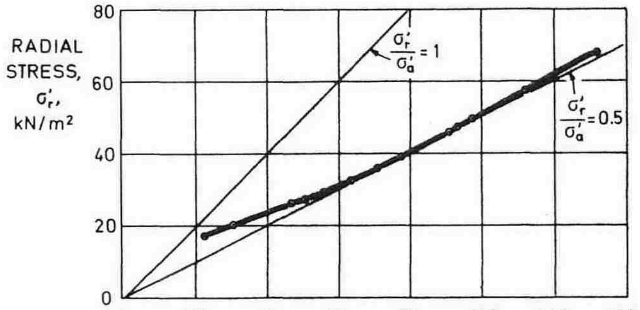

Fig. 11. Results of a K_0'-triaxial test performed with the two-channel regulation box.

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*) The volume capacity, and thereby the accuracy, can easily be changed by changing burette.

Another regulation box, but which takes in signals from only one transducer has been developed. The box switches the regulation motor off or on in one of the two directions, depending on whether the transducer signal is too low or too high. This one-channel box has been used successfully for about four years to keep the specimen height constant in simple shear tests. It is also used to keep the specimen height constant for swelling oedometer tests. For triaxial tests it has been used to adjust the cell pressure in constant volume tests.

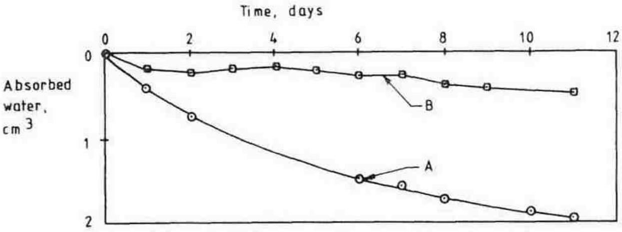

Fig. 12. Absorption of water (from triaxial specimen) versus time for rubber membranes with diameter 54 mm and height 100 mm.

A: Membrane made of 50% neoprene and 50% natural rubber.

B: New membrane (polychloroprene from Nordiska Latex A/B).

TESTING PROCEDURE

General

Undisturbed specimens, if less than 80 mm in diameter, are usually mounted with full cross-section. Bigger specimens are trimmed down to a diameter of 54 or 80 mm. It is required that the specimen height be from 1.6 to 2.0 times the diameter.

Coarse filter stones are kept dry during mounting to prevent swelling of the specimen by sucking in water from the stones. High air entry value stones are always kept saturated. For soils with a strong tendency to suck in water, the compartments behind high air entry value stones are filled with air. The air entry value should be higher than the negative pore pressure in the specimen. The stones (or the compartments behind the high air entry value stones) are flushed with water after application of a cell pressure about equal to the initial negative pore pressure in the specimen.

The triaxial cell is usually filled with liquid paraffin. Problems with leakage through the rubber membrane are then reduced. The paraffin also act as a lubricant for the piston through the top of the cell.

The specimen is usually confined by a rubber membrane made of 50% natural rubber and 50% neoprene. Such membranes have very good mechanical properties and very seldom give leakage problems. However, they absorb some water especially when they are new (see Fig. 12).

The initial absorption can be greatly reduced if the membrane is stored in water some days before its use. When a membrane absorbs water it swells slightly, and may become bigger than the pedestal and top cap, which may again lead to leakage problems. The increase in diameter can, however, be compensated for by using membranes with a slightly smaller diameter before soaking than the initial diameter of the specimen. In Fig. 12 is also shown absorption versus time for a polychloroprene membrane. This is a trial membrane delivered by Geonor, who has again got it from the Swedish firm Nordiska Latex AB. This new membrane seems to absorb much less water than the one made of neoprene and natural rubber. Its elastic modulus is about 2000 kN/m^2. For membranes made of neoprene and natural rubber the elastic modulus is around 1300 kN/m^2.

Membranes which contain neoprene rubber may stiffen slightly when subjected to temperatures below ordinary room temperature (for example cold tap water). This stiffening can be reversed by placing the membrane in an oven at +50°C for about 10 minutes or longer.

No perfect solution has been found for keeping the water content of the specimen sufficiently constant for undrained tests lasting several days. The best technique for avoiding changes in water content of the specimen consists of using the paraffin method with no rubber membrane around the specimen (see next section). However, with the equipment available today this technique can be used safely only for compression tests on soft homogeneous clays when the required effective radial stress is less than one bar. If use of a rubber membrane is required, it seems that membranes made of natural rubber latex in combination with paraffin in the cell gives a minimum of water migration. (It is better to use paraffin in the cell than deaired water because water tends to leak through the membrane and the leakage cannot easily be detected.) The combination natural rubber and paraffin has been used a lot at NGI. However, membranes of natural rubber swell when exposed to paraffin. A lot of folds then become visible on the membrane, and local damage to the membrane may occur, leading to leakage. Preliminary tests with natural rubber membranes combined with silicone or castor oil (resinous oil) in the cell seems to give a migration of water from the specimen into the membrane. The amount of water transport appears to be of the same order of magnitude as the average of the two curves in Fig. 12, but more tests are required to clarify this observation.

Special procedures when mounting normally and slightly overconsolidated clay specimens

If the diameter of a specimen of normally and slightly overconsolidated clay is too large for mounting with full cross-section, the specimen is trimmed with a wire saw as described by Andresen and Simons (1960). If the clay is quick or extremely soft, trimming is done as described by Landva (1964) and Berre (1969). The cylinder, described by Landva and Berre, into which the sample is extruded has been modified so that the membrane is mounted inside it. The sample is then pushed directly into the rubber membrane. A suction can then be applied to the specimen before the cylinder is removed. This version is used when the sample contains so much silt and sand that the specimen cannot stand upright unless it is supported laterally. A similar device has previously been developed by Börgesson at the Techical University in Luleå in Sweden.

Tests carried out at NGI indicate that end friction is of minor importance for soft clays. No attempts are therefore made to reduce end friction for such clays except for cyclic tests. The specimen is usually mounted without side drains. A filter stone with two drainage tubes is placed at both top and bottom of the specimen. (When the side drain filter paper strips are placed in spirals as indicated in Fig. 14, the paper restraint is probably so small that such drains can also be used for soft clays. With the use of side drain filters the allowable rate of axial strain can be increased.)

