British Standard

BRITISH STANDARD

BS 1377-6: 1990

Incorporating Amendement No. 1

Methods of test for

Soils for civil engineering purposes —

Part 6: Consolidation and permeability tests in hydraulic cells and with pore pressure measurement

Committees responsible for this British Standard

The preparation of this British Standard was entrusted by the Road Engineering Standards Policy Committee (RDB/-) to Technical Committee RDB/38, upon which the following bodies were represented:

Association of Consulting Engineers
British Civil Engineering Test Equipment Manufacturers' Association
County Surveyors' Society
Department of the Environment (Property Services Agency)
Department of the Environment (Building Research Establishment)
Department of Transport
Department of Transport (Transport and Road Research Laboratory)
Coopted members

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Contents

Foreword

This Part of BS 1377 has been prepared under the direction of the Road Engineering Standards Policy Committee. It is a part revision of clause **5** of BS 1377:1975 which is superseded by amendment.

BS 1377:1975 which has now been withdrawn is replaced by the following Parts of BS 1377:1990:

— *Part 1: General requirements and sample preparation;*

— *Part 2: Classification tests;*

— *Part 3: Chemical and electro-chemical tests;*

— *Part 4: Compaction-related tests;*

— *Part 5: Compressibility, permeability and durability tests;*

— *Part 6: Consolidation and permeability tests in hydraulic cells and with pore pressure measurement;*

— *Part 7: Shear strength tests (total stress);*

— *Part 8: Shear strength tests (effective stress);*

— *Part 9: In-situ tests.*

Reference should be made to Part 1 for further information about each of the Parts.

It has been assumed in the drafting of this British Standard that the execution of its provisions is entrusted to appropriately qualified and experienced personnel.

A British Standard does not purport to include all the necessary provisions of a contract. Users of British Standards are responsible for their correct application.

Compliance with a British Standard does not of itself confer immunity from legal obligations.

Summary of pages

This document comprises a front cover, an inside front cover, pages i to iv, pages 1 to 64, an inside back cover and a back cover.

This standard has been updated (see copyright date) and may have had amendments incorporated. This will be indicated in the amendment table on the inside front cover.

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1 Scope

This Part of BS 1377 specifies methods of test for determination of consolidation and permeability characteristics of saturated soils using apparatus which is more complex than that used for the tests described in Part 5.

Two types of equipment are used:

a) hydraulically loaded one-dimensional consolidation cell;

b) a triaxial consolidation cell.

The most significant capabilities of both types of apparatus are:

1) measurement of pore water pressure;

2) control of drainage;

3) application of back pressure to the specimen.

Consolidation or triaxial cells of large diameter enable large specimens to be tested so that some account can be taken of the effects of the soil fabric.

These procedures appear for the first time in this standard.

Reference should be made to BS 1377-1 for general requirements that are relevant to all Parts of this standard, and for methods of preparation of soil and specimens for testing.

2 Definitions

For the purposes of this Part of BS 1377 the definitions given in BS 1377-1 apply, together with the following.

2.1
diaphragm pressure of a hydraulic consolidation cell

the pressure applied to the fluid above the flexible loading diaphragm

2.2
applied total stress

the mean pressure actually transmitted to the surface of the specimen

2.3
free strain loading

application of a uniformly distributed pressure to the surface of the specimen from the flexible diaphragm

2.4
equal strain loading

application of pressure to the surface of the specimen through a rigid disc so that the surface always remains plane

2.5
pore pressure ratio

the ratio of the incremental change in pore pressure to the applied increment of vertical stress when drainage is not allowed

2.6
cell pressure (σ_3)

the pressure of the cell fluid which applies isotropic stress to the specimen in a triaxial cell

2.7
back pressure (u_b)

pressure applied directly to the pore fluid in the specimen voids

2.8
effective cell pressure

the difference between the cell pressure and pore water pressure

2.9
effective consolidation pressure (σ'_3)

the difference between the cell pressure and the back pressure against which the pore fluid drains during the consolidation stage, calculated as:

$$\sigma'_3 = \sigma_3 - u_b$$

2.10
pore pressure coefficients A and B

changes in total stresses applied to a specimen when no drainage is permitted produces changes in the pore pressure in accordance with the equation

$$\Delta u = B\{\Delta\sigma_3 + A(\Delta\sigma_1 - \Delta\sigma_3)\}$$

where

Δu	is the change in pore pressure;
$\Delta\sigma_1$	is the change in total major principal stress;
$\Delta\sigma_3$	is the change in total minor principal stress;
$(\Delta\sigma_1 - \Delta\sigma_3)$	is the change in deviator stress;

A and B are the pore pressure coefficients.

NOTE In a saturated soil (except very stiff soils) the value of B is theoretically equal to 1.

3 Determination of consolidation properties using a hydraulic cell

3.1 General

3.1.1 *Introduction.* These procedures cover the determination of the magnitudes and rates of consolidation of soil specimens of relatively low permeability using hydraulically loaded apparatus. They provide a convenient means of testing large specimens, and enable drainage in either the horizontal or vertical directions to be investigated. The specimen is in the form of a cylinder confined laterally, subjected to vertical axial pressure applied hydraulically.

