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Geotechnical investigation and testing — Laboratory testing of soil —

Part 9: Consolidated triaxial compression tests on water-saturated soil

Reconnaissance et essais géotechniques — Essais de sol au laboratoire —

Partie 9: Essai triaxial consolidé sur sol saturé

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Foreword

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ISO/TS 17892-9 was prepared by the European Committee for Standardization (CEN) in collaboration with Technical Committee ISO/TC 182, *Geotechnics*, Subcommittee SC 1, *Geotechnical investigation and testing*, in accordance with the Agreement on technical cooperation between ISO and CEN (Vienna Agreement).

Throughout the text of this document, read "...this European pre-Standard..." to mean "...this Technical Specification...".

ISO 17892 consists of the following parts, under the general title *Geotechnical investigation and testing — Laboratory testing of soil*:

— *Part 1: Determination of water content*

— *Part 2: Determination of density of fine-grained soil*

— *Part 3: Determination of particle density — Pycnometer method*

— *Part 4: Determination of particle size distribution*

— *Part 5: Incremental loading oedometer test*

— *Part 6: Fall cone test*

- *Part 7: Unconfined compression test on fine-grained soil*
- *Part 8: Unconsolidated undrained triaxial test*
- *Part 9: Consolidated triaxial compression tests on water-saturated soil*
- *Part 10: Direct shear tests*
- *Part 11: Determination of permeability by constant and falling head*
- *Part 12: Determination of the Atterberg limits*

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Foreword

This document (CEN ISO/TS 17892-9:2004) has been prepared by Technical Committee CEN/TC 341 "Geotechnical investigation and testing", the secretariat of which is held by DIN, in collaboration with Technical Committee ISO/TC 182 "Geotechnics".

According to the CEN/CENELEC Internal Regulations, the national standards organizations of the following countries are bound to announce this Technical Specification: Austria, Belgium, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, Switzerland and United Kingdom.

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— *Part 12: Determination of Atterberg limits*

Introduction

This document covers areas in the international field of geotechnical engineering never previously standardised. It is intended that this document presents broad good practice throughout the world and significant differences with national documents is not anticipated. It is based on international practice (see [1]).

1 Scope

This document covers the determination of stress-strain relationships and effective stress paths for a cylindrical, water-saturated[1)] specimen of undisturbed, remoulded or reconstituted soil when subjected to an isotropic or an anisotropic stress under undrained or drained conditions and thereafter sheared under undrained or drained conditions within the scope of the geotechnical investigations according to prEN 1997-1 and -2. The test methods provide data that are appropriate to present tables and plots of stress versus strain, and effective stress paths.

Special procedures such as:

a) Tests with lubricated ends;

b) tests with local measurement of strain or local measurement of pore pressure;

c) tests without rubber membranes;

d) extension tests;

e) shearing where cell pressure varies;

f) shearing at constant volume (no pore pressure change)

are not covered.

The conventional triaxial apparatus is not well suited for measurement of the initial moduli at very small strains. However, strains halfway up to failure are considered to be large enough to be measured in conventional triaxial cells.

2 Normative References

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

prEN 1997-2, *Eurocode 7: Geotechnical design - Part 2: Design assisted by laboratory testing*

prEN 1997-1, *Eurocode 7: Geotechnical design - Part 1: General rules*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply..

3.1
CIU-test
isotropically consolidated undrained test

3.2
CAU-test
anisotropically consolidated undrained test

3.3
CID-test
isotropically consolidated drained test

1) Water saturated refers to the in-situ condition. The material tested need not necessarily be saturated at all stages during the laboratory testing.

3.4
CAD-test
anisotropically consolidated drained test

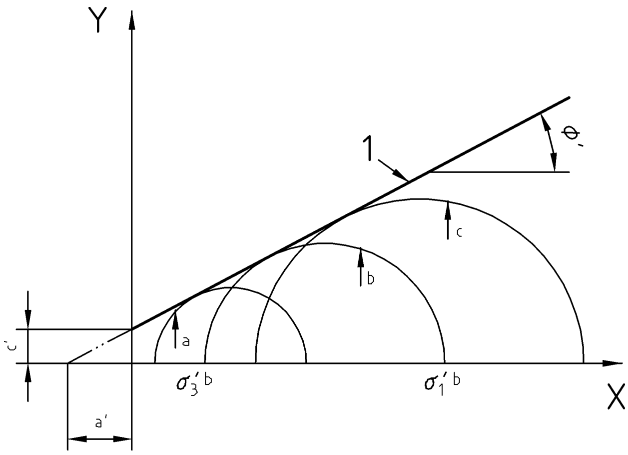
3.5
back pressure
external pressure by which the pore pressure is increased prior to consolidation or shearing in order to saturate the filters, the pore pressure measuring system and the specimen

3.6
failure
stress or strain condition at which failure takes place

NOTE If no specification for the failure state is given, failure may be considered to occur at the peak deviator stress.

3.7
effective shear strength parameter
friction angle ϕ' and cohesion intercept c' both in terms of effective stress (see Figure 1)

NOTE These parameters relate to the shear stress mobilized at the failure state specified.



Key

a Test 1
b Test 2
c Test C
X effective normal stress
Y shear stress
c´ effective cohesion intercept
a' attraction intercept
ϕ' effective friction angle

Figure 1 — Mohr stress circles at failure

3.8
cohesive soils
soils that behave as if they were actually cohesive, e.g. clay and clayey soils

NOTE Most soils in this group behave cohesively due to negative pore pressure and friction, and not due to cohesion.