For compression tests on soft homogeneous clays the so-called paraffin method is used (Iversen and Moum, 1974). In this method the cell is filled with liquid paraffin and no rubber membrane is used around the specimen. The interfacial tension between paraffin and pore water completely prevents the paraffin from penetrating into the pores of either the clay or the high air entry value filter stones (see Fig. 13).

In this type of test, the specimen is consolidated and pore pressures are measured in the same manner as for tests with rubber membranes. Development of cracks in the specimen during shearing can be more easily observed (Iversen & Moum, 1974). The rubber membrane correction, which for very soft clays can account for more than 10 per cent of the measured shear stress at high strains, is completely avoided. With the equipment available today at NGI this method does not cause any water-paraffin interface leakage problems at all for soft, homogeneous clays when testing with effective horizontal stresses up to 100 kN/m^2.

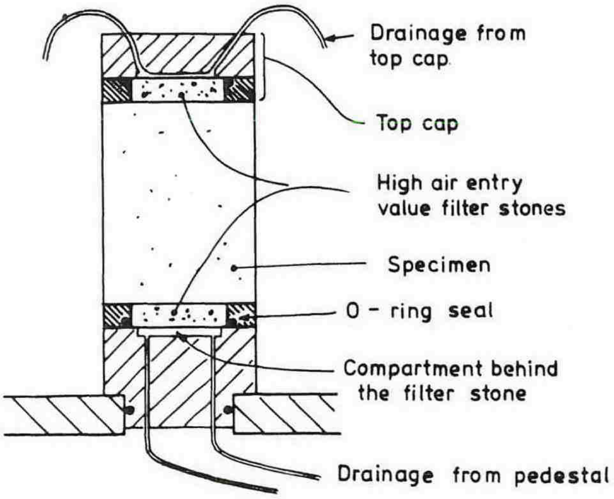

Fig. 13. Arrangement for the paraffin method where no rubber membrane is placed around the triaxial specimen.

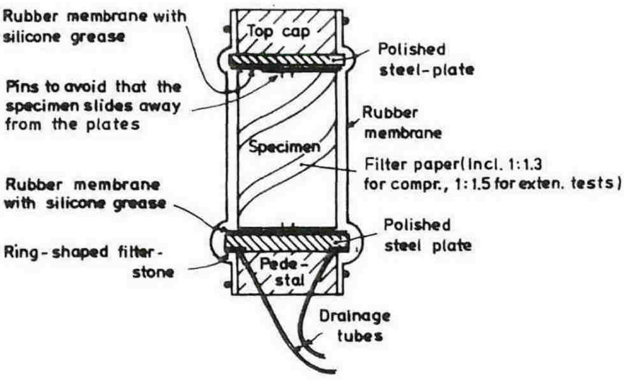

Fig. 14. Arrangement for reduction of end friction in triaxial tests.

Special procedures when mounting heavily overconsolidated clay specimens

Jacobsen (1967) found that the undrained shear strenght for very stiff boulder clay increased by about 50 per cent when provisions were made to decrease end friction by the technique recommended by Rowe and Barden (1964). According to Lee (1978), the importance of using smooth ends increases with increasing tendency for dilatancy of the soil and is more important for cyclic than for static testing. Thus to reduce end friction, heavily overconsolidated clays are always mounted between polished, stainless steel plates covered with silicone grease (Dow Corning No. 111) and one rubber membrane, as shown in Fig. 14. In special cases up to three rubber membranes with grease in between have been used at each end. The use of a larger number of rubber membranes will generally reduce end friction, but very stiff specimens may tend to split up vertically at the ends if too many membranes are used. (This is due to the low elastic modulus and high Poisson's ratio of rubber). Four strips of filter paper are placed on the side of the specimen and down to the ring filter. The inclination of the spirals is chosen such that they do not affect radial deformation of the specimen. Geometrical considerations show that for undrained compression tests, the inclination should be about 1:1.3. (1 is vertical distance and 1.3 distance along the specimen perimeter).

For undrained extension tests, the computations indicate an inclination of 1:1.5. For undrained two-way cyclic tests, the strips are placed at an inclination of 1:1.4. The filter paper is soaked in water at approximately the same salt concentration as the pore water of the clay, but free water on the surface of the paper is wiped away before it is placed on the specimen. *Small pieces of white teflon tape are placed over the edge of the rubber membrane on the bottom plate at the places where the filter papers come down to the plate. This is done to avoid that silicone grease, pressed out from the membranes, cloggs the filter paper drain.*

When the rubber membrane is placed on the specimen, a suction is applied to the drainage tubes to suck out as much air as possible between the specimen and the membrane. The suction, which is about 0.35 bar, is not released before an equally high cell pressure has been applied. (The suction is reduced if the initial negative pore pressure is believed to be lower than 0.35 bar. However, it may then be difficult to avoid a pocket of air in the corner between the end plates and the specimen, since the diameter of the end plates is greater than the diameter of the specimen. The fact that the confining membrane swells when it comes in contact with water helps to overcome this difficulty).

The mounting of overconsolidated clays is done in a cabinet with humidity around 97 per cent to minimize evaporation from the specimen. If the diameter of the specimen is too large for mounting with full cross-section or if the outer part of the sample is strongly disturbed, the specimen is trimmed with a soil lathe (see Fig. 15). The specimen is placed between top and bottom plates equipped with steel pins. The two plates are driven at exactly the same speed. (Normally in such machines only one plate is driven, which tends to apply more torque on the specimen.) Rate of rotation can be varied continuously.