The apparatus and procedures described here are based on the extendable-bellows type of hydraulic cell. Specimen diameters typically range from 75 mm to 254 mm. Other types of hydraulically loaded cell, incorporating for instance a rolling-seal diaphragm, are also available. The test method is not restricted to a particular design of cell provided that the essential requirements are fulfilled.

3.1.2 *Types of test.* In this type of cell, pressure may be applied to the surface of the specimen either directly from the flexible diaphragm (giving a uniform stress distribution, the "free strain" condition), or through a rigid loading plate which ensures that the top surface remains plane (the "equal strain" condition). With either type of loading the following drainage conditions are possible. The various configurations are indicated diagrammatically in Figure 1, as follows:

a) vertical drainage to the top surface only, with measurement of pore pressure at the centre of the base [Figure 1(a) and Figure 1(b)];

b) vertical drainage to both top and bottom surfaces [Figure 1(c) and Figure 1(d)];

c) radial drainage outwards to the periphery only, with measurement of pore pressure at the centre of the base [Figure 1(e) and Figure 1(f)];

d) radial drainage inwards to a central drain with measurement of pore pressure at one or more points off centre [Figure 1(g) and Figure 1(h)].

Each method requires its own curve-fitting procedure and multiplying factors for deriving the relevant coefficient of consolidation. The factors also depend on whether data are derived from pore pressure measurements at a single point, or from "average" measurements (volume change or settlement) for the specimen as a whole.

3.1.3 *Test conditions.* The following test conditions shall be specified before starting a test:

a) size of test specimen;

b) drainage conditions;

c) loading conditions;

d) location of pore pressure measurement point (when required);

e) whether void ratios are to be calculated and plotted;

f) sequence of effective pressure increments and decrements;

g) criterion for terminating each primary consolidation and swelling stage;

h) whether secondary compression characteristics are required.

The requirements of Part 1 of this standard, where appropriate, shall apply to the test methods described in this clause.

3.1.4 ***Environmental requirements and safety***

3.1.4.1 *Temperature.* These tests shall be carried out in a laboratory in which the temperature is maintained constant to within ± 2 °C, in accordance with **6.1** of BS 1377-1:1990. All apparatus shall be protected from direct sunlight, from local sources of heat and from draughts.

3.1.4.2 *Hazard warning*

NOTE Users of this equipment should be conversant with regulations for pressure vessels.

Consolidation cells and ancillary equipment shall not be used at pressures above their safe working pressures.

3.2 Apparatus

3.2.1 *Hydraulic consolidation cell and accessories*

3.2.1.1 *General requirements for the cell*

3.2.1.1.1 All metal body components shall be impervious and corrosion resistant. The cell body, top and base shall all be of the same material to minimize the possible effects of electrolytic corrosion.

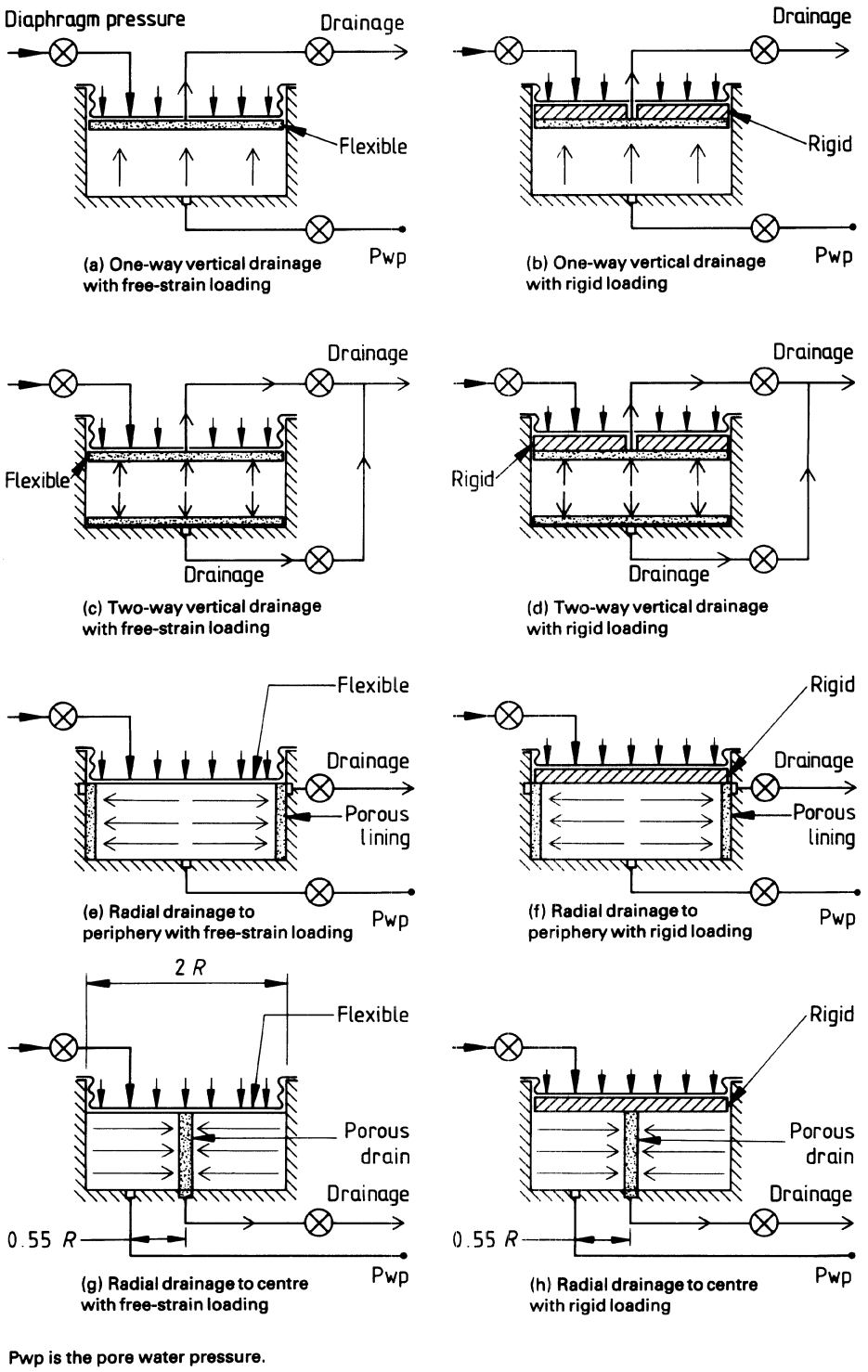
3.2.1.1.2 The cell when assembled shall be capable of withstanding sustained internal water pressures of up to 1 000 kPa without significant leakage or distortion.