3.9
undisturbed simple
sample of quality class 1 according to prEN 1997-2

4 Symbols

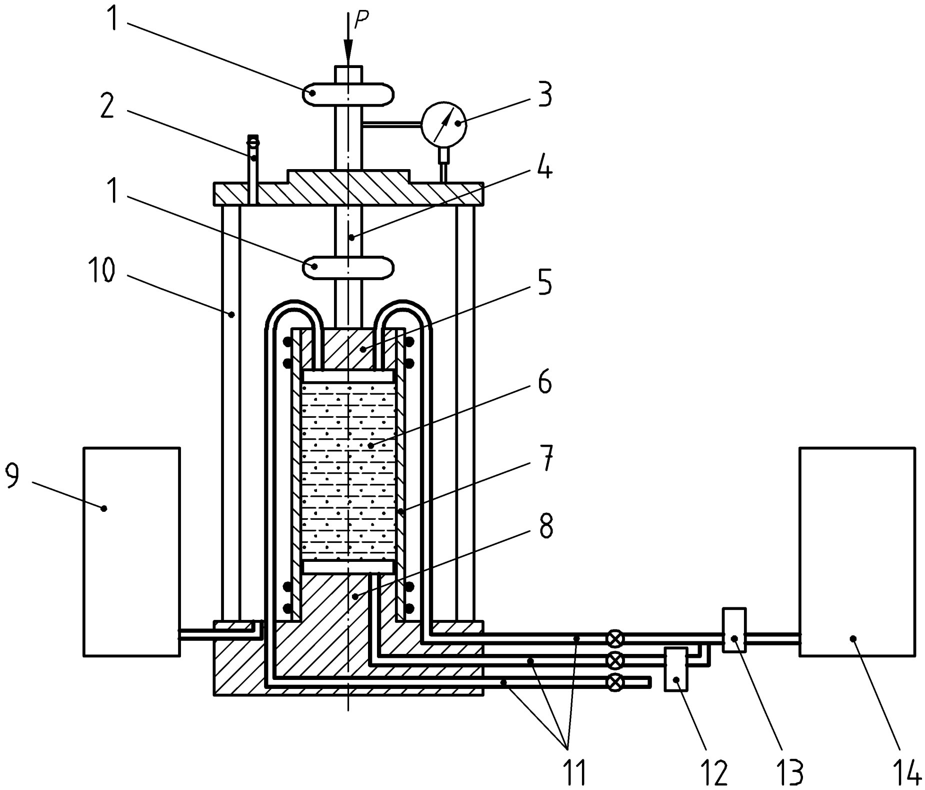
ε_1 and ε_{vol}	vertical and volumetric strain, respectively, during shearing.
σ_{cell}	total cell pressure.
σ_1 and σ_1'	major total and major effective stress, respectively (see note).
σ_3 and σ_3'	minor total and minor effective stress, respectively (see note).
$\sigma_1 - \sigma_3$	deviator stress.
u and Δu	total pore pressure and change in pore pressure respectively.
σ_{1C}'	major effective stress at end of consolidation.
σ_{3C}'	minor effective stress at end of consolidation.

NOTE Except perhaps in the case of anisotropic consolidation of strongly overconsolidated materials, σ_1 will be equal to the vertical stress and σ_3 will be equal to the horizontal stress for all tests described in this draft. If the vertical stress is greater than the horizontal one, the vertical stress shall be called σ_V instead of σ_1 and the horizontal stress σ_H instead of σ_3.

5 Equipment

5.1 General

A schematic diagram of an apparatus for triaxial testing is shown in Figure 2.



Key

1 alternative positions for load measuring device
2 air bleed
3 vertical compression measuring device
4 piston
5 top cap
6 soil specimen
7 membrane
8 pedestal
9 device for measurement and control of cell pressure
10 triaxial cell
11 drainage tubes
12 pore pressure sensor
13 volume change sensor
14 device for measurement and control of back pressure
P vertical load

Figure 2 — Example of a triaxial test unit

5.2 Triaxial cell

5.2.1 The triaxial cell shall be able to withstand a total cell pressure equal to the sum of the consolidation stress and the back pressure without significant of cell fluid out of the cell.

A cell with a maximum cell pressure of 2000 kPa will be sufficient for nearly all cases. Transparent cells should be used.

5.2.2 The sealing bushing and piston guide shall be designed such that the piston runs smoothly and maintains alignment.

5.2.3 The testing procedure, the accuracy of the load measuring device, the design of the piston, its sealing and guide and the design of the connection between the piston and the top cap shall be such that the load at failure is known to an accuracy of ± 3 % or to an accuracy of ± 1 N, whichever is the greater. It shall be ensured that this accuracy can be achieved with the worst possible combination of vertical and horizontal force and bending moment acting at that end of the piston that projects into the triaxial cell.

If the load measuring device is situated outside the triaxial cell (see Figure 2), it shall be ensured that the friction between the piston and its sealing bushing is low enough or repeatable enough to permit the failure load to be determined with the required accuracy.

NOTE Smooth running of the piston when subjected to no horizontal load and no cell pressure is no guarantee that this is the case.

If the load measuring device is situated inside the triaxial cell, it shall be ensured that the device is sufficiently insensitive to horizontal forces and/or bending moments to achieve the required accuracy. The influence of the cell pressure on the load cell, if any shall be sufficiently repeatable to be corrected for.

5.2.4 The top cap and the pedestal and the connection between the top cap and the piston shall be designed such that their deformations are negligible compared to the deformations of the soil specimen.

5.2.5 The diameter of the top cap and of the pedestal shall normally be equal to the diameter of the specimen. Specimens with diameters smaller than the diameter of the end caps may be tested provided cavities under the membrane at the ends of the specimen can be avoided.

5.2.6 The vertical stress applied on the specimen due to the weight of the top cap shall not exceed 3 % of the unconfined compressive strength (compressive strength is equal to two times the shear strength) of the specimen or 1 kPa whichever is the greater.

For cohesionless specimens held together with a suction the unconfined compressive strength in this connection may be assumed to be equal to the maximum deviator stress the specimen can sustain with the applied suction without collapsing.

5.2.7 The valves on the drainage tubes coming from the filter discs shall not cause a pressure change greater than 1 kPa when operated in a closed saturated pore pressure system. All valves shall be able to withstand the applied pressure without leakage.

Both the top and the pedestal should, preferably, have two drainage tubes so that the filter discs can be flushed with water after mounting of the specimen.

5.3 Confining membrane

5.3.1 The soil specimen shall be confined by an elastic membrane which effectively prevents the cell fluid from penetrating into the specimen.

