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Geotechnical investigation and testing — Laboratory testing of soil —

Part 9: Consolidated triaxial compression tests on water saturated soils

Reconnaissance et essais géotechniques — Essais de laboratoire sur les sols —

Partie 9: Essais en compression à l'appareil triaxial consolidés sur sols saturés

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation on the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see the following URL: www.iso.org/iso/foreword.html.

This document was prepared by the European Committee for Standardization (CEN) Technical Committee CEN/TC 341, *Geotechnical investigation and testing*, in collaboration with ISO Technical Committee TC 182, *Geotechnics*, in accordance with the agreement on technical cooperation between ISO and CEN (Vienna Agreement).

This first edition of ISO 17892-9 cancels and replaces ISO/TS 17892-9:2004, which has been technically revised. It also incorporates ISO/TS 17892-9:2004/Cor.1:2006.

A list of all the parts in the ISO 17892 series can be found on the ISO website.

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 Reference [1]).

Geotechnical investigation and testing — Laboratory testing of soil —

Part 9: Consolidated triaxial compression tests on water saturated soils

1 Scope

This document specifies a method for consolidated triaxial compression tests on water-saturated soils.

This document is applicable to the laboratory determination of triaxial shear strength under compression loading within the scope of geotechnical investigations.

The cylindrical specimen, which can comprise undisturbed, re-compacted, remoulded or reconstituted soil, is subjected to an isotropic or an anisotropic stress under drained conditions and thereafter is sheared under undrained or drained conditions. The test allows the determination of shear strength, stress-strain relationships and effective stress paths. All stresses and strains are denoted as positive numerical values in compression.

NOTE 1 This document provides a test for a single specimen. A set of at least three relatable tests are required to determine the shear strength parameters from these tests. Procedures for evaluating the results are included in Annex B and, where required, the shear strength parameters are to be included in the report.

Special procedures such as:

a) tests with lubricated ends;

b) multi-stage tests;

c) tests with zero lateral strain (K_0) consolidation;

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

e) tests without rubber membranes;

f) extension tests;

g) shearing where cell pressure varies,

are not fully covered in this procedure. However, these specific tests can refer to general procedures described in this document.

NOTE 2 This document fulfils the requirements of consolidated triaxial compression tests for geotechnical investigation and testing in accordance with EN 1997-1 and EN 1997-2.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements 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.

ISO 14688-1, *Geotechnical investigation and testing — Identification and classification of soil — Part 1: Identification and description*

ISO 17892-1, *Geotechnical investigation and testing — Laboratory testing of soil — Part 1: Determination of water content*

ISO 17892-2, *Geotechnical investigation and testing — Laboratory testing of soil — Part 2: Determination of bulk density*

ISO 17892-3, *Geotechnical investigation and testing — Laboratory testing of soil — Part 3: Determination of particle density*

3 Terms and definitions

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

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— IEC Electropedia: available at https://www.electropedia.org/

— ISO Online browsing platform: available at https://www.iso.org/obp

3.1
CIU-test
isotropically consolidated undrained test

3.2
CAU-test
anisotropically consolidated undrained test

3.3
CID-test
isotropically consolidated drained test

3.4
CAD-test
anisotropically consolidated drained test

3.5
pore pressure
pressure of water in the void space within the soil specimen

3.6
back pressure
external pressure by which the pore pressure is increased prior to consolidation or shearing to ensure saturation

3.7
cell pressure
pressure applied to the cell fluid

3.8
deviator stress
difference between the vertical total stress and the horizontal total stress

3.9
effective stress
difference between the total stress and pore pressure

3.10
failure
stress or strain condition at which one of the following criteria are met:

— peak deviator stress

— peak effective stress ratio i.e. the ratio between the vertical and horizontal effective stress

— a specified deformation criterion e.g. 10 % vertical strain

— other definitions if required

4 Symbols

A_i	initial cross sectional area of the specimen
A_{cor}	cross-sectional area of the specimen at any point in time
a	cross-sectional area of the piston if an external load cell is used
B	pore pressure coefficient i.e. the ratio of the increase in pore pressure, Δu resulting from an increment of cell pressure, $\Delta\sigma_\mathrm{c}$ under undrained conditions
D_c	specimen diameter at the end of consolidation
D_i	initial specimen diameter
D_m	initial internal diameter of the confining membrane (before it is placed on specimen)
E_m	elastic modulus of the confining membrane
F	factor for calculating the rate of displacement of the load frame
f	factor relating the vertical strain to the specimen volumetric strain
H_c	specimen height at the end of consolidation
H_i	initial height of specimen
h	distance from the top of the top cap to the mid-height of the specimen
K_{fp}	load (when fully mobilized) carried by filter paper covering a unit length of the specimen perimeter
P	vertical load reading
P_{fp}	fraction of perimeter covered by filter paper
t_m	initial thickness of the unstressed membrane
t_{50}	time required for 50 % primary consolidation to take place
t_{100}	time required for 100 % primary consolidation to take place
u	pore pressure at the mid height of the specimen
u_B	back pressure (i.e. the pore pressure at start of shearing)
V_i	initial volume of specimen
v_{max}	rate of vertical displacement of the load frame during shearing
W	gravity force acting on the sum of the deadweight hanger (if used), the piston, the top cap and one half of the soil specimen
ΔH	specimen change in height (with compression being a positive numerical value)