NOTE The main features of the extending-bellows type of a 250 mm diameter cell are shown diagramatically in Figure 2.

3.2.1.2 *Components of the cell*

3.2.1.2.1 *Cell body,* the inside face of which shall be smooth and free from pitting.

NOTE The internal surface of the body and base may be lined with a thin smooth impervious layer of plastics material bonded on, to reduce wall and base friction and inhibit corrosion.



Pwp is the pore water pressure.

Figure 1 — Drainage and loading conditions for consolidation tests in hydraulic cells

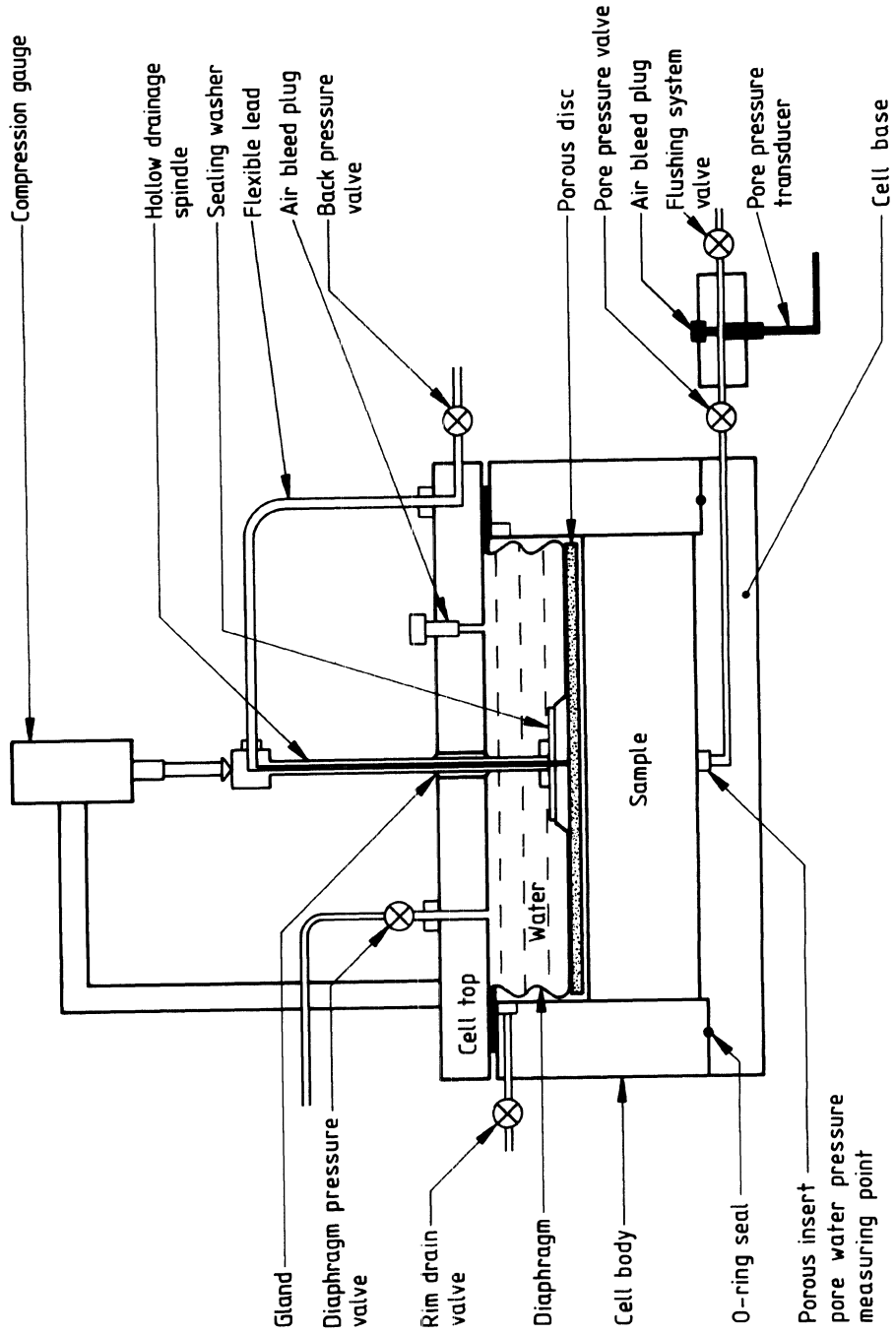


Figure 2 — Arrangement of hydraulic cell for vertical drainage consolidation [test type (a)]

3.2.1.2.2 *Top cover,* fitted with an air bleed plug and a bushing or seal for a hollow rod (the drainage stem) which is attached to an impermeable flexible diaphragm, e.g. of butyl rubber. Since the drainage stem permits drainage to take place from the top face of the specimen, provision shall be made for measurement of the vertical movement of that face.

3.2.1.2.3 *The diaphragm,* selected from a range of diaphragms of various stiffnesses so that it is appropriate to the soil type and the type of test.

NOTE In cells using a bellows type of diaphragm the folds pressing against the cell wall can impede the removal of excess water for some considerable time. It is advantageous to fit a strip or collar of porous plastics material between the diaphragm and the rim drainage aperture to provide a free drainage path which enables this water to be removed quickly.

3.2.1.2.4 *Cell base,* incorporating a central recess for a porous insert (the pore pressure measurement point) connected to a valve on the periphery.

NOTE Pore pressure is usually measured at the centre of the base of the specimen in tests with vertical drainage. Some cell bases of large diameter are fitted with additional off-centre pore pressure points, one (or more) of which is used for some tests in which radial drainage takes place.

3.2.1.2.5 *Connection ports* incorporated into the top cover and cell base as shown in Figure 2. Each port shall be fitted with either a valve, or a blanking plug if it is not required for the test. The ports shall be connected as follows (the corresponding valve designations are indicated in brackets):

a) from the pore pressure measurement point in the cell base to the pore pressure measuring device (the pore pressure valve);

b) from the pore pressure measuring device mounting block to the flushing system (the flushing system valve);