5.3.2 Combinations of confining membranes and filter strips that give a combined correction on the deviator stress (σ_1-σ_3) of more than 10 % at failure should not be used (see 5.5, 7.4 and 7.5).

5.3.3 If O-rings are used to seal the confining membrane to the top and to the pedestal, their dimensions and elastic properties shall be such the confining membrane is firmly sealed to the top cap and to the pedestal.

If rubber membranes are used, membranes with following properties should be used.

— unstretched diameter between 95 % and 100 % of specimen (after being stored in water);

— thickness not exceeding about 1 % of the specimen diameter;

— elastic modulus (measured in tension) not exceeding 1600 kPa.

5.4 Porous discs

5.4.1 The diameter of the porous discs at the ends of the soil specimen shall be equal to that of the specimen. The discs have a plane and smooth surface and their compression shall be negligible compared to the compression of the soil specimen.

5.4.2 The coefficient of permeability of the porous discs shall for tests on clay and silt specimens be between 10^{-6} m/s and 10^{-4} m/s. For tests on coarser materials more permeable porous discs should be used.

5.4.3 The discs should be boiled in distilled water for 10 minutes before use and kept immersed in de-aired water until required.

5.5 Filter paper

5.5.1 Filter paper for side drain shall be of a type which does not dissolve in water and has a coefficient of permeability not less than 10^{-7} m/s for a normal pressure of 600 kPa.

Filter paper strips should not be used for soils with a coefficient of permeability equal to and higher than about 10^{-9} m/s.

5.5.2 To avoid hoop tension, vertical filter paper strips shall not cover more than 50 % of the specimen periphery.

NOTE No correction for filter paper strength is needed if only four, inclined filter paper strips are used where the width of each strip does not exceed about 10 % of the specimen diameter and where the inclination of each strip is about 1:√2, 1 being the vertical distance √2 the corresponding distance along the specimen perimeter.

5.5.3 Filter paper discs (of the same type as for the side drain) may be used between the specimen and the end porous discs in cases where soil particles tend to be washed through the discs.

5.6 Fluid pressure devices

The devices for keeping the cell and the pore pressure constant shall be accurate enough to keep the difference between cell and pore pressure during consolidation constant to within ± 2 % of the required value or within ± 1,0 kPa, whichever is the greater. The tubings between the triaxial cell and the pressure measuring device shall be wide enough to ensure negligible pressure difference between these two components.

5.7 Load frame

5.7.1 The load frame shall be able to provide the rates of vertical strain specified in 6.8.2 and 6.8.3. The actual rate shall not deviate more than ± 10 % from the required value. The movement of the platen shall be smooth without fluctuations or vibrations.

A load frame with a maximum load capacity of 15 kN which is able to advance to the piston with rates varying from about 0,0005 to about 2 mm per minute with a minimum of ten different advance rates is considered to be sufficient for most testing on material more fine-grained than gravel.

5.7.2 The stroke of the load frame shall be at least 30 % of the specimen height.

5.8 Measuring devices

5.8.1 Vertical load

The accuracy of the vertical load sensor shall be compatible with the accuracy by which the failure load is required to be known (see 5.2.3).

5.8.2 Pressure

5.8.2.1 Cell pressure and pore pressure measuring devices shall be sufficiently accurate to permit the difference between total cell pressure and pore pressure to be known within ± 2 % or within ± 1,0 kPa whichever is the greater. These devices shall indicate correct pressures at the level corresponding approximately to the half height of the specimen.

5.8.2.2 The pore pressure system shall be sufficiently rigid. The requirement expressed by equation (1) below should be used as a guide to the maximum permitted volumetric expansion when pressurised:

$$\frac{\Delta V_{ms}}{\Delta V \times \Delta u} \leq 0{,}5 \times 10^{-6}\,\text{m}^2/\text{kN} \quad (1)$$

where

ΔV_{ms}	is the $(\Delta V_{ms})_{tubings} + (\Delta V_{ms})_{ppm}$ (2)
$(\Delta V_{ms})_{tubings}$	is the change in volume of tubings due to a pore pressure change Δu. This includes all tubings which are subjected to pore pressure change during undrained shearing;
$(\Delta V_{ms})_{ppm}$	is the change in volume of the pore pressure measuring device (e. g., an electronic sensor) due to a pore pressure change Δu;
V	is the total volume of specimen.

5.8.3 Compression

5.8.3.1 The vertical displacement of the specimen is usually determined by measuring the distance the piston travels relative to the cell. The distance travelled by the piston shall be measured with an accuracy better than ± 0,10 % of the initial specimen height.

5.8.3.2 The displacement sensor, with the applied reading equipment, shall be readable to ± 0,015 % of the initial specimen height.

5.8.3.3 Possible false displacement due to cell pressure change shall be accounted for.

5.8.3.4 If stress-strain moduli are to be measured, the accuracy of the compression measurement shall be adjusted to be compatible with the desired accuracy for the measurement of the stress-strain moduli.

5.8.4 Volume change

The amount water and air going into or out of the specimen shall be measured with an accuracy better than ± 0,20 % of the initial volume of the specimen. The volume change sensor, with the applied reading equipment, shall be readable to ± 0,05 % of the initial volume of the specimen.

6 Test procedure

6.1 General requirement and equipment preparation

6.1.1 Test specimen shall be cylindrical with diameter not less than 35 mm and height from 1,85 to 2,25 times the diameter. For materials with uniform grading (i. e. materials with uniformity coefficient $C_u = d_{60}/d_{10}$ <5), the largest soil particle size should not exceed 1/10 of the specimen diameter. For other materials the largest particle size may be up to 1/6 of the specimen diameter.

6.1.2 The specimen height and diameter shall be measured or evaluated in such a way their average values are known within ± 0,1 mm. The mass of the specimen shall be measured to within ± 0,1%.

6.1.3 Care shall be taken to maintain the water content of the specimen during the preparation process. If the process for some reason is interrupted, the specimen shall be carefully wrapped in plastic foil. Air circulation around the specimen shall be avoided.

6.1.4 It shall be checked prior to each test that the drainage tubes and valves are not clogged and are without leakage are without leakage when pressurized.