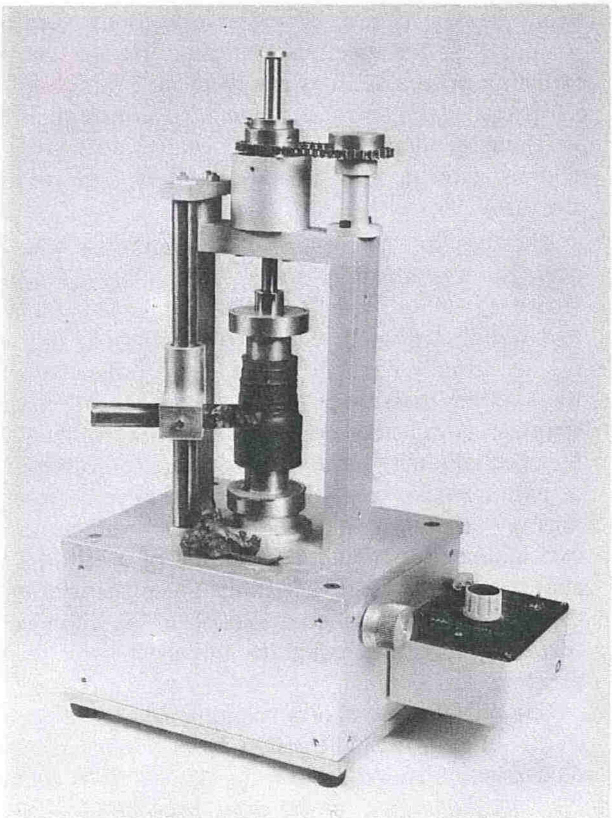

Fig. 15. Trimming machine for specimens of stiff clay.

Mounting of sand specimens

If the sand specimen does not collapse under its own weight, the mounting is done in the same manner as for clays. Loose specimens are mounted in the same way as soft clays, except that coarse filter stones and no filter paper strips are used. Dense specimens are mounted in the same way as described for stiff clays.

Specimens of remoulded sand are normally reconstituted according to the method of undercompaction described by Ladd (1978). Pluvial compaction is also used especially for sands with a uniform grading, but it has proved difficult with this method to obtain very high densities such as encountered for some of the sand sediments in the North Sea (Kildalen and Stenhamar, 1977). The free-end technique is not used for routine testing of remoulded sand specimens. Flow of carbon dioxide (CO_2) through the specimen is sometimes used to increase the degree of saturation.

Determination of consolidation stresses

Triaxial test specimens are usually consolidated under the same effective stresses as those carried in the field before sampling. This requires an estimate of the effective horizontal and vertical stresses in the field, p_{oh}' and p_{ov}'. Whereas p_{ov}' is generally determined with ease, special procedures are required for obtaining p_{oh}'.

At NGI the following procedure is used for a deposit with an approximately horizonatal surface:

1. The ratio between the preconsolidation stress, p_c', and the vertical effective stress in the field, p_{ov}', is determined. For soft clays, p_c' is obtained from oedometer tests by Casagrande (1936), the Schmertmann (1955) or the Janbu (1970) method. For stiff clays, p_c' is also estimated from undrained shear strength, s_u, and plasticity index, I_p, as previously described by Andresen, Berre, Kleven and Lunne (1979). By this method the value of s_u is determined by unconfined compression or unconsolidated undrained tests. The preconsolidation stress, p_c', is computed in the following way:

$$p_c' = \frac{s_u}{\left(\frac{s_u}{p_c'}\right)}$$

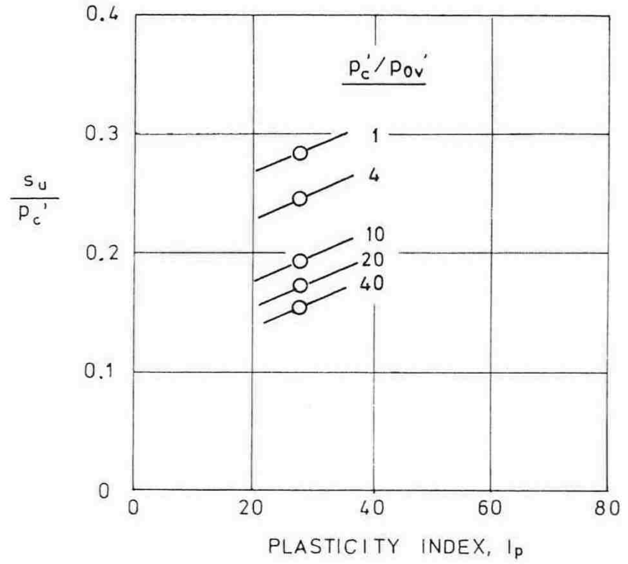

Fig. 16. Relation between s_u/p_c', plasticity index, I_p, and overconsolidation ratio, p_c'/p_{ov}', for plastic clay from Drammen. (After Andresen, Berre, Kleven and Lunne, 1979.)

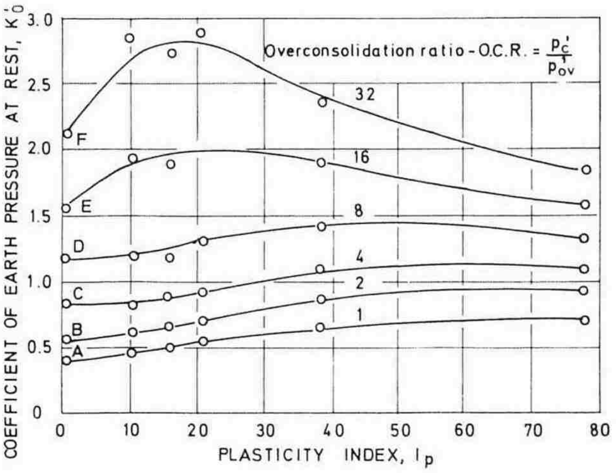

Fig. 17. Relationship between K_o', I_p and OCR. Determined on resedimented specimens consolidated in the laboratory (Brooker and Ireland, 1965). This diagram should be used with caution for cemented materials and for overconsolidated soils which have been partly reloaded after unloading.

The value of s_u/p_c' is taken from Fig. 16 at an estimated value of p_c'/p_{ov}'. If the first estimate proves to be too far off, the computation of p_c' is repeated, once or twice with new values of s_u/p_c'.

This method is considered to be the most reliable one for stiff clays, if the specimen quality is poor.

2. When the values of p_c'/p_{ov}' and I_p are known, the earth pressure coefficient at rest, K_o', is determined from the curves in Fig. 17. The value of the effective horizontal stress in the field, p_{oh}', is then set equal to $K_o' \cdot p_{ov}'$.