c) from the diaphragm pressurizing chamber to the diaphragm pressure system (the diaphragm pressure valve);

d) from the top of the specimen via the drainage stem to the back pressure system (the back pressure valve);

e) from the rim drain (when required) to the back pressure system (the rim drain valve).

3.2.1.2.6 *Porous discs,* for the drainage and pore pressure measuring points. Their permeability shall be substantially greater than that of the soil, and they shall withstand the maximum vertical pressure likely to be imposed. The discs shall be checked before each use to ensure that they are not clogged by soil particles. They shall be boiled for at least 10 min in distilled water before use and kept immersed in deaerated water until required.

3.2.1.2.7 *On-off valves,* capable of withstanding the maximum working pressure without leakage. They shall produce negligible volume displacement during operation.

NOTE Ball valves with PTFE seals have been found to comply with this requirement.

3.2.1.2.8 *Flexible porous disc,* to act as a drainage layer through which water from the specimen can drain into the hollow spindle to the back pressure line. The diameter of the disc shall be about 1 mm less than the internal diameter of the cell. It shall be flexible enough to accommodate non-uniform surface settlement of the larger diameter specimens. In other respects the disc shall comply with **3.2.1.2.6**.

3.2.1.2.9 *Rigid metal circular loading plate,* with detachable lifting handle, to provide "equal strain" loading when required. A plug shall be provided to fill the central hole when necessary.

3.2.1.2.10 *Peripheral drain,* of porous plastics material of about 1.5 mm thick, for radial drainage tests. The inside face of the material shall be smooth.

3.2.1.2.11 *Drainage disc,* of porous plastics material up to 3 mm thick, for use as a drainage layer when two-way vertical drainage is used.

3.2.2 *Instrumentation attached to the cell*

3.2.2.1 *A calibrated dial gauge or displacement transducer,* referred to as the compression gauge, complying with **4.2.1.3** of BS 1377-1:1990. It shall be suitably supported for measuring the vertical compression or swelling of the specimen throughout the test. For specimens up to 75 mm diameter the gauge shall be readable to 0.002 mm and have a travel of at least 10 min.

NOTE For larger specimens the resolution and range of travel should be appropriate to the stiffness of the soil specimen.