ΔH_c	vertical change in height during consolidation, including any vertical change in height during saturation, if measured
Δu	change in pore pressure at the mid height of the specimen
ΔV	specimen volume change (with a reduction in volume being a positive numerical value)
ΔV_c	volume change up to the end of consolidation
$\Delta \sigma_c$	change in cell pressure
$(\Delta \sigma_h)_m$	correction to horizontal total stress due to membrane restraint
$(\Delta \sigma_v)_{fp}$	correction to vertical total stress due to restraint of the filter paper
$(\Delta \sigma_v)_m$	correction to vertical total stress due to membrane restraint
γ	unit weight of the cell fluid
ε	strain (with compression being a positive numerical value)
ε_{sv}	vertical strain during shear (expressed as a ratio)
ε_{svol}	volumetric strain during shear (expressed as a ratio)
ε_v	vertical strain (expressed as a ratio)
ε_{vf}	expected vertical strain at failure (expressed as a ratio)
$(\varepsilon_v)_m$	vertical strain of the membrane (expressed as a ratio)
ε_{vol}	volumetric strain
$(\varepsilon_{vol})_m$	volumetric strain of the volume enclosed by the membrane (expressed as a ratio)
σ_c	cell pressure
σ_h	horizontal total stress at the mid height of the specimen (see note)
σ'_h	horizontal effective stress at the mid height of the specimen (see note)
σ'_{hc}	horizontal effective stress at the mid height of the specimen at the end of consolidation
σ_v	vertical total stress at the mid height of the specimen (see note)
σ'_v	vertical effective stress at the mid height of the specimen (see note)
$\sigma_v - \sigma_h$	deviator stress
$(\sigma'_v - 2\sigma'_h)/3$	mean effective stress
σ'_{vc}	vertical effective stress at the mid height of the specimen at the end of consolidation

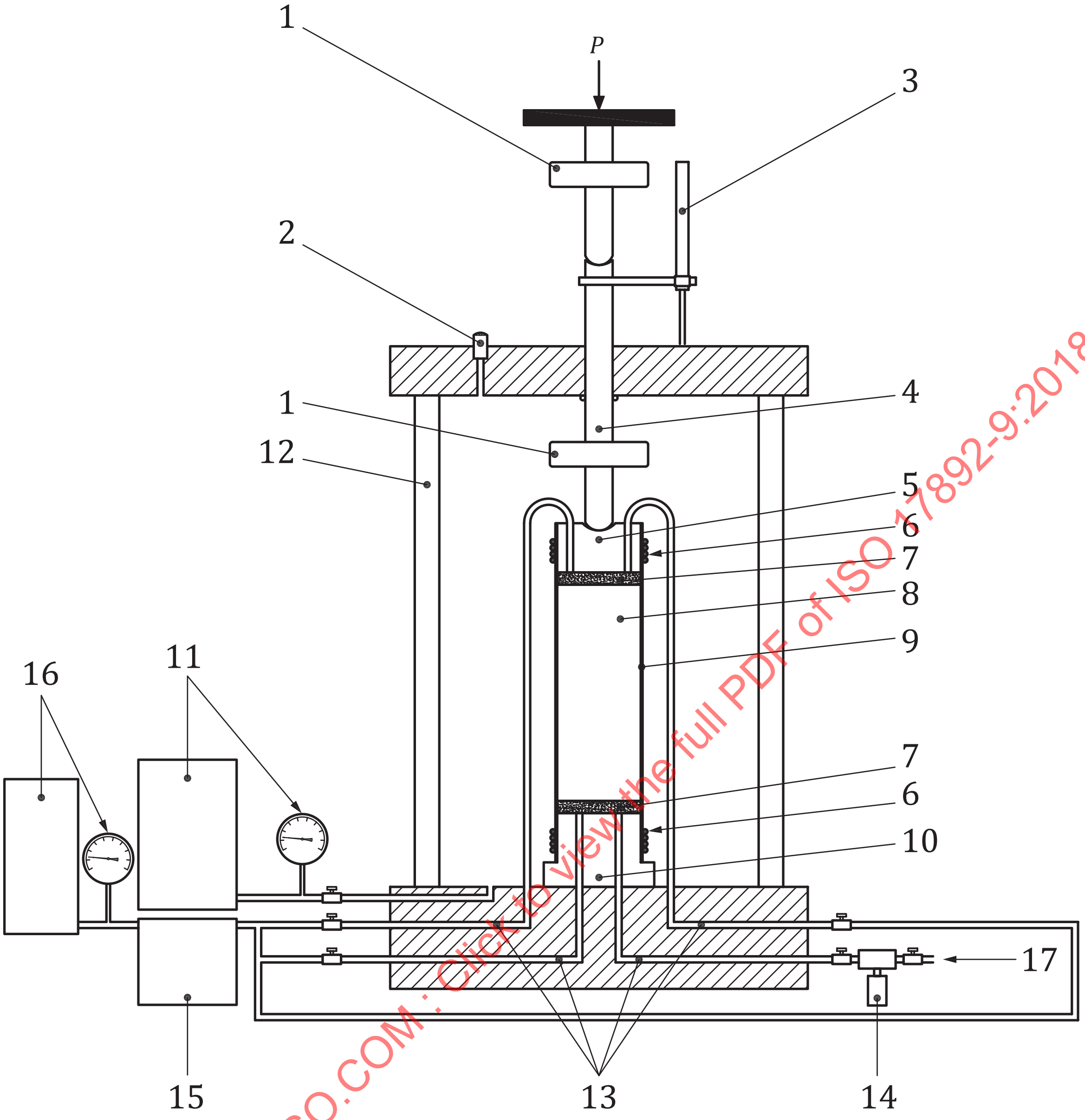
NOTE Throughout this document, effective stresses are indicated by a prime. Vertical and horizontal directions are indicated by the suffixes “v” and “h” respectively. This convention ensures that the directions of the action of stress acting on the specimen are clear and independent of their relative magnitudes.