Procedures for application of the consolidation stresses

Undisturbed clay specimens can have negative pore pressures varying from almost zero to 4 p_{ov}', depending on degree of overconsolidation, plasticity index, and sampling disturbance. The first step in the consolidation of a clay specimen is to apply a cell pressure roughly equal to the initial negative pore pressure. If the initial negative pore pressure is completely unknown, the cell pressure is increased until the vertical deformation dial gauge shows a deformation of about 0.1 mm. (Deadweights are applied on the piston as the cell pressure is increased to keep it in contact with the top cap). The filter stones are then flushed with water at approximately the same salt concentration as the pore water of the specimen. Thereafter the drainage tubes are connected to a device for detecting small volume changes (usually a mercury null-indicator). If the specimen tends to change volume, the cell pressure is adjusted until the volume remains constant. The mercury null-indicator is adjusted to zero after each adjustment of the cell pressure to avoid influence of possible false volume change. The process of adjusting the cell pressure is continued up to 45 minutes if the cell pressure comes close to the specified consolidation stresses. If the cell pressure becomes very low compared to the specified consolidation stresses, the adjusting process is cut down to about 5 minutes. The cell pressure, when the volume stays constant, is approximately equal to the initial negative pore pressure of the specimen. This pressure is called "the swelling pressure".

The swelling pressure is now compared with the average consolidation stress, $\sigma_{av.c}' = 1/3(\sigma_{ac}' + 2\sigma_{rc}')$, where σ_{ac}' and σ_{rc}' are the specified values of the axial and radial stresses at end of consolidation. (σ_{ac}' and σ_{rc}' are usually equal to p_{ov}' and p_{oh}' respectively). If the swelling pressure is higher than $\sigma_{av.c}'$, the original estimate of σ_{rc}' may be too low. On the other hand, the specimen may have lost water due to evaporation, or high negative pore pressures could have been set up during sampling due to the dilatancy effect. In the two latter cases the specified value of σ_{rc}' is left unchanged. However, if the estimate of σ_{rc}' is considered erroneous, the specified value of σ_{rc}' is changed so that $\sigma_{av.c}'$ becomes equal to the measured swelling pressure.

The cell pressure is now set equal to the finally specified value of σ_{rc}'. The piston force is then increased, or decreased, in steps, until the axial stress is equal to the specified value of the axial consolidation stress, σ_{ac}'. If the cell pressure has to be increased to become equal to σ_{rc}' (that is, swelling pressure lower than σ_{rc}'), clay specimens are allowed to consolidate over night at σ_{rc}' before the axial stress is changed over one, or sometimes two, days to σ_{ac}'.

K_o'-consolidation in triaxial cell

During K_o'-consolidation the stresses are applied in such a way that no radial displacement of the specimen takes place. Such tests are done in order to obtain values of K_o' and to check data from oedometer tests. Sometimes the specimen is K_o'-loaded to the preconsolidation pressure, p_c', thereafter K_o'-unloaded to the vertical effective stress in the field today, p_{ov}', and then sheared undrained or drained. This can be considered as an alternative to the consolidation procedure described in the former section where the specimen was loaded to only p_{ov}'. K_o'-consolidation to p_c' and back to p_{ov}' may become more extensively used in the future than now, but the procedure sometimes leads to a considerable reduction in water content.

The cell pressure at the start of K_o'-consolidation is equal to the initial negative pore pressure of the specimen. The deviator stress $(\sigma_a - \sigma_r)$ is usually increased continuously by a loading press, while the cell pressure is adjusted manually or automatically, such that the radial displacement remains equal to zero (Bishop, 1958). The test must be performed so slowly that almost no pore pressure builds up in the specimen. Clay specimens should therefore be as small as possible and always have filter paper on the side (in spiral) and drainage at both ends. Rate of strain is the same as for drained, static shearing, see page 13. The test may take several days for clay specimens. If the cell pressure is regulated manually, the loading press is stopped during the night and the deviator stress kept constant by dead-weights.

Consolidation time, back pressure

As a general rule, shearing is started one day (16–24 hours) after application of the last consolidation stress increment. It is also required that the amount of expelled water from a standard size specimen be less than 0.25 mm^3 per minute before shearing starts. The mercury 0-indicator is used to check this. Specimens with pronounced tendency for creep are sheared as soon as this requirement is fulfilled (but not before one day after application of the last consolidation stress increment). Volume change during consolidation is sometimes plotted versus square root of time to check that primary consolidation is finished before start of shearing.

Dense and medium dense specimens of pure sand and silt may be sheared the same day as the consolidation stresses are applied, as consolidation is completed rapidly and their parameters are probably not influenced by time effects.

Before start of undrained shearing, a back pressure is applied on the specimen. For specimens assumed fully saturated in the field, it is attempted to reach a B-value equal to at least 0.95 for static tests and 0.97 for cyclic tests. For soft clays, a back pressure of about 200 kN/m^2 may be sufficient. For very stiff clays and dense sands, back pressures up to 1500 kN/m^2 may be required. It seems to be more important to obtain a high B-value for dilatant than for non-dilatant materials. For soft clays, B-values as low as 90% seems to be acceptable for static testing. If it proves difficult to obtain a satisfactory B-value, a constant volume test may be carried out instead of an undrained test.

Specimens assumed partly saturated in the field, are usually subjected to a back pressure equal to the pore pressure in the field if the in-situ pore pressure is positive. In the case of a negative pore pressure in the field, no back pressure is applied.

The back pressure is applied so slowly that almost no deformations take place during this process. The triaxial cells are calibrated on beforehand so that the false deformation due to the increase in cell pressure is known. The maximum allowable true axial strain during application of the back pressure is 0.15%. For partly saturated, very soft specimens of clay or clayey sand or silt, this requirement sometimes may be difficult to achieve. The back pressure is then applied before consolidation of the specimen previously mounted with fully saturated high air entry value filter stones. The cell pressure is first increased, in steps, without allowing drainage from the specimen. The pore pressure, which is measured, is allowed to equalize at each cell pressure step. The increase of the cell pressure is stopped either when the effective isotropic stress, σ_c', tends to exceed the specified value of σ_{rc}' or when σ_c' does not increase any more, depending on which occurs first. The specimen is now connected to a volume change measuring device with back pressure equal to the finally measured pore pressure. The cell pressure is now increased such that the difference between cell and pore pressure becomes equal to σ_{rc}'. The specimen is then allowed to consolidate overnight. The next day the piston force is increased, or decreased, in steps, until the difference between the total axial stress and the pore pressure is equal to the specified value of the axial consolidation stress, σ_{ac}'. The specimen is then again left overnight. The next day the B-value is measured. If B is too low, the cell and back pressure are increased until the required value of B is obtained.