3.2.2.2 *A calibrated pore water pressure measuring device* consisting of an electric pressure transducer reading to 1 kPa mounted in a de-airing block fitted with an air bleed plug. One side of the block shall be fitted to the pore pressure valve on the cell base and the other side to the flushing system valve. The whole assembly when closed shall allow no movement of water into or out of the port leading to the cell base pedestal. The pore pressure assembly shall allow no more than a negligible amount of water to move into or out of the specimen.

3.2.3 *Ancillary equipment for preparation and operation of the cell*

3.2.3.1 *Two independent pressure systems,* for applying and maintaining the desired pressure in the cell and in the specimen drainage line (referred to as the diaphragm pressure system and back pressure system respectively). They shall be capable of maintaining the pressure constant to within ± 0.5 %.

NOTE Pressure systems dependent on self-compensating mercury pots (see Warning in **5.3.2** of BS 1377-1:1990), air pressure regulators, dead-weight pressure cells and oil pressure regulators have been successfully used. Their capacity to supply or take in water should be enough to compensate for any leakage and drainage to or from the specimen.

If air-water systems are used a diaphragm, e.g. of butyl rubber, shall separate air from water.

3.2.3.2 *A calibrated pressure gauge,* of test grade, for independent measurements of diaphragm pressure and back pressure, complying with **4.2.1.7** of BS 1377-1:1990.

NOTE For measurement of pressures below 50 kPa a mercury manometer or a pressure transducer should be used.

Calibration data shall be clearly displayed. The gauge shall be permanently connected to the two pressure systems.

The level of the pressure gauge relative to a datum level (usually the mid-height of the test specimen) shall be taken into account.

Alternatively, two independent gauges may be used, each permanently connected to its own pressure system.

3.2.3.3 *A calibrated volume-change indicator* (burette or transducer type) complying with **4.2.1.8** of BS 1377-1:1990, connected into the back pressure line.

NOTE A pressurized paraffin burette device is suitable if the scale markings can be read to the required degree of accuracy. A transducerized volume-change unit of appropriate range and sensitivity is convenient when an electronic readout or recording system is available. In precise work, or where the differential pressure is small, account should be taken of pressure variations which occur due to movement of the interface between the water and the lower density paraffin in the burettes.

3.2.3.4 *Suitable tubing,* to connect the components of each pressure system to the cell. The expansion coefficient of the tubing due to internal pressure shall not exceed 0.001 mL/m for every 1 kPa increase in pressure.

3.2.3.5 *Timing device,* readable to 1 s.

3.2.3.6 *Materials,* as follows:

a) *silicone grease or petroleum jelly;*

b) *porous plastics sheets,* about 1.5 mm and 3.5 mm thick;

c) *disc of latex rubber,* or similar impermeable material to cover the metal disc under the centre of the diaphragm (required for **3.7** only);

d) *a supply of de-aerated tap water,* as specified in **5.2** of BS 1377-1:1990.

3.2.3.7 *Pressurized system for distribution of de-aerated water.*

3.2.3.8 *Immersion tank* (optional), to enable the cell to be assembled under water.

3.2.3.9 *A calibrated thermometer, readable* to 0.5 °C.

3.2.4 *Equipment for specimen preparation and measurement*

3.2.4.1 *Procedures.* Procedures are given for the preparation of three types of specimen:

a) specimen of undisturbed soil from a sampling tube (see **3.3.2**);

b) specimen of undisturbed soil from a block sample (see **3.3.3**);

c) specimen of compacted soil (see **3.3.4** to **3.3.7**).

3.2.4.2 *Equipment for preparation of specimen from an undisturbed sampling tube or block sample*

3.2.4.2.1 *Two cutting shoes,* each clearly identified, having internal diameters as follows:

a) equal to the internal diameter of the cell;

b) equal to the internal diameter of the cell less twice the thickness of the porous plastics lining material.

The tolerance range for these dimensions shall be between 99.8 % and 100 % of the relevant diameter.

Each shoe shall be capable of being securely attached to the top flange of the cell body so that its internal face is in precise alignment with the cell wall or face of the lining material.

NOTE With soft soils it might be difficult to intrude a specimen of the precise diameter into the cell without disturbance. There may then be some advantage in using a slightly smaller cutting shoe to obtain a fractional clearance. The undersize should not exceed 1 mm for a 250 mm diameter cell, or the same proportion for other sizes.

3.2.4.2.2 *Extruder* (for a sample taken in a sampling tube), suitable for ejecting the undisturbed sample from the sampling tube through the cutting shoe directly into the cell body. Extrusion shall be vertically upwards to avoid distortion of soft soils, and in the same direction relative to the tube as the soil entered the tube. The device shall enable the cell body assembly to be securely held in place with its axis in alignment with the direction of extrusion.

3.2.4.2.3 *A means of holding the cell* (for a block sample), with cutting ring and maintaining it in alignment while it is pushed into the block sample.

3.2.4.2.4 *Balance,* of sufficient capacity and accuracy to determine the mass of the specimen in the cell to an accuracy of within 0.1 %.

3.2.4.2.5 *Equipment for determination of moisture content* (see **3.2** of BS 1377-2:1990).