5 Apparatus

5.1 General

The equipment shall undergo regular calibration, maintenance and checks as specified in Annex A.

A schematic diagram of a typical apparatus for triaxial compression testing is shown in Figure 1.



Key

1	alternative positions for load measuring device	10	pedestal
2	air bleed	11	device for measurement and control of cell pressure
3	vertical displacement measuring device	12	triaxial cell
4	piston	13	drainage tubes
5	top cap	14	pore pressure sensor
6	O-rings	15	device for measurement of volume change
7	porous disc	16	device for measurement and control of back pressure
8	soil specimen	17	flushing system
9	membrane (with or without side drains)	*P*	vertical load

Figure 1 — Schematic diagram of a typical triaxial apparatus

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 leakage of cell fluid out of the cell. Transparent cells should be used where possible.

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

5.2.3 The material of the top cap and the pedestal and the connection between the top cap and the piston shall be such that their deformations are negligible compared to the deformations of the soil specimen. In the case of stiff soils and if required (see A.3.3) the vertical deformation shall be corrected for apparatus compliance.

5.2.4 The diameter of the top cap and of the pedestal should 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.

5.2.5 The vertical stress applied on the specimen due to the weight of the top cap should not exceed 2 % of the estimated undrained shear strength of the specimen or 1 kPa, whichever is greater.

5.2.6 The valves on the drainage tubes coming from the porous discs should 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 cap and the pedestal should preferably have two drainage tubes so that the porous 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.

NOTE Membranes with an elastic modulus of around 1 400 kPa have been found to be suitable.

5.3.2 Combination of confining membrane and side drains that give a combined correction on the deviator stress of more than 10 % at failure should not be used (see 5.5, 7.2.3 and 7.2.4).

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 that the confining membrane is firmly sealed to the top cap and to the pedestal.

5.3.4 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 1 % of the specimen diameter.

5.4 Porous discs

5.4.1 Porous discs shall be rigid, non-corrodible and shall have a compressive strength in excess of the soils to be tested.

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

5.5 Filter paper

5.5.1 A filter paper (or similar material) may be placed between the specimen and the porous disc in order to keep fine material from being washed into the porous disc. The filter paper shall not react with the specimen. New filter paper shall be used for each test.

5.5.2 New filter paper strips ("side drains") may also be used to enhance drainage from the radial edges of low permeability specimens. These may be orientated vertically or spirally, i.e. at an oblique angle. Spiral drains do not require a filter paper correction and are preferred for specimens with an undrained shear strength below about 50 kPa.

5.5.3 Vertically orientated filter paper strips shall be evenly spaced and shall not cover more than 50 % of the specimen's radial surface. Spiral orientated strips shall be equally spaced, should be orientated at 30 ° to 45 ° to the vertical and shall not cover more than 50 % of the specimen's radial surface.

5.6 Pressure systems

The devices for applying pressure to the cell and to the back pressure system shall be capable of maintaining a stable pressure either:

— within 1 kPa or 1 % of the absolute pressure, whichever is greater, or

— within 2 kPa or 3 % of the required effective stress, whichever is greater.

Care needs to be taken when testing at low effective stresses, as it may not be possible to meet the first requirement.

5.7 Load frame

5.7.1 The load frame shall be able to provide a range of rates of vertical strain as required for the test (see 6.7.2 and 6.7.3). The actual rate applied up to failure shall not fluctuate more than 10 % from the intended rate. The movement of the platen shall be smooth without vibration such that fluctuations do not occur in the test results.