Undrained static shearing (CAU-Tests)

The compression test (CAU_c = consolidated anisotropically, undrained compression) is performed by keeping the total radial stress, σ_r, constant while increasing the axial stress, σ_a. The extension test (CAU_e) is performed by keeping σ_r constant while decreasing σ_a. The results of compression tests are used in the active part of a potential slip surface and the results of extension tests in the passive part (see Fig. 18). The undrained shear strength is taken out at the same axial strain for the compression and the extension tests. The strengths so obtained are not necessarily the maximum ones.

Fig. 18 shows that the extension tests for such a foundation problem ought to be performed by increasing the total radial stress instead of decreasing the total axial stress. However, theoretically these two types of tests should give the same result, provided the specimens are fully saturated. Tests carried out at NGI and tests reported by Bishop and Wesley (1975) support this belief. A test where the axial stress is reduced is preferred to a test with increasing radial stress for practical reasons.

A special problem with extension tests consists in necking of the specimen after a certain strain, as the diameter decreases over a small portion of the specimen height. For overconsolidated, slightly nonhomogeneous clays, necking may start below 5% axial strain. The strength values used for the passive part of a slip surface can therefore be somewhat too low.

If effective shear strength parameters are wanted, the rate of loading must be slow enough for the pore pressure to equalize throughout the specimen. The handbook by Bishop and Henkel (1962) is used to estimate the maximum allowable rate of strain. For soft clays, where failure usually takes place at small strains and where side-drains are not always used, the rate of axial strain is about 0.75 per cent per hour. For stiff clays, where side-drains are always used, the rate of axial strain usually is 2 or 4 per cent per hour. These rates of strain values are used for specimens with diameter 54 mm and height 100 mm.

Fig. 19 shows typical results for triaxial compression and triaxial extension tests, all performed on a heavily overconsolidated clay from the North Sea. It is seen that the undrained shear strength for the extension test is about 60 per cent of the strength for the compression test. For soft, lean marine clays, a 30 per cent ratio is quite common.

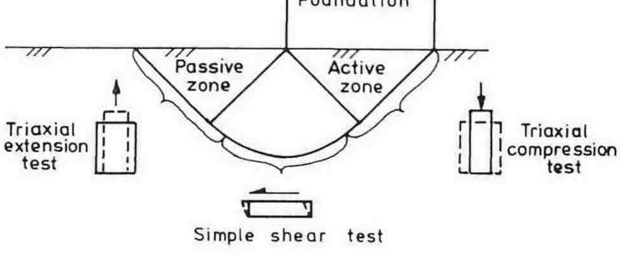

Fig. 18. Principles for use of triaxial and simple shear test results for stability analysis.

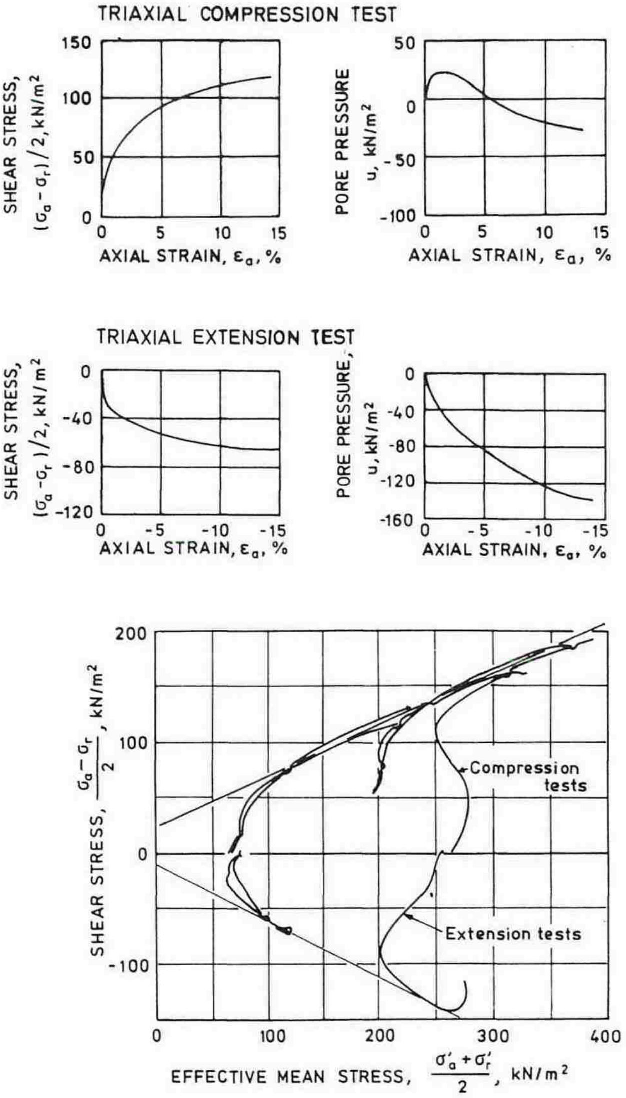

Fig. 19. Typical results of undrained triaxial tests on an overconsolidated clay from the North Sea.

Fig. 18 shows that simple shear tests are also used in connection with a stability analysis. Further information about the simple shear test are given by Bjerrum and Landva (1966) and by Andresen, Berre, Kleven and Lunne (1979).