3.2.4.2.6 *Equipment for determination of soil particle density* (see **8.2** or **8.3** of BS 1377-2:1990).

3.2.4.2.7 *Cutting and trimming tools,* appropriate to the type of soil, such as:

a) sharp trimming knife;

b) spatula;

c) wire saw of fine piano wire;

d) cheese-wire;

e) metal straightedge at least 50 mm longer than the specimen diameter.

3.2.4.2.8 *A flat surface,* about 500 mm square (or flat glass plate for the smallest size of cell).

3.2.4.2.9 *Vernier calipers,* for measuring the internal diameter of cells up to 150 mm diameter.

NOTE For larger cells a calibrated engineer's steel rule of suitable length with 0.5 mm graduations is suitable.

3.2.4.2.10 *A calibrated depth gauge,* for measuring the height of the test specimen in the cell, readable to 0.1 mm.

3.2.4.2.11 *Mandrel and guide jig,* for forming a central drainage hole (required only for tests in which drainage takes place to the centre).

3.2.4.2.12 *Fine sand,* or other suitable drainage material, for use in a central drainage well.

3.2.4.2.13 *A reference straightedge,* such as an engineer's steel rule.

3.2.4.3 *Equipment for preparation of a specimen of compacted soil*

3.2.4.3.1 The items listed in **3.2.4.3.2** to **3.2.4.3.6** are required for the preparation of soil and for compacting it into the consolidation cell, in addition to the items listed in **7.2** of BS 1733-1:1990.

3.2.4.3.2 *Test sieve of aperture size,* approximately one-sixth of the height of the test specimens to be prepared.

3.2.4.3.3 *Measuring cylinder.*

3.2.4.3.4 *Metal rammer,* as described either in **3.3.2** (2.5 kg rammer), or in **3.5.2** (4.5 kg rammer), of BS 1377-4:1990, as appropriate.

3.2.4.3.5 *Trimming tool,* for preparing a flat surface on the specimen inside the cell at a given depth below the top end of the cell.

3.2.4.3.6 Items **3.2.4.2.4** to **3.2.4.2.12**, as appropriate.

3.2.5 *Calibration of cell*

3.2.5.1 *Measurements.* The following measurements of the cell and its accessories shall be determined and recorded; linear measurements shall be made to an accuracy of 0.5 % and measurements of mass to an accuracy of 0.1 %:

a) internal diameter of cell body, and of body with peripheral drain fitted;

b) overall height of cell body;

c) internal depth from top edge of cell body to the base when bolted together;

d) thickness of porous disc, porous plastic disc, and porous peripheral drain material;

e) thickness of rigid loading disc;

f) mass of cell body with normal attachments;

g) mass of cell body assembled on base, including bolts and attachments;

h) mass of rigid disc and each porous disc (dry);

i) mass of a typical porous liner;

j) projection of the drainage spindle above the cell top when the diaphragm is at the upper and lower limits of its extension (to the nearest mm);

k) thickness of diaphragm.

3.2.5.2 *Calibration of diaphragm*

3.2.5.2.1 The force exerted by the diaphragm on a rigid top platen may be less than that calculated from the hydraulic pressure and cross-sectional area of the cell, owing to diaphragm stiffness and side friction.

NOTE Friction may be reduced by applying a film of silicone grease or petroleum jelly to the inside wall of the cell behind the diaphragm when a peripheral drain is not used.

The difference between the actual and the calculated force shall be determined. This effect is more significant in a small cell than in a large one, and can vary with both the applied pressure and the diaphragm extension, and is greatest at low pressures. This correction does not apply to "free strain" tests.

3.2.5.2.2 The force applied by the diaphragm can be measured by the following method which has been found to be satisfactory, but alternative methods may be used.

Mount the inverted cell (without base) on the platen of a load frame fitted with a suitable calibrated force measuring device in the manner shown in Figure 3, and then pressurize the water under the diaphragm. The actual pressure, σ (kPa), applied to the area of cross section of the cell is given by the equation

$$\sigma = \frac{P + 9.81m}{A} \times 100$$

where

P is the force measured by the force measuring device (in N);

m is the mass of the rigid plate (in kg);

A is the area of the cell (in mm^2).

The relationship between diaphragm pressure, p_d, and the pressure correction to be applied, δp(where $\delta p = p_d - \sigma$), can be plotted for a load-unload cycle up to the maximum working pressure. Similar calibration curves may be obtained for a range of diaphragm extensions.

The actual pressure σ on the specimen for a diaphragm pressure p_d at a certain extension of the diaphragm is given by the equation $\sigma = p_d - \delta p$ if the pressure due to the depth of water above the diaphragm is neglected.

This calibration automatically allows for the absence of pressure on the external diameter of the drainage spindle.

Repeat the calibration at intervals to allow for changes in the characteristics of the diaphragm with time.

3.2.6 *Preparation and checking of apparatus*

3.2.6.1 *General.* Apparatus used for tests in the hydraulic cell shall be subjected to rigorous inspection and check testing before use. The checks described in **3.2.6.2** to **3.2.6.6** shall be carried out on the diaphragm pressure, back pressure and pore pressure systems at the frequency stated below. Checks on these systems are of two kinds, "complete" checks and "routine" checks.