NOTE Frames with a load capacity in the range 10 kN to 50 kN which are able to advance the piston with displacement rates varying from about 0,000 5 mm to about 2 mm per minute with a minimum of 10 different constant rates have been found to be sufficient for most testing.

5.7.2 The stroke of the load frame shall be more than that required for the test. A value of 30 % of the specimen height is normally suitable.

5.8 Measuring devices

5.8.1 Load measuring device

The accuracy of the vertical load measuring device, in the range 20 % to 100 % of the capacity of the device, shall be 1 N or 1 % of the actual value, whichever is greater. The device should be insensitive to changes in horizontal forces or bending moments, and to changes in temperature or cell pressure during a test, unless the performance is sufficiently stable that the effect can be corrected.

The capacity of the load measuring device should be chosen so that the failure load is at least 20 % of its capacity.

NOTE Class 1 load measuring devices to ISO 7500-1 meet this accuracy requirement.

5.8.2 Pressure measuring devices

5.8.2.1 Cell pressure and pore pressure measuring devices shall be sufficiently accurate to permit the determination of total cell pressure and pore pressure to 1 kPa or 0,5 % of the full range of the device, whichever is greater.

5.8.2.2 For the shear stage of an undrained test, the pore pressure measuring device and its couplings shall be sufficiently rigid so that its change in volume shall be negligible.

5.8.3 Vertical displacement measuring device

The device for measuring the change in height of the specimen shall be accurate to 0,1 mm or to 0,1 % of the initial specimen height, whichever is greater.

5.8.4 Volume change measuring device

The amount of water and air going into or out of the specimen shall be measured with an accuracy of 0,1 % of the initial volume of the specimen or to 0,1 cm^3, whichever is greater.

5.9 Cell and back pressure fluids

5.9.1 The cell fluid should be selected such that it does not significantly penetrate through the membrane into the specimen nor extract pore water from the specimen through the membrane.

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

5.9.2 The fluid used to saturate (or flush) the porous discs and filter papers shall be de-aired. Tap water is often used but water with a similar chemistry as the specimen pore water may be used in circumstances where the results may be affected.

5.9.3 The cell fluid and the fluid used to saturate the specimen should be stabilized to the same temperature as the test location.

5.10 Ancillary apparatus

The ancillary apparatus consists of:

— balance, accuracy 0,01 g or 0,1 % of the weighed mass, whichever value is greater,

— timer readable to 1 s;

— maximum/minimum thermometer readable to 1 °C;

— apparatus for determination of water content;

The apparatus for the specimen preparation consists of:

— cutting and trimming tools (e.g. a sharp knife, wire saw, spatula, cutting ring, soil lathe);

— steel straight edge, with a maximum deviation from straight of 0,1 % of its length;

— try-square or a jig (e.g. a mitre box) or split mould to ensure that flatness shall be accurate to within 0,5 % of each dimension and that right-angles are within 0,5 ° of true;

— callipers, either analogue or digital, readable to 0,1 mm or 0,1 % of the measured length, whichever value is greater.

6 Test procedure

6.1 General requirements and equipment preparation

6.1.1 The test specimen shall be cylindrical with a diameter not less than 34 mm and a height from 1,8 to 2,5 times the diameter. The largest particle size should not exceed 1/6 of the specimen diameter. Specimens of other sizes or height to diameter ratios may be tested using special procedures.

6.1.2 The drainage tubes and valves shall be checked before each test to confirm that they are not clogged.

6.1.3 Confining membranes should be immersed in water for at least 24 h before being used. The membranes shall be free of excess surface water on the inside before being placed onto the soil specimen.

6.1.4 The porous discs shall be clean and not clogged.

6.1.5 Prior to each test check that there is no visible sign of damage to any of the equipment and that the piston runs smoothly.

6.1.6 If leakage of water from the cell or any water line is observed at any time during the test, the test shall be halted, the pressure removed from the leaking part if necessary and the leak eliminated before resuming the test. The effect of the leak on the sample shall be evaluated and if detrimental the test may be judged invalid.

6.1.7 The system may be checked for leaks when the set-up is ready for the triaxial cell to be mounted. A small suction, (for example 10 kPa but not more than the intended effective stress) may be applied to the drainage tubes. The vacuum shall then be shut off. If the vacuum decreases over a time period of about 2 min, efforts should be made to detect and eliminate any leaks in the membrane or drainage tubes.

6.2 Preparation of specimens

6.2.1 The following procedures shall apply to undisturbed, remoulded, re-compacted or reconstituted samples.

6.2.2 Examine undisturbed samples prior to testing. If significant disturbance is apparent in the specimen this should be recorded in the test report. Highly disturbed samples will not provide meaningful results and should not be tested.