Undrained cyclic shearing

Fig. 20 illustrates the use of laboratory tests to simulate the stress strain behaviour under a gravity platform during a storm. For specimens from the North Sea, the load period has been around 10 seconds for most of the cyclic testing done so far. Although frictionless end plates are used in connection with cyclic

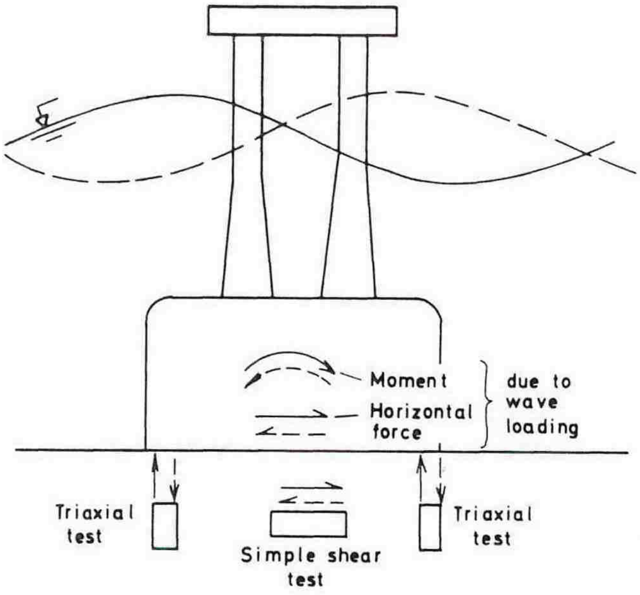

Fig. 20. Simplified representation of stress variations below a gravity platform by means of laboratory tests.

triaxial tests, the pore pressures will be somewhat unevenly distributed in the specimen due to the rapid variation in the vertical stress. To allow the pore pressure to equalize, the cyclic loading is stopped after 500 and 1500 cycles.

Usually equalization takes at least 15 minutes. Cycling is always stopped at the end of a cycle, where the cyclic shear stress is zero. After the cyclic loading, an undrained compression or extension test is performed in order to study the effect of cyclic loading on the static undrained shear strength.

Drained static shearing

Drained tests must be performed so slowly that almost no excess pore pressure builds up in the specimen. The handbook by Bishop and Henkel (1962) provides guidelines to estimate the maximum allowable rate of strain. For clay specimens with height 100 mm, diameter 54 mm, side-drains and drainage at both ends, rate of axial strain is usually about 0.2 per cent per hour. In cases where it is very important that the side-drains are 100% effective (that is when free-end plates are used, and when the permeability of the clay is very low) a back pressure of at least 200 kN/m² is applied.

Drained tests are often performed with incremental loading. The advantage with this type of loading is that any stress path can be easily followed with very simple equipment. Fig. 21 shows shear strain contours

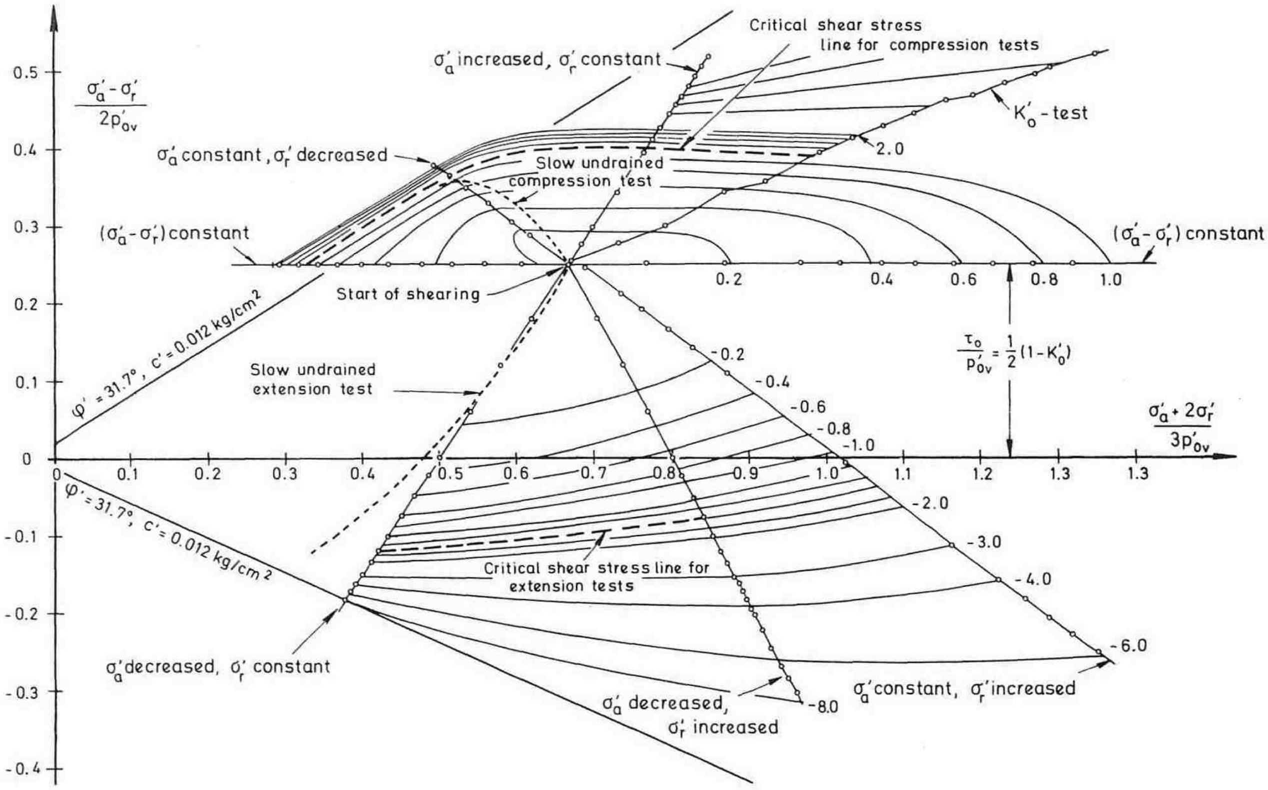

Fig. 21. Shear strain contours observed in drained triaxial tests on plastic clay from Drammen. Shear strain is equal to the difference between axial and radial strain. The radial strain has been computed from the axial and the volumetric strain. (After Berre and Bjerrum, 1973.)

based on different types of drained tests with incremental loading. (Two undrained tests are also included.)

The drained tests were loaded with one load increment per 24 hours. Each point in Fig. 21 represents one load increment. The specimens had drainage only at top and bottom, and were about 130 mm high. The tests were performed with the following, very simple, equipment: A triaxial cell, hangers for dead-weights (for both positive and negative forces), a burette for measurement of volume change and a valve selector block with pressure supply for the cell pressure. (No back pressure was used for the drained tests).