"Complete" checks in accordance with **3.2.6.2**, **3.2.6.3** and **3.2.6.5** shall be carried out:

a) when any item of new equipment is introduced into a system;

b) if an integral part of a system has been removed, stripped down, overhauled or repaired;

c) at intervals not exceeding 3 months.

"Routine" checks in accordance with **3.2.6.4** and **3.2.6.6** shall be carried out immediately before starting a test.

Before checking, the pressure systems and connecting lines shall be filled with freshly de-aerated water complying with **5.2** of BS 1377-1:1990.

NOTE A screw-type hand pump (control cylinder) may be used as an aid to flushing and checking the pressure systems.

The procedures described in **3.2.6.7** shall be carried out on porous discs, and on any porous drainage materials fitted into the cell, immediately before each test.

3.2.6.2 *Diaphragm pressures system (complete check).* A pressure test of the diaphragm and its pressure system shall be made to ensure that the maximum test pressure stated in **3.2.1** can be maintained at all times during a test.

3.2.6.3 *Back pressure system (complete check)*

3.2.6.3.1 Flush freshly de-aerated water through the back pressure connecting line from the volume-change indicator and through the specimen drainage line. In this operation work the indicator at least twice to its limits of travel, allowing water to pass out of the drainage stem and replacing it with freshly de-aerated water from the pressure system.

3.2.6.3.2 Seal the end of the drainage stem with a watertight plug.

3.2.6.3.3 Pressurize the back pressure to 750 kPa with the drainage line valve open, and record the volume change indicator reading when steady.

3.2.6.3.4 Leave the system pressurized for at least 12 h and record the volume-change indicator reading again.

3.2.6.3.5 If the difference between the two readings, after deducting the volume change due to expansion of the tubing, does not exceed 0.1 mL the system can be considered to be leak-free and ready for a test.

3.2.6.3.6 If the corrected difference exceeds 0.1 mL investigate the leaks and rectify them so that when **3.2.6.3.1** to **3.2.6.3.4** are repeated the requirement **3.2.6.3.5** is achieved.

3.2.6.4 *Back pressure system (drainage stem or rim drain) (routine check)*

NOTE The following check can be carried out at the same time as the pore pressure system check given in **3.2.6.6**.

3.2.6.4.1 Flush the back pressure line and drainage connections as in **3.2.6.3.1**. Close the drainage line valve.

3.2.6.4.2 Increase the pressure in the back pressure system to 750 kPa, and record the volume change indicator reading after 5 min.

3.2.6.4.3 Proceed as in **3.2.6.3.4** to **3.2.6.3.6**.

3.2.6.5 *Pore pressure system (complete check)*

3.2.6.5.1 Open the valve between the transducer mounting block and the flushing system. Pass freshly de-aerated water through the mounting block and cell base and out through the base port. Continue until no air bubbles are visible in the emerging water, to ensure that the entire system is filled with de-aerated water.

3.2.6.5.2 Close the pore pressure valve on the cell base and then remove the bleed plug in the transducer mounting block.

3.2.6.5.3 Inject a solution of soft soap into the bleed plug hole. Open the flushing system valve so that water flows from the de-aerated supply and out of the bleed hole.

3.2.6.5.4 Screw the bleed plug back into the transducer mounting while water continues to emerge.

3.2.6.5.5 Open the pore pressure valve and allow about 500 mL of de-aerated water to pass out of the pore pressure measurement port (see note), then close the valve.

NOTE This is to ensure that any further air, or water containing air, in the transducer mounting block is removed.

3.2.6.5.6 Seal the porous insert in the pore pressure measurement port, while water is emerging in order to avoid trapping air, by covering with a piece of latex rubber and a small flat metal disc held down by a clamping arrangement.

3.2.6.5.7 Pressurize the system to 700 kPa and again allow about 500 mL of water to pass out of the pore pressure measurement port.

3.2.6.5.8 Leave the system pressurized for at least 12 h.

3.2.6.5.9 After this period, check for leaks and if none are found allow about 500 mL of water to pass out of the pore pressure measurement port.

NOTE A more positive means of detecting leaks than by visual observation is to connect the system to a sensitive volume change indicator.

If leaks are evident rectify them and repeat **3.2.6.5.1** to **3.2.6.5.8**.

3.2.6.5.10 When checks confirm that the system is free of leaks, open the flushing system valve and the pore pressure valve and apply the maximum pressure achievable within the limitations of the pressure system and the pore pressure transducer to the cell base.

3.2.6.5.11 Close the flushing system valve on the transducer mounting block and record the pore pressure reading.

3.2.6.5.12 If the pore pressure reading remains constant over a minimum 6 h period the pore pressure connections can be assumed to be air and leak free.

3.2.6.5.13 If there is a decrease in the pressure reading this indicates that there is a defect in the system, which shall be rectified. The complete pore pressure system check described above shall be repeated until the system is proved to be free of entrapped air and leaks.