6.2.3 Take care to maintain the water content of the specimen during the preparation process. If the process is interrupted, the specimen shall be protected so that the water content does not change. Air circulation around the specimen shall be avoided.

6.2.4 Cut and trim the specimen to the required dimensions. Take care to avoid deforming the specimen during the cutting and trimming process.

6.2.5 The soil specimen end surfaces shall be plane and perpendicular to the longitudinal axis in accordance with ISO 17892-2. Grooves and holes in the ends and sides of the specimen should be removed by further trimming or a new specimen selected if available. Otherwise, fill grooves or holes not exceeding 1/6 of the specimen diameter with remoulded sample material. Grooves and holes in the ends may be filled with a material that hardens with time and which does not release or absorb water.

6.2.6 Undisturbed clay and clayey specimens that may swell in contact with water shall be prevented from swelling caused by the specimen sucking water from the porous discs. The preferred method to achieve this is to mount the specimen with dry porous discs and to flush them with water while applying a vertical and horizontal stress high enough to inhibit swelling, but below the intended effective stress required at the end of consolidation.

6.2.7 Specimens may be prepared in the laboratory by compacting the material in layers into a split mould with or without the rubber membrane mounted inside. If water is mixed into the material, at least 16 h should be allowed for the water to equalize over the whole soil mass, before compaction. Under-compaction in layers may be used for sand to achieve a homogeneous specimen. Reconstituted specimens of sand may also be prepared by pluvial compaction in air or under water.

6.2.8 Specimens of coarse grained material may be held together by applying a slight vacuum (typically 10 to 20 kPa) when the split mould is removed, until a positive cell pressure of equal magnitude has been applied.

6.2.9 Measure the specimen height, diameter and mass in accordance with ISO 17892-2 by linear measurement.

6.2.10 Check that the membrane to be used is free from damage that may cause leakage during the test.

6.2.11 Mount the specimen into the apparatus, with the filter papers (if used), membrane and O-rings so that it is centred with respect to the top and bottom platens. Take extreme care to avoid, as much as possible, deforming the specimen during the mounting process. Very soft specimens may have to be mounted without touching the specimen by hand at any stage during the preparation.

6.2.12 Complete the assembly of the triaxial cell.

6.3 Saturation of specimen

6.3.1 Saturation

6.3.1.1 The porous discs and filter papers, the pore pressure measuring system and the specimen shall be sufficiently saturated so that the measured pore pressure corresponds to an undrained soil condition during undrained shearing, and that an accurate volume change is measured during drained shearing.

6.3.1.2 The cell pressure shall be raised in order to apply an effective stress to the specimen sufficient to prevent swelling of the specimen, but lower than the intended effective stress required at the end of consolidation.

6.3.1.3 If the specimen or the porous discs and filter papers are to be saturated (or flushed) with water after mounting, de-aired water meeting the requirements of 5.9 shall be used.

6.3.1.4 Sand specimens may be flushed with carbon dioxide prior to flushing with water to speed up the saturation process as carbon dioxide is much more soluble than air in water. A volume of about 3 sample volumes has been found to be sufficient. The volume of carbon dioxide passing through the specimen can be roughly estimated by collection in a burette or a similar device. Some specimens may be chemically affected by the acidity of carbon dioxide dissolved in water, in which case carbon dioxide flushing should not be used.

6.3.2 Application of cell and back pressure

6.3.2.1 Adequate saturation of the specimen may be achieved either by:

— the application of increments of cell pressure with closed drainage, with resulting increase in pore water pressure, or

— the application of increments of both cell and back pressure with open drainage.

The selection of the method of saturation shall ensure that the effective stresses within the specimen are not raised to a level that affects behaviour during the shear stage.

NOTE A pore water pressure at the end of saturation of at least 300 kPa is normally required to ensure adequate saturation except in the case of soft clay specimens taken from below groundwater, when this high pore water pressure is not necessary.

6.3.2.2 The effective stresses acting on the specimen during saturation shall not exceed the specified effective consolidation stresses.

6.3.2.3 If performing saturation with closed drainage, the following should also be met:

— the observed increase in back pressure during increments of cell pressure should be at least 90 % of the corresponding increase in cell pressure.

— for effective consolidation stresses below 20 kPa the difference in the increment of cell and back pressure should be kept below 2 kPa.

If these criteria cannot be met, saturation using open drainage should be considered to ensure that the requirements of 6.3.2.2 are met.

If applying back pressure using open drainage, the change in effective stress should be not greater than 5 kPa during saturation.

6.3.2.4 For dilatant materials, the back pressure should be high enough to prevent gas coming out of solution during shearing of the specimen.

6.3.3 Saturation checks

6.3.3.1 The following check to ensure that the saturation is adequate may be performed prior to consolidation or immediately prior to shearing. The latter option will give higher confidence that the specimen is adequately saturated for the shearing stage.