Multistage testing

When the testing conditions are varied during a test for the purpose of testing as few specimens as possible, it is called multistage testing. Examples of such testing are:

a) *Multistage consolidation.* The specimen is first consolidated as usual but shearing is stopped near failure. The consolidation stresses are then increased and a new shearing carried out. A multistage consolidation test is usually run to determine the Mohr-Coulomb failure envelope over a wide stress range by testing only one specimen.

b) *Multistage cyclic loading.* Cycling is done at two ore more cyclic shear stress levels. More information can thus be obtained from each specimen. However, data from multistage cycling must be used with caution, especially at high shear stress levels.

c) *Shearing one specimen with different rates of strain.* The loading press is stopped when failure is reached or just before failure. The specimen then continues to deform as the shear stress decreases. A relation between shear stress and rate of strain can then be obtained. This is also called a relaxation test. In addition to the relaxation test the speed of the loading press may also be varied.

Attempts have also been made to determine the degree of strength anisotropy of a clay by running compression and extension tests on the same specimen as suggested by Holmberg (1974). This was not successful for lean, soft, sensitive Norwegian clays, but it may be possible to use this procedure for les sensitive and more plastic clays.

Multistage testing is very attractive, especially when it is difficult to obtain specimens with comparable material properties, and it should probably be more extensively used than it is today. However, one can never be absolutely certain of the reliability of the test results, and information about post-failure behaviour is usually incomplete.

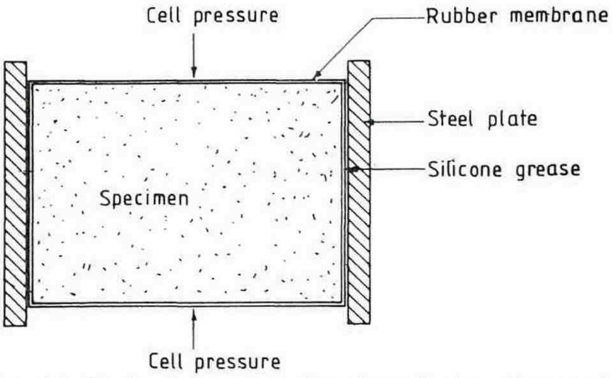

Fig. 22. Horizontal cross-section through side plates and specimen for a compression plane strain triaxial test.

PLANE STRAIN TRIAXIAL TESTS

For plane strain situations ordinary triaxial tests are suitably corrected or plane strain triaxial tests are performed. In the latter case the circular pedestal in an ordinary triaxial cell is replaced by a rectangular pedestal with the same size as the specimen, that is: 70 × 50 mm. The height of the specimen is 90 mm. Two stainless steel plates, (side plates), prevent displacement in one of the two horizontal directions (see Fig. 22). The cell pressure is acting in the other horizontal direction. The upper part of the top cap and the lower part of the pedestal are made circular so that the membrane can be sealed to them with rubber 0-rings. Silicone grease (Dow Corning No. 111) is smeared on the side plates to reduce the friction between the membrane and the plates. The membranes used for these tests are the same as for 80 mm circular specimens. Air between membrane and specimen is removed by applying a small suction inside the membrane. The suction is not released before a small cell pressure has been applied.

If no membrane is used (the paraffin method), a sheet of rubber membrane is placed between each side plate and the specimen. Silicone grease is used between the side plate and the rubber sheet. The rubber sheets cannot be made of natural rubber latex because this rubber swells very much when it comes in contact with paraffin. A rubber sheet made of 50 % neoprene and 50 % natural rubber latex seems to be satisfactory for tests which last only a few days. (A new rubber sheet is stored in water a few days before the test to avoid that it absorbs water from the specimen and swells).

The two side plates are held together by four tension rods. The distance between the two side plates is kept constant during the whole test. To avoid gaps between the side plates and the specimen, the specimen area must not be allowed to decrease during the consolidation. Usually plane strain test specimens are K_0'-consolidated.

Attempts will be made to measure more accurately the very small strains at shear stresses less than about 5% of the shear strength. It will then probably be necessary to measure the displacements with the measuring devices attached directly on the specimen. Such measuring devices will also be used for K_o'-triaxial tests.

For undrained tests performed too rapidly for pore pressure equalization to occur, it will be tried to measure pore pressure with small probes inserted into the specimen.

Further studies are required to examine the effects of rate of strain on shear resistance, and for finding the best way of consolidating "undisturbed" specimens to restore their *in situ* properties or backfigure them by a normalizing process. Tests, which simulate better than conventional triaxial tests the mode of deformation in the field, should be performed, such as plane strain tests for plane strain situations. This seems to be especially important for the extension type tests; see Ladd and Foott (1974).

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APPENDIX

COMPUTATIONS AND PRESENTATION OF TEST RESULTS, DEFINITION OF SYMBOLS

The following formulas are used to compute stresses and strains in triaxial tests:

Axial strain: $$\varepsilon_a = \frac{\Delta H}{H_i}$$

Volumetric strain: $$\varepsilon_{vol.} = \frac{\Delta V}{V_i}$$

Average area of specimen: $$A = \frac{V_i - \Delta V}{H_i - \Delta H}$$

Effective axial stress: $$\sigma_a' = \sigma_a - u$$

Total axial stress: $$\sigma_a = \frac{P + K}{A} + \sigma_r\left(1 - \frac{a}{A}\right)$$

Effective radial stress: $$\sigma_r' = \sigma_r - u$$

Pore pressure change: $$\Delta u = u - u_B$$

where: ΔH = Axial displacement
H_i = Initial height of specimen
ΔV = Volume change
V_i = Initial volume of specimen
P = Force on top of piston
a = Area of piston
K = $W - [(A-a) \cdot \gamma \cdot h]$ where W is weight of hanger, piston, top cap, one half of the specimen and so on, γ unit weight of cell liquid and h distance from top of top cap to mid-height of specimen.
σ_r = Total radial stress = cell pressure
u = Total pore pressure
u_B = Back pressure

The following formulas are used to compute the membrane correction.