6.1.5 The confining membrane shall be checked for leakage before each test, for example by subjecting it to a small air pressure on the inside and looking for air bubbles when immersing it in water. The membranes shall be dry on the inside before being placed onto the soil specimen.

If rubber membranes are used, they shall be stored in water at least 24 hours before being used because dry membranes tend to adsorb water.

6.1.6 The filter discs shall be regularly checked to determine whether they have become clogged.

A filter disc may be checked for clogging in the following way: tape shall be mounted along the perimeter of the filter, some water is placed on top of it and air is blown upwards through the filter. The operation shall be repeated with a new, unused filter for comparison.

6.1.7 When the set up is ready for the triaxial cell to be mounted, a small suction, (5 kPa to 50 kPa, low enough not to cause any harm to the specimen) shall be applied to the drainage tubes. The vacuum shall then be shut off. If the vacuum decreases more than about 2 % over a time period of about 2 minutes, investigations shall be made to detect possible leaks in the membrane or drainage tubes.

6.1.8 If the vertical load is measured outside the triaxial cell, it shall be checked prior to each test that the piston runs smoothly, and if a rotation bushing is used, it shall be checked during each test, by direct observation of the bushing, preferably at high loads, that it really rotates.

6.1.9 To fill the cell, a liquid shall be used which does not significantly penetrate the membrane enclosing the specimen or absorb a significant amount of water from the specimen through the membrane.

NOTE De-aired water is generally found to meet these requirements.

6.1.10 The water used to saturate (or flush) filter discs and filter papers shall be de-aired. If the salt content of the pore water is known, filter discs and filter papers should be saturated (or flushed) using water with this known salt content. If the salt content is unknown, fresh water shall be used.

6.2 Preparation of undisturbed specimens

6.2.1 Disturbed material near the ends of a sample should not be used for triaxial testing.

6.2.2 Extreme care shall be take to avoid, as much as possible, deforming the specimen during the mounting process. Very soft specimens (undrained shear strength < 12,5 kPa) may have to be mounted without touching the specimen by hand at any stage during the preparation.

6.2.3 The end surfaces shall be plane and perpendicular to the longitudinal axis as possible. The angle between each end surface and the longitudinal axis shall not deviate from a right angle by more than ± 0,6°. Grooves and holes in the ends and sides of the specimen shall be filled with remoulded material if they cannot be removed by further trimming and if new specimens cannot be trimmed. Grooves and holes in the ends greater than 1/10 of specimen diameter shall be filled in with a material that hardens with time and which does not release or absorb water.

6.2.4 Undisturbed clay and clayey specimens shall be prevented from swelling caused by the specimen sucking water from the filter discs (see note). Exception from the requirement to prevent swelling can only be made if it can be documented that the swelling occurring does not lead to significant softening of the specimen.

NOTE The safest method to achieve this is to mount the specimen with dry filter discs and to flush them with water with a cell pressure high enough to inhibit swelling. The procedure is recommended especially for specimens that may swell appreciably when in contact with water.

6.3 Artificially prepared specimens

6.3.1 Remoulded or reconstituted specimens may be prepared by tamping/kneading /vibrating the material in layers into a split mould with the rubber membrane mounted inside (see note). The top of each layer should be scarified prior to the addition of material of the next layer. Water mixed into the material should be given time before the compaction to equalize over the whole soil mass. Under-compaction should be used (except for remoulded specimens) to achieve a homogeneous specimen. Specimens of noncohesive material may be held together by a negative pore pressure of 10 kPa to 20 kPa when the split mould is removed, until a positive cell pressure of equal magnitude has been applied. Reconstituted specimens of sand may also be prepared by pluvial compaction (sand raining) in air or under water.

NOTE Remoulded specimens are specimens made of cohesive remoulded material at a water content near the in situ water content.

6.3.2 If the specimen is to be saturated (or flushed) with water after mounting de-aired water shall be used. A dry soil containing its natural salt content shall be flushed with fresh water. For tests where a high degree of water saturation is necessary to meet the requirements for the B-value (see 6.4.1.2), CO_2 (which will dissolve in water) should be flushed through the specimen prior to flushing with water. The volume of CO_2 flushed through the specimen should be at least about 6 times the pore volume.

NOTE The volume of CO_2 passing the specimen can be roughly estimated by taping a plastic bag to the tubing where the CO_2 is coming out of the specimen.

6.4 Saturation and application of back pressure

6.4.1 Saturation

6.4.1.1 The filters, the pore pressure measuring system and the specimen shall be sufficiently saturated, if necessary with back pressure, to allow a reliable measurement of pore pressure during undrained shearing, and accurate volume change measurements during drained shearing.

6.4.1.2 Unless it can be documented that the procedure followed gives satisfactory measurements, that saturation shall be checked by measuring the B-value. This parameter is defined by equation (2):

$$B = \frac{\Delta u}{\Delta \sigma} \qquad (2)$$

where

Δu is the increase in pore pressure when both σ_1 and σ_3 are increased, under undrained conditions by a value of $\Delta\sigma$.

The value of $\Delta\sigma$ shall be from 25 kPa for soft soils, to 100 kPa for stiff soils. The value of Δu used to compute B should preferably be recorded no later than 2 minutes after application of $\Delta\sigma$, and under no circumstances shall it be recorded later than 10 minutes after application of $\Delta\sigma$.

6.4.1.3 If the rate of volumetric strain prior to the B-value measurement exceeds 0,0001 %/min due to secondary consolidation, the measured pore pressures during the B-value measurement shall be corrected for the increase in pore pressure due to secondary consolidation. This correction shall be determined prior to the B-value measurement by closing the drainage system, and recording the increase in pore pressure with time when there is no increase in cell pressure.

6.4.1.4 A B-value of at least 0,95 when measured at end of consolidation is required unless it can be documented that lower values give satisfactory pore pressure measurements. A B-value lower than 0,95 can be accepted if it can be shown that a 50 % increase in back pressure does not give any increase in the B-value.