6.3.3.2 The saturation of the specimen shall be checked by measuring the B-value. To perform the check, close the drainage to the specimen, increase the cell pressure by an isotropic increment ($\Delta\sigma$) and record the corresponding increase in pore pressure (Δu). The value of the isotropic increment needs to be carefully chosen, reflecting the nature of the sample and the intended final effective stresses required on the sample, but increments between 10 kPa and 100 kPa are often found to be appropriate.

6.3.3.3 Calculate the B-value according to Formula (1):

$$B = \frac{\Delta u}{\Delta\sigma_c} \tag{1}$$

6.3.3.4 Saturation should be considered complete when a B-value of at least 0,95 is achieved. If the B-value is less than 0,95, further increments of cell pressure, or cell and back pressure (6.3.2.1) shall be applied and the B-value re-measured (6.3.3.2 and 6.3.3.3). If during repeated increments the B-value shows no significant increase, the saturation stage may be considered complete.

6.3.3.5 The measured B-value may increase with time. If the B-value requirement is not satisfied within 10 min after application of an isotropic increment, steps should be taken to improve the saturation of the specimen and system before performing shear, for example by applying a higher level of back pressure and/or longer duration of back pressure. The B value measurement shall be repeated.

6.3.3.6 The measured B-value may decrease with time, for example if a system with an air-bearing is used in the triaxial cell. If so, further B-value checks may also be required at later stages of the test.

6.3.3.7 If the end of saturation stage B-value requirement (6.3.3.4) cannot be accomplished, this shall be reported as a deviation which could also include a description of the measures taken to improve the saturation.

6.4 Isotropic consolidation (CIU and CID tests)

6.4.1 Adjust the cell pressure until the difference between the cell pressure and the pore pressure becomes equal to the specified effective stress.

6.4.2 If the cell pressure has been applied under undrained conditions, open the drainage line. Record the volume change as a function of time.

NOTE The vertical strain during consolidation can be measured by keeping the piston in contact with the top cap by applying a small load on the piston throughout the consolidation stage, by attaching the piston to the top cap by a suction device or by a fixed connection.

6.5 Anisotropic consolidation (CAU and CAD tests)

6.5.1 The effective stress path followed during anisotropic consolidation shall not approach failure at any time during consolidation.

6.5.2 Anisotropic consolidation may be achieved by one of the following methods:

a) The specimen may be isotropically consolidated with an effective stress equal to one of the required effective consolidation stresses. Once primary consolidation is complete under isotropic consolidation, deviator stress shall be applied by adjusting either the vertical or horizontal stress until the required anisotropic stress state is achieved with the specimen fully drained. This procedure may need to be carried out in steps to avoid excessive excess pore pressure.

b) Pressure ramps which control the horizontal and vertical stresses simultaneously to a pre-defined anisotropic stress state.

c) Pressure ramps that apply horizontal and vertical stresses that are controlled by the specimen behaviour, for example by maintaining a constant diameter of the specimen.

6.6 End of consolidation

The consolidation stage should be considered complete when the volume change is less than 0,1 % of the specimen volume per hour or 0,1 cm^3/h, whichever is greater, and the excess pore pressure when measured, is at least 95 % dissipated. If this criterion cannot be met the implications for the test results shall be evaluated and included in the test report.

6.7 Shearing

6.7.1 General

6.7.1.1 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 5.6) and the specimen loaded to failure (sheared) by moving the piston into the triaxial cell with a constant rate (with the accuracy specified in 5.7).

6.7.1.2 Initial readings of all measuring devices shall be taken and the position of all valves checked. Record the rate of volumetric strain immediately prior to shearing.

6.7.1.3 Select an appropriate logging frequency for all measurement devices commensurate with the parameters that are to be reported. Ideally at least 15 readings should be taken prior to failure, and at intervals no greater than 1 % vertical strain. For brittle materials, readings may need to be taken at smaller intervals of strain to define failure.

6.7.1.4 If the axial strain at which the test is to be stopped has not been specified, the test may be stopped when the strain reaches 15 %, or exceeds the strain at peak deviator stress by 5 %, or when the deviator stress has reduced by 20 % from the peak value, whichever occurs earlier.

6.7.2 Undrained tests (CIU and CAU)

6.7.2.1 Close the drainage lines so that no drainage can take place during shearing.

6.7.2.2 The rate of strain shall be selected so that adequate equalization of pore pressure occurs during the shear stage. If no documented information about allowable rate of strain is available, the rate of vertical displacement of the load frame, v_{max} shall not exceed the value calculated from Formula (2) based on the undrained F values in Table 1:

$$v_{max} = \frac{H_c \times \varepsilon_{vf}}{F \times t_{50}} \text{ or } v_{max} = \frac{H_c \times \varepsilon_{vf}}{(F/4) \times t_{100}} \quad (2)$$

The values of the consolidation times, t_{50} and t_{100}, can be determined from a plot of volume against time during consolidation, following one of the methods in ISO 17892-5.