Correction to be subtracted from axial stress:

$$\frac{2 \cdot t \cdot E}{r} \cdot \left(\varepsilon_a + \frac{\varepsilon_{vol.}}{3}\right)$$

Correction to be subtracted from radial stress:

$$\frac{2 \cdot t \cdot E}{r} \cdot \frac{\varepsilon_{vol.}}{3}$$

where: t = Thickness of membrane
E = Young's modulus for rubber
r = Radius of specimen

In these formulas, Poisson's ratio for rubber is assumed to be 0.5, and it is supposed that no sliding takes place between specimen and rubber. The above formulas result in approximately the same corrections as those given by Duncan and Seed (1967).

No correction is applied for the filter paper side drains when the paper is placed in spirals as explained previously.

Fig. 19 shows how results of triaxial shear are presented. For the shear stage axial and volumetric strains are computed as:

Plane strain extension tests have been performed with the side plates inside the membrane to ensure that the specimen does not separate from the plates when the cell pressure becomes the major principal stress. The side-plates are then held to the pedestal by screws, no tension rods are used. Silicone grease is smeared on both sides of the side plates and rubber sheets are placed between the specimen and the side plates. However, it is not yet clear if this is enough to decrease sufficiently the side friction forces in connection with extension tests. More tests are required to clarify this.

So far plane strain tests have only been done on soft clays; and only static tests have been performed. No attempt has therefore been made to reduce the friction between pedestal and specimen and between top cap and specimen.

Special equipment has been built for trimming and mounting specimens for plane strain tests.

CORRECTIONS OF TRIAXIAL TEST RESULTS

Some of the corrections applied at NGI on results of triaxial tests have been described by Berre (1979). The most important of those is probably the reduction of the undrained shear strenght for very plastic clays. Fig. 23 shows the factor of safety, computed from simple shear, triaxial compression and triaxial extension strengths, versus plasticity index for three test fills which failed. (This is the same figure as figure 5 in Berre (1979), except that the point for Thailand has been changed from 1.26 to 1.46. The last value is based on more complete test data than the first one.)

The curve in Fig. 23 is used to reduce the undrained shear strenght, determined by triaxial and simple shear tests, when the plasticity index is higher than about 30%.*) Usually this correction is believed to account for rate effects, which are assumed to increase with increasing plasticity index. However, laboratory data indicate that the rate effect may be considerable also for lean clays. The reason for the experience that a rate correction is not necessary for lean clays may be that lean clays consolidate more quickly than the more plastic ones. The curve in Fig. 23 is based on cases where the most critical circle at no point was deeper than 5–10 meters. A rate correction should probably be applied also for lean clays if any point on the most critical circle is deeper than this.

In the investigation of nearly normally consolidated, non layered clays of plasticity index below about 30%, the simple shear test is sometimes omitted. The simple shear strength is then replaced by the average value of the triaxial compression and the triaxial extension strength. However, the experience so far indicate that in all other cases simple shear tests should always be carried out. If no information is available about the simple shear strength for a plastic clay, it may be set equal to the triaxial extension strength.

No correction accounting for the possibility of progressive failure in brittle materials is applied. However, it is believed that this factor is, at least partly, accounted for by taking out the shear strength at the same strain for compression and extension tests, as mentioned previously in this paper.

For soft, very sensitive, lean, silty clays, the decrease in volume during consolidation to the in-situ effective stresses may in the worst cases be up to 8% of the total volume of the specimen, even if the most careful sampling and handling technique have been used to avoid sampling disturbance. For Norwegian clays of this type, no correction is applied to the undrained shear strength to account for this, because the experience so far with Norwegian clays indicates that, as more water is expelled during consolidation, the undrained shearing resistance, at low strains, becomes lower. The undrained shear strength values to be used in stability analysis for the very sensitive, silty, Norwegian clays are usually taken out at axial strains (during shearing) less than or equal to 2%.

FURTHER DEVELOPMENTS

A PRIME 400 computer is now used for computations and drawing standard diagrams like those in Fig. 19. In the future this computer will also be used for data logging, not only for static, but also for cyclic tests. It will also be used for adjusting piston force, cell pressure and pore pressure during consolidation and shearing.

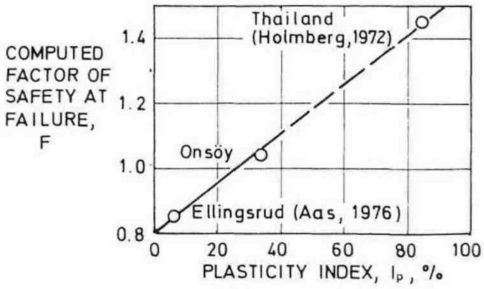

Fig. 23. Computed factors of safety versus plasticity index for three test fills which failed. The clays below the fills were almost normally consolidated. The clay at Ellingsrud was quick.

Note: The data are based upon tests where the final consolidation stresses were left on overnight and shear was carried out at a rate of strain equal to 0.6% per hour. Other test conditions can lead to different strengths.

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*) According to Fig. 23 the undrained shear strength could be increased for clays with plasticity index lower than about 30%. However, it is not recommended to do this at the present state of knowledge.

$$\varepsilon_a = \frac{\Delta H_s}{H_c} \text{ and } \varepsilon_{vol.} = \frac{\Delta V_s}{V_c}$$

where: ΔH_s = height change during shear (set at zero at start of shear)
ΔV_s = volume change during shear (set at zero at start of shear)
H_c = height of specimen at start of shear
V_c = volume of specimen at start of shear

Definition of other symbols used in the text:

CAU_c - Undrained compression test. Anisotropic consolidation.
CAU_e - Undrained extension test. Anisotropic consolidation.
I_p - Plasticity index.
K_0' - Coefficient of earth pressure at rest.
p_c' - Preconsolidation pressure.
p_{oh}' - Effective horizontal stress in the field.
p_{ov}' - Effective vertical stress in the field.
s_u - Undrained shear strength.
σ_{ac}' - Specified axial consolidation stress.
σ_{rc}' - Specified radial consolidation stress.
$\sigma_{av \cdot c}'$ - Specified average consolidation stress,

$$\sigma_{av \cdot c}' = \frac{\sigma_{ac}' + 2\sigma_{rc}'}{3}$$

σ_c' - Effective isotropic stress.

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