6.4.2 Application of back pressure

6.4.2.1 The following requirements shall be met during application of the back pressure:

— Variations of more than ± 10 % in the difference between cell pressure and pore pressure shall be avoided. For effective stresses below 20 kPa the variations shall be kept below ± 2 kPa.

— The effective stresses acting on the specimen shall not exceed the specified effective consolidation stresses unless special permission to do so is given by the engineer or office requesting the tests.

NOTE 1 Too high variations in the difference between cell pressure and pore pressure during application of backpressure can be avoided by using a …"..

NOTE 2 Too high effective stresses during application of back pressure is avoidable by applying the back pressure in steps, each step being smaller than the smallest specified effective consolidation stress, minus the effective stress acting on the specimen at start of application of the back pressure, and allowing each step to come to equilibrium before applying a new step. The vertical compression during application of the back pressurer ΔH_{sat} is measured for example, by adding dead-weight on the piston so that is comes into contact with the top cap at the start and at the end of the period with back pressure application. The volume change during this period ΔV_{sat} is calculated from the following equation:

$$\Delta V_{sat} = \frac{\Delta H_{sat}}{H_i} \times 3 \times V_i$$

where

V_i and H_i are initial volume height of specimen respectively.

A step reaches equilibrium when a plot of vertical displacement (or amount of water going into the specimen) versus square root of time levels out (like a consolidation curve).

6.4.2.2 Back pressure may be applied before or after consolidation. However, for poorly saturated specimens, application prior to consolidation makes it easier to avoid the effective stresses exceeding the final consolidation stresses when applying the back pressure.

6.4.2.3 For dilatant materials, the back pressure shall be high enough to prevent too early failure due to cavitation of the pore water. The total pore water pressure shall be positive at failure.

6.4.2.4 When the back pressure is fully applied, is shall be carefully checked whether there are any droplets of water leaking out from any drainage tubes, valves or connections. Any leakage shall be repaired before the testing is continued.

6.5 Isotropic consolidation (CIU and CID tests)

6.5.1 Adjust the cell pressure until the difference between the total cell pressure and the total pore pressure becomes equal to the specified $\sigma'_{1C} = \sigma'_{3C}$ value. Stress increments that are so high that particles tend to come out from the specimen shall be avoided.

6.5.2 The vertical compression during consolidation ΔH_c could be measured. This can be done if the piston is kept in contact with the top cap, for example by adding weights on top of the piston throughout the consolidation stage. The accuracy of the displacement measurement is improved by adding dead weight on the piston somewhat ahead of the cell pressure increments so that the piston force acting on the top cap always is positive, or by attaching the piston to the top cap by a suction device or a similar device.

6.5.3 The primary consolidation shall be completed before start of shearing. If there is any doubt about whether primary consolidation is finished or not before start of shearing and/or what rate of strain shall be used during shearing, time-volume change readings shall be taken during the consolidation and interpreted with regards to the end of consolidation as described in the standard for oedometer tests with incremental loading.

6.5.4 In cases where rate of volumetric strain at start of shearing, due to secondary consolidation, is likely to exceed 0,0001 % per min, the value of this parameter should be measured and reported.

6.6 Anistropic consolidation (CAU and CAD tests)

6.6.1 The effective stress path followed during anisotropic consolidation shall be approved. It shall be ensured that the stress state does not approach any failure envelope at all stages of the consolidation. To check and control this, the vertical displacement and volume change shall be measured and the stresses frequently computed (see 7.3).

6.6.2 Anisotropic consolidation may be achieved as follows:

a) The specimen shall be isotropically consolidated with an effective stress equal to the required horizontal effective consolidation stress σ'_{3C};

b) a deviator stress, with the specimen fully drained shall be applied until the required vertical effective consolidation stress σ'_{1C} is reached.

6.6.3 The load P to be applied to the piston to reach σ'_{1C} may be calculated from the equation (3):

$$P = (\sigma'_{1c} - \sigma'_{3c}) \times A - K + (\sigma'_{3c} + u_B) \times a \tag{3}$$

NOTE The symbols other than σ'_{1c} and are σ'_{3c} are explained in 7.3. In the equation above the corrections for the restraints in confining membrane and side drains are neglected because the strains during consolidation are normally small, and because small differences between specified and real consolidation stresses can generally be tolerated. However, these corrections should, whenever significant, be included in the final computations.

6.6.4 In cases where rate of volumetric strain at start of shearing, due to secondary consolidation, is likely to exceed 0,0001 % per min, the value of this parameter should be measured and reported.

6.7 Consolidation for multi-stage tests

Multistage testing means that several stages of consolidation (separated by stages with shearing) are applied to the same specimen, the consolidation stresses being increased for each stage. Each consolidation stage (isotropic or anisotropic) shall be performed as described in 6.5 and 6.6.

6.8 Shearing

6.8.1 General

6.8.1.1 For all types of shearing described in this document, the total cell pressure shall be kept constant (with the accuracy that can be achieved with the equipment specified in 5.2) and the specimen loaded to failure (sheared) by moving the piston into the triaxial cell with a constant rate (with the accuracy specified in 5.6) on the loading frame.

6.8.1.2 The temperature during undrained shearing may not vary by more than ± 2 °C.

6.8.1.3 Before start of shearing, the entire drainage tubes, valves or connections shall be inspected to ensure there are no leaks and droplets of water visible on the outside of the triaxial cell. Any leakage shall be repaired before start of shearing. Zero readings of all measuring devices shall be taken and the position of all valves checked, also of the cell pressure system. When the vertical load is measured outside the triaxial cell, the load shall be corrected for friction between piston and bushing, if this is significant.

6.8.1.4 During shearing, readings shall be taken on all measuring devices at intervals such that stress-strain curves and stress paths can be obtained from the readings. As a minimum, 15 readings shall be taken prior to failure, and thereafter at every 1 % vertical strain. For brittle materials, readings shall be taken more frequently around failure than during the rest of the test. If the secant modulus E_{50} (see 7.3.9), is to be determined from the test, readings shall be taken frequently enough to allow false displacement readings to be identified and evaluated.