Table 1 — Factors for calculating rate of displacement of load frame

Drainage conditions during consolidation	Values of F (for $H_i/D_i = 2$)	
	Undrained test	**Drained test**
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

6.7.3 Drained tests (CID and CAD)

6.7.3.1 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 load frame, v_{max} shall not exceed the value calculated from Formula (2) based on drained F values in Table 1. These F values assume that the drainage conditions during consolidation and drained shearing are the same.

6.7.3.2 For drained tests the maximum rate of vertical displacement of the loading frame, v_{max} should not exceed 10 % per hour

6.7.3.3 For drained tests on specimens with no side drains, and one-way drainage, the choice of strain rate may be verified by measuring the pore pressure and the constant back pressure to show that they differ by no more than 4 % of the effective horizontal stress.

6.8 Dismounting

6.8.1 For coarse grained soils a rough sketch of the specimen indicating the main failure planes may be made, or a photograph taken, before the pressures are removed.

6.8.2 Close the specimen drainage valves, unload the piston and reduce the cell and back pressure to zero. Drain the cell fluid.

6.8.3 Remove the specimen from the triaxial cell as quickly as possible and remove the membrane and porous discs and filter papers if used.

6.8.4 Sketch or photograph the specimen to illustrate the mode of failure.

6.8.5 Weigh the whole specimen.

6.8.6 Cut the specimen open to allow any internal structures or inhomogeneity to be identified and recorded. If there are particles greater than 1/10 of the specimen diameter, their size and approximate proportion shall be noted. A photograph of the cut specimen may be taken.

NOTE The presence of particles greater than 1/10 of the specimen diameter can affect the results. The magnitude of the effects will depend on the nature of the specimen and the quantity, location and composition of these particles.

6.8.7 Either determine the dry mass of the entire specimen, or determine the water content of a representative part of the specimen without further delay in accordance with ISO 17892-1 in order that the dry mass may be calculated. If a failure surface is present, an additional water content may be taken from near the failure surface.

7 Test results

7.1 Bulk density, dry density and water content

7.1.1 Calculate the initial water content from the final dry mass and the initial wet mass if the whole specimen has been dried. Otherwise the water content of the representative part of the specimen (6.8.7) shall be used.

7.1.2 Calculate the initial bulk and dry densities from the initial measurements of specimen dimensions and mass following the linear measurement procedures in accordance with ISO 17892-2.

7.1.3 The initial void ratio and initial degree of saturation, based on a particle density value measured in accordance with ISO 17892-3, or estimated, may be calculated if required.

7.2 Calculations of test parameters

7.2.1 Height after consolidation

If the height of the specimen after isotropic consolidation, H_c is not measured, it should be estimated according to Formula (3).

$$H_c = (1 - f \times \frac{\Delta V_c}{V_i}) \times H_i \tag{3}$$

NOTE The value of f is typically 1/3 for homogenous soils with isotropic stresses but other values can be appropriate for soils with anisotropic stresses.

7.2.2 Corrected cross sectional area

The corrected cross sectional area of the specimen will vary with time during the test. The cross sectional area at any point in time shall be determined from the volume change and height change at that time according to Formula (4).

$$A_{cor} = \frac{V_i - \Delta V}{H_i - \Delta H} \tag{4}$$

NOTE Formula (4) is not strictly valid after the formation of shear planes.

When the height change during isotropic consolidation is not measured the estimated value from Formula (3) should be used to calculate ΔH in Formula (4).

7.2.3 Corrections for elastic membrane

Corrections for the stresses imposed by the elastic membranes on the specimen should be determined according to Formulae (5) and (6).

Correction to total vertical stress:

$$(\Delta\sigma_v)_m = \frac{4 \times t_m \times E_m}{D_m} \times \left[(\varepsilon_v)_m + \frac{(\varepsilon_{vol})_m}{3} \right] \tag{5}$$

Correction to total horizontal stress:

$$(\Delta\sigma_h)_m = \frac{4 \times t_m \times E_m}{D_m} \times \frac{(\varepsilon_{vol})_m}{3} \tag{6}$$

The elastic modulus of the membrane, E_m may be measured for the material or may be provided by the manufacturer. If a latex membrane is used a value of 1 400 kPa may be assumed.

As an approximation the values of $(\varepsilon_v)_m$ and $(\varepsilon_{vol})_m$ may be assumed to be zero just after placing the membrane on the specimen (i.e. that there are no initial strains) and may be assumed to be equal to subsequent strains in the specimen.

NOTE These formulae for computing the membrane correction assume that no slippage takes place between the membrane and the specimen and therefore that the membrane deforms as the specimen. These formulae are not strictly valid after the formation of shear planes.

7.2.4 Correction for filter paper strips

7.2.4.1 General

The correction for vertical filter paper strips during shearing should be determined either in accordance with Formula (7) or Formula (8).

7.2.4.2 Correction to vertical total stress

The correction to the vertical total stress during the first 2 % of strain should be determined according to Formula (7):

$$(\Delta\sigma_{v})_{fp} = \frac{\varepsilon_{sv} \times K_{fp} \times P_{fp}}{0{,}005 \times D_{c}} \tag{7}$$

The correction to the vertical total stress for strains after 2 % should be determined according to Formula (8):

$$(\Delta\sigma_{v})_{fp} = \frac{K_{fp} \times P_{fp}}{0{,}25 \times D_{c}} \tag{8}$$

A value of K_{fp} of 0,19 kN/m may be taken.

7.2.4.3 Correction to horizontal total stress

Correction to the horizontal stress for the presence of filter papers is not required.

7.2.5 Vertical total stress

The vertical total stress applied at the mid height of the specimen shall be determined according to Formula (9):

$$\sigma_{v} = \frac{P + K + \sigma_{c}(A_{cor} - a)}{A_{cor}} - (\Delta\sigma_{v})_{m} - (\Delta\sigma_{v})_{fp} \tag{9}$$

where

K is equal to the value of $W - [(A_{cor} - a)h \cdot \gamma]$

This expression for K and Formula (9) are valid when using a load measuring device that is placed outside the triaxial cell (see Figure 1) and for which zero-reading is taken when the load measuring device is un-coupled without being in contact with the specimen. The value of K may be considered as a constant for a particular specimen size and specific triaxial equipment and may be negligible for small specimens and/or light equipment.

Other arrangements and/or procedures may require modifications of the expression for K and of Formula (9).

7.2.6 Vertical effective stress

The vertical effective stress shall be determined according to Formula (10):

$$\sigma'_{v} = \sigma_{v} - u \tag{10}$$

7.2.7 Horizontal total stress

The horizontal total stress shall be determined according to Formula (11):

$$\sigma_{\mathrm{h}} = \sigma_{\mathrm{c}} - \left(\Delta\sigma_{\mathrm{h}}\right)_{\mathrm{m}} \tag{11}$$

7.2.8 Horizontal effective stress

The horizontal effective stress shall be determined according to Formula (12):

$$\sigma'_{\mathrm{h}} = \sigma_{\mathrm{h}} - u \tag{12}$$

7.2.9 Pore pressure change

The pore pressure change shall be determined according to Formula (13):

$$\Delta u = u - u_{\mathrm{B}} \tag{13}$$

7.2.10 Vertical strain

The total vertical strain shall be determined according to Formula (14):

$$\varepsilon_{\mathrm{v}} = \frac{\Delta H}{H_i} \tag{14}$$

7.2.11 Vertical strain during shear

The vertical strain during shear shall be determined according to Formula (15):

$$\varepsilon_{sv} = \frac{\Delta H - \Delta H_c}{H_i - \Delta H_{\mathrm{c}}} \tag{15}$$

7.2.12 Volumetric strain

The total volumetric strain shall be determined according to Formula (16):

$$\varepsilon_{\mathrm{vol}} = \frac{\Delta V}{V_i} \tag{16}$$

7.2.13 Volumetric strain during shear

The volumetric strain during shear shall be determined according to Formula (17):

$$\varepsilon_{\mathrm{svol}} = \frac{\Delta V - \Delta V_{\mathrm{c}}}{V_i - \Delta V_{\mathrm{c}}} \tag{17}$$

8 Test report

8.1 Mandatory reporting

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

a) method of test used, i.e. CIU, CAU, CID or CAD;

b) identification of the specimen tested, e.g. by borehole number, sample number and sample depth and any other relevant details required, e.g. depth of specimen within a sample, method of sample selection if relevant;

c) visual description of the specimen tested including any observed features noted after testing, following the principles in ISO 14688-1 including a description of particles that exceed 1/10 of the specimen diameter if present and a note that the results may have been affected if any particles exceed 1/6 of the specimen diameter;

d) specimen type i.e. undisturbed or artificially prepared and the procedure used for the preparation of specimens;

e) initial specimen dimensions (mm);

f) water content (%);

g) initial bulk density (Mg/m^3);

h) dry density (Mg/m^3);

i) data from the stages prior to shearing;

   — type of drainage conditions used during consolidation;

   — effective stresses at the end of each consolidation stage (kPa);

   — final back pressure applied (kPa);

   — vertical strain and volumetric strain at the end of consolidation (%);

   — the rate of volumetric strain immediately prior to shearing (% per hour);

   — final B-value.

j) the following information during the shearing stage;

— type of drainage conditions during shearing;

— rate of vertical strain (% per hour).

k) the following information at failure;

— the failure criterion adopted;

— the effective stresses (kPa) and strain values (%);

— the membrane and filter paper corrections applied (kPa);

— description of, sketch and/or photograph showing the type of failure;

l) any deviation from the procedure or specified test conditions;

m) effective shear strength parameters and associated plots (see Annex B) where a set of three or more mutually relatable specimens have been tested.