NOTE False displacement readings are likely to occur at the start of shearing for tests with isotropic consolidation where the deviator load starts from almost zero and for tests with anisotropic consolidation where the deviator load passes from tension to compression (for heavily overconsolidated specimens).

6.8.1.5 If the strain at which the test shall be stopped has not been specified, the test may be stopped when the axial strain reaches 15% or exceeds, by 5%, the strain at peak deviator stress, whichever is earlier.

6.8.1.6 The false displacements at these points may be evaluated by plotting load versus displacement at an enlarged scale and regarding the more or less horizontal part of the plot as representing false displacement.

6.8.1.7 The false displacements can be reduced by attaching the piston to the top cap by using a suction cap or a similar device, or by using internal strain sensors, mounted directly on the side of the specimen.

6.8.2 CIU and CAU tests

6.8.2.1 In this document, only CIU and CAU tests with pore pressure measurements are covered.

6.8.2.2 No drainage shall be allowed to take place during shearing and the rate of strain shall be low enough to secure equalisation of pore pressure at failure. If no documented information about allowable rate of strain is available, the rate of vertical displacement of the loading platen, $v_{max,}$ shall not exceed the value calculation from the equation (4):

$$v_{\max} = \frac{(H_i - \Delta H_c) \times \varepsilon_{1f}}{F \times t_{50}} \quad (4)$$

where

t_{50} is the time required for 50 % primary consolidation to take place;

ε_{1f} is the expected vertical strain (absolute value) at failure. If pore pressure equalization is wanted at a lower strain than ε_{1f}, this strain value shall be used in the equation;

F is the factor depending on type of test and drainage conditions. Values of F corresponding to 95 % pore pressure dissipation are given in Table 1;

ΔH_c is the change in specimen height during consolidation.

Table 1 — Factors for calculating rate of loading press

Drainage conditions during consolidation	**Values of F (for H_i/D_i = 2)**	
	Undrained test[a]	**Drained test[b]**
from one end	2,1	34
from both ends	8,4	34
from radial boundary and one end	7,2	56
from radial boundary and two ends	9,2	64

[a] For stiff, fissured soils, the F-values given for drained tests shall be used also for undrained tests.

[b] The drainage conditions during consolidation and drained shearing shall be the same for the F-values to apply.

6.8.2.3 The following variables shall be recorded during the test:

— vertical load;

— vertical compression;

— total cell pressure and total pore pressure (alternatively the difference between total cell pressure and pore pressure maybe measured).

6.8.3 Drained tests (CID and CAD)

6.8.3.1 Tests shall be run slowly enough to ensure negligible pore pressure changes in the specimen during shearing. The specimen shall be allowed to drain freely during shearing. If no documented information about allowable rate of strain is available, the rate of vertical displacement of the loading press, $v_{max,}$ shall not exceed the value calculated from equation (4).

6.8.3.2 For drained tests on dilatant materials the use of equation (4) and Table 1 may give too high values of allowable rate of vertical displacement $v_{max.}$ In such cases other procedures should be used to obtain reliable values of $v_{max.}$ For specimens with no side drains, the procedure described in 6.8.3.5 may be used.

6.8.3.3 The rate of axial strain for free draining materials (sand) shall not exceed 0,2 % per minute.

6.8.3.4 The following variables shall be recorded during the test:

— vertical load;

— vertical displacement;

— volume change;

— total pressure and total pore pressure (alternatively, the difference between total cell pressure and total pore pressure may be measured).

For drained tests on specimens with no side drains, a sufficiently low rate of strain to secure fully drained conditions may be secured as follows;

— free draining towards a constant back pressure at one end of the specimen shall be allowed;

— pore pressure at the other, undrained and shall be measured;

6.8.3.5 If the measured pore pressure differs from the constant back pressure by more than 4 % of the effective horizontal stress, the rate of strain shall be decreased.

6.8.4 Multistage tests

Shearing for multistage tests shall be performed as described in 7.3 except that shearing between two consolidation stress levels shall be stopped at a relatively small strain specified by the engineer or office requesting the tests. If no such specification is given, shearing for these intervals may be stopped as soon as the shear stress shows a tendency to become constant.

6.9 Dismounting

6.9.1 Specimens of cohesive soil

6.9.1.1 The drainage valve shall be shut (if it is not already done), the piston shall be unloaded and the cell pressure shall be reduced to zero.

6.9.1.2 As quickly as possible the specimen shall be removed from the triaxial cell and the membrane and filters shall be stripped off.

6.9.1.3 A rough sketch of the specimen indicating the failure planes shall be made or a photograph of the specimen shall be taken.

6.9.1.4 The whole specimen shall be weighed and immediately afterwards a representative part shall be selected and the moisture content shall be determined.

6.9.1.5 The specimen shall be broken into pieces and the soil shall be described. If there are particles greater than permitted, this shall be noted (see 6.1.1).

6.9.1.6 Particle Size Distribution, liquid and plastic limits on material that has not been dried, and particle density tests, if required, should be determined for at least one triaxial test specimen on each type of material included in the investigation.

6.9.1.7 The total volume of the whole specimen should be determined after the test, for example by submerged weighing in a liquid that does not penetrate into it.

6.9.2 Specimen of non-cohesive soil

6.9.2.1 A rough sketch of the specimen shall be made before the pressures are removed, indicating the main failure planes.

6.9.2.2 The whole specimen shall be dried after dismounting it from the triaxial cell to determine the dry mass. The dry mass of the whole specimen may also be determined from the initial weighing provided corrections are made for possible initial water content of the material.

6.9.2.3 The particle size distribution should be determined for at least one triaxial test specimen on each type of material included in the investigation.

7 Test results

7.1 Bulk density, dry density and water content

7.1.1 Cohesive soils

Initial water content and bulk density shall be calculated from initial measurements of height, diameter and mass of the specimen and from final weighings.

Initial void ratio (or initial porosity) and initial degree of saturation based on a measured or estimated particle density should be computed.

7.1.2 Non-cohesive soils

Initial dry density shall be calculated from initial measurements of height and diameter, and from final measurement of specimen dry mass.

7.2 Consolidation

7.2.1 If the vertical displacement during consolidation, ΔH_c is not measured, it shall be calculated. The equation (5) may be used:

$$\Delta H_c = \frac{1}{3}\frac{\Delta V_c}{V_i} \times H_i \tag{5}$$

where

ΔV_c is the volume change at end of consolidation;

V_i is the initial volume of specimen;

H_i is the initial height of specimen.

If ΔV_{sat} and ΔH_{sat} are determined they shall, in the following equations, be included in ΔV_c and ΔH_c respectively.

7.2.2 Stresses during and at end of consolidation may be computed from the equations given in 7.3.

7.3 Shearing (all types of test)

7.3.1 Average area of specimen:

$$A = \frac{V_i - \Delta V_c - \Delta V}{H_i - \Delta H_c - \Delta H} \tag{6}$$

7.3.2 Total vertical stress:

$$\sigma_1 = \frac{P + K - a \times \sigma_{cell}}{A} + \sigma_{cell} - (\Delta\sigma_1)_m - (\Delta\sigma_1)_{fp} \tag{7}$$

7.3.3 Effective vertical stress:

$$\sigma'_1 = \sigma_1 - u \tag{8}$$

7.3.4 Total horizontal stress:

$$\sigma_3 = \sigma_{cell} + (\Delta\sigma_3)_m \tag{9}$$

7.3.5 Effective horizontal stress:

$$\sigma'_3 = \sigma_3 - u \tag{10}$$

7.3.6 Pore pressure change: (for undrained tests)

$$\Delta u = u - u_B \tag{11}$$

7.3.7 Vertical strain:

$$\varepsilon_1 = \frac{\Delta H}{H_i - \Delta H_c} \tag{12}$$

7.3.8 Volumetric strain (for drained tests only):

$$\varepsilon_{vol} = \frac{\Delta V}{V_i - \Delta V_c} \tag{13}$$

7.3.9 Secant modulus:

$$E_{50} = \frac{(\sigma_1)_{50} - \sigma_{1c}}{(\varepsilon_1)_{50}} \tag{14}$$

where

ΔV_c is the volume change at end of consolidation;

V_i is the initial of specimen;

H_i is the initial height of specimen;

ΔH_C is the vertical compression during shearing;

ΔV is the volume change during shearing;

P is the vertical load = load on top of piston;

a is the area of piston;

K is W-[$(A$-$a)h$ x γ] where W is gravity force acting on dead weight hanger (if used), piston, top cap, one half of the soil specimen and so on, γ is unit weight of cell fluid and h is distance from top of top cap to mid-height of specimen (see NOTE 2);

σ_{cell} is the total cell pressure;

u is the total pore pressure;

u_B is the back pressure (= total pore pressure at start of shearing);

$(\Delta\sigma_1)_m$ is the correction on vertical total stress due to membrane restraint:.

$(\Delta\sigma_1)_{fp}$ is the correction on vertical total stress due to restraint in vertical filter paper strips.

$(\Delta\sigma_3)_m$ is the correction on horizontal total stress due to membrane restraint;

$$(\sigma_1)_{50} = \frac{\sigma_{1f} + \sigma_{1c}}{2}$$

σ_{1f} is the major total stress at failure;

σ_{1c} is the major total stress at end of consolidation;

$(\varepsilon_1)_{50}$ is the value of ε_1 at $(\sigma_1)_{50,}$ corrected for possible false displacements.

NOTE 1 Use of more accurate expressions than the above is permitted.

NOTE 2 The expression for K given above and equation (7) are valid when using a load measuring device that is placed outside the triaxial cell (see Figure 2) and for which zero-reading is taken when the device is hanging over the piston, without being in contact with it.

Other arrangements and/or procedures may require modifications of the expression for K and of equation (7).

For tests with only isotropic consolidation equation (7) may be simplified as follows:

$$\sigma_1 = \frac{P + K}{A} + \sigma_{cell} - (\Delta\sigma_1)_m - (\Delta\sigma_1)_{fp}$$

where P is the load recorded by the load cell, (the zero-reading being taken just before start of shearing with the piston moving into the cell, but clear of the top cap) and K is the submerged weight of the top cap and one half of the specimen. In this case the value of K is so low that it in many cases can be neglected. The term a x σ_{cell} shall not be included in the computation of σ_1 for triaxial cells where the uplift force on the piston due to the cell pressure is automatically compensated for, nor for triaxial cells where the load-measuring device in placed inside the triaxial cell.

7.3.10 Effective shear strength parameters

The effective shear strength parameters shall be determined for each of the types of materials included in the testing programme. This may be done by drawing the Mohr circle at failure for each of the tests on the type of material considered, and drawing a best fit tangent to the circles as shown in Figure 1. The slope of the line gives the friction angle in terms of effective stress, ϕ'. Its intercept with the shear stress axis gives the cohesion intercept, c'.

The failure line is usually determined by linear regression among the stress coordinates representing failure.

The intercept between the failure line and the effective normal stress axis determines the attraction intercept, a' (see Figure 1). This parameter (given as a positive number) is, in most cases, more practical to work with than c'. Therefore a' in addition to c' should be determined and reported.

7.4 Corrections for elastic membrane

7.4.1 Corrections for elastic membranes are applied both for the consolidation and for the shear stage. If not more accurate expression are used, equations (15) and (16) shall be used to compute the membrane correction.

7.4.2 Correction to total vertical stress:

$$(\Delta\sigma_1)_m = \frac{4 \times t \times E}{D_i}\left[(\varepsilon_1)_m + \frac{(\varepsilon_{vol})_m}{3}\right] \quad (15)$$

7.4.3 Correction to total horizontal stress:

$$(\Delta\sigma_3)_m = \frac{4 \times t \times E}{D_i} \times \frac{(\varepsilon_{vol})_m}{3} \quad (16)$$

where

t is the initial thickness of membrane;

E is the elastic modulus for membrane, measured in tension;

D_1 is the initial diameter of membrane (diameter before it is placed on specimen);

$(\varepsilon_1)_m$ is the vertical strain of membrane (expressed as a ratio);

$(\varepsilon_{vol})_m$ is the volumetric strain of membrane (expressed as a ratio).

The values of $(\varepsilon_1)_m$ and $(\varepsilon_{vol})_m$ are usually computed by assuming these strains to be zero just after placing the membrane on the specimen (that there are no initial strains) and assuming D_i to be equal to the initial diameter of the specimen. However, true membrane strains shall be used in the computation whenever significant. When computing the membrane correction for the shear stage, the strains during consolidation shall be included.

If the membrane correction at failure is smaller than about 5 % of the deviator stress, simpler expressions in which only the deviator stress is corrected may be used, (i.e. assuming $(\varepsilon_{vol})_m)$) to be zero in equation 15 and 16. If the correction is smaller than about 1 % at failure, it may be omitted.

Equations 15 and 16 for computing of the membrane correction are based on the assumptions that the specimen deforms as a cylinder and that no slippage takes place between the membrane and the specimen. Equation based on such assumptions may give somewhat too high membrane corrections on the deviator stress if the membrane wrinkles and considerably too low corrections if the specimen deforms along a single shear-plane (even if the membrane wrinkles).

7.5 Correction for filter paper strips

7.5.1 General

Correction for filter paper strips is applied only for the shear stage. If not more accurate expressions are used, equation (17) and (18) should be used to compute the correction for vertical filter paper strips during shearing.

7.5.2 Correction to vertical stress

For $\varepsilon_1 \leq 0{,}02$:

$$(\Delta\sigma_1)_{fp} = \frac{\varepsilon_1 \times K_{fp} \times P_{fp} \times O}{0{,}02 \times A_c} \quad (17)$$

for $\varepsilon_1 > 0{,}02$:

$$(\Delta\sigma_1)_{fp} = \frac{K_{fp} \times P_{fp} \times O}{A_c} \quad (18)$$

where

K_{fp} is the load (when fully mobilized) carried by filter paper covering a unit length of the specimen perimeter.

P_{fp} fraction of perimeter covered by filter paper (P_{fp} may be up to 50 % of the perimeter of the specimen);

ε_1 vertical strain for the shear stage as defined by equation 11;

A_c specimen area at end of consolidation;

O circumference.

8 Test report

8.1 General

The test shall affirm that the test was carried out in accordance with this document and shall include the following:

a) method of test used;

b) identification of the sample (material) being tested, e.g. boring number, sample number, sample depth, test number etc.;

c) description of tested material, including, when determined, liquid limit, plastic limit, and size of sand- and clay fractions;

d) procedure used for the preparation of specimens;

e) initial and final water content (i.e. water content after dismounting);

f) initial bulk density (cohesive soils) or dry density (non-cohesive soils);

g) initial void ratio or porosity, when determined;

h) data from the stage prior to shearing:

- consolidation stresses σ'_{1C} and σ'_{3C};
- time period for which the stresses were kept constant at end of consolidation, together with criteria used to decide when consolidation is finished;
- vertical strain after consolidation (ε_{1C});
- volumetric strain after consolidation ($\varepsilon_{vol\,c}$);
- rate of volumetric strain et end of consolidation if more than 0,0001 % per min., if determined;
- B-value, if measured;

i) the following data at failure:

- the failure criterion adopted;

$\frac{\sigma_1 - \sigma_3}{2}$ or $\sigma_1 - \sigma_3$;

$\sigma'_{3,}$ $\frac{\sigma'_1 + \sigma'_3}{2}$, or $\frac{\sigma'_1 + 2\sigma'_3}{3}$;

- Δu (for undrained tests only);
- $\varepsilon_{1;}$
- ε_{vol} (for drained tests only);
- rate of vertical strain (recommended unit: % per hour);
- secant modulus E_{50}, when required;

— effective shear strength parameters;

— drawing or photo showing the type of failure (degree of bulging, dominating failure planes and so on);

j) type of equipment used, including drainage conditions, the type of connection used between the piston and the top cap (between pedestal and piston if the piston is at the bottom of the cell). The information shall be accompanied by a principal drawing where information is given about how much the top cap is allowed to tilt and/or move horizontally during the test;

k) description of deviations from the procedures prescribed in this document;

l) other information required for proper interpretation of the test results.

Items (a) and (b) shall be repeated on all pages of the report.

All data reported in a numerical format shall have at least three significant digits.

It is further recommended to include in the report the in-situ effective overburden stress, and the in-situ preconsolidation stress, if known.

The laboratory shall maintain records of all data. These shall be made available for inspection if required.

8.2 Graphic presentation

The laboratory shall present graphic plots for each triaxial test specimen according to the following:

— plot of volume during consolidation versus square root of time if such a plot is used to decide when primary consolidation is finished, or to decide the rate of strain during shearing;

— shear stress, $(\sigma_1 - \sigma_3)/2$ or deviator stress, $(\sigma_1 - \sigma_3)$ versus vertical strain ε_1;

— pore pressure change during shearing, Δu, versus vertical strain (for CIU and CAU tests only);

— volumetric strain during shearing, $\Delta V/V_c$, versus vertical strain (for CID and CAD tests only).

— One of the following stress paths:

— σ_1' versus σ_3'

— $(\sigma_1' - \sigma_3')/2$ versus σ_3'

— $(\sigma_1' - \sigma_3')/2$ versus $(\sigma_1' + \sigma_3')/2$

— $(\sigma_1' - \sigma_3')$ versus $(\sigma_1' + 2\,\sigma_3')/3$.

The stress paths should be marked with values of ε_1, for example at ε_1 = 0 %; 0, 2 %; 0,5 %; 1,0 %; 2,0 %; 5 % and 10 %.

Water contents, porosities and so on and all strains (but not void ratios), should be reported as percentages. In equations these parameters should be treated as dimensionless ratios.

The value of $(\sigma_1' - \sigma_3')/2$ at failure for undrained tests is usually called 'undrained shear strength' and is usually denoted c_u. However, the symbol s_u should be used to make it clear that the undrained shear strength is basically not due to actual cohesion, but mainly due to friction and effective stresses.

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