3.2.6.5.14 Pass freshly de-aerated water through the connection to any ports in the cell base that are not to be used. When they are completely filled, close the valves on these lines and keep them closed throughout the test.

3.2.6.6 *Pore pressure system (routine check)*

3.2.6.6.1 Follow the procedures described in **3.2.6.5.1** to **3.2.6.5.9**.

3.2.6.6.2 When checks confirm that the system is free of leaks, close the flushing system valve on the transducer mounting block.

3.2.6.6.3 Keep the cell base covered with de-aerated water until the test specimen is ready for setting up.

3.2.6.7 *Porous media*

3.2.6.7.1 The drainage disc shall be inspected and checked to ensure that water drains freely through it. A disc that is clogged by soil particles shall be rejected.

Before use, boil a porous disc for at least 10 min, and a porous plastics disc for at least 30 min, in distilled water, and then keep it under de-aerated water until required.

3.2.6.7.2 Boil porous insets for pore pressure measuring points in distilled water for the times stated in **3.2.6.7.1** before use, and discard them when clogged with soil particles.

3.2.6.7.3 Boil porous plastics lining material in distilled water for at least 30 min before use. Place the smooth side towards the soil, but do not grease it. The material shall be used once only and then discarded.

3.2.6.7.4 Sand for use in a central drainage well shall be de-aerated by boiling in distilled water and allowed to cool in an airtight container.

3.3 Preparation of specimens

3.3.1 *General*

3.3.1.1 *Types of specimen.* Test specimens shall be cylindrical with plane ends normal to the axis, and of a height/diameter ratio of 1/2.5 to 1/4. Specimens may be of undisturbed soil, or of disturbed soil that is compacted or compressed into the cell.

Five methods of specimen preparation are described:

a) *method 1* (see **3.3.2**): preparation of an undisturbed specimen from a sampling tube;

b) *method 2* (see **3.3.3**): preparation of a specimen from a block sample;

c) *method 3* (see **3.3.5**): compaction of disturbed soil into the cell by applying a specified compactive effort;

d) *method 4* (see **3.3.6**): compaction of disturbed soil into the cell to achieve a specified dry density;

e) *method 5* (see **3.3.7**): compression of disturbed soil into the cell under static pressure to achieve a specified dry, density.

The preparation of soil for compaction is given in **3.3.4**. (Form 6.A of Appendix A is suitable for recording specimen details and measurements.)

3.3.1.2 *Undisturbed specimens.* Specimens are prepared by method 1 or method 2, depending on the type of sample. Method 2 may also be used for taking a specimen from a suitably trimmed exposure on site.

The diameter of the largest particle included in the specimen should not exceed one-sixth of the specimen height.

NOTE 1 If after test a specimen is found to contain larger particles the size range and mass of these inclusions should be reported.

An undisturbed specimen shall be carefully selected to represent as closely as possible the condition of the soil in-situ especially with regard to the soil "fabric". Undisturbed specimens shall be prepared with the minimum change of the soil structure and moisture.

NOTE 2 In soils containing laminations, equilibrium of pore pressure throughout the whole specimen might take more time than is indicated by pore pressure measurement at a single point because of variations in permeability at successive horizons.

NOTE 3 Preparation of undisturbed specimens should be carried out in an atmosphere in which the relative humidity is controlled at not lower than 40 %. Moisture loss from soil not being used immediately should be prevented by wrapping in clinging plastics film followed by aluminium foil.

3.3.1.3 *Compacted specimens.* Specimens may be prepared by dynamic compaction (methods 3 and 4), or by static compression (method 5). These methods relate to compaction or compression into the larger sizes of consolidation cell. Specimens of smaller sizes can be trimmed from soil that is first compacted into a 1 L compaction mould, or a CBR mould (see clauses **3** and **7** respectively of BS 1377-4:1990), in the same way as preparing undisturbed specimens.

The diameter of the largest particle present in the soil shall not exceed one-sixth of the specimen height.

3.3.2 *Preparation of undisturbed specimen from sample tube*

3.3.2.1 Samples taken from site in tubes shall whenever possible be extruded, trimmed and fitted into the cell body in one operation.

NOTE 1 When this is not practicable the sample should be extruded from the tube and treated in the same way as a block sample (see **3.3.3**).

NOTE 2 In very organic clays and silts, oxidation can take place in contact with air which releases bubbles of gas. Extrusion of these soils should ideally be carried out under water, e.g. by mounting a horizontal extruder ram in a water tank.

The procedure for vertical extrusion is as described in **3.3.2.2** to **3.3.2.15**.

3.3.2.2 Attach the cutting shoe of the correct diameter to the top end of the cell body, ensuring that the cutting edge is exactly in alignment with the cell wall. If the test is to be carried out with radial drainage to the periphery, fit the saturated peripheral drain into the cell body first using the appropriate diameter of cutting shoe (see **3.2.4.2.1**); intrude the sample as quickly as possible before the drain loses its saturation.

3.3.2.3 Assemble the sample tube and cell body with shoe on the extruder, ensuring correct alignment and secure fixing.

3.3.2.4 Extrude the sample until the cell is filled with a few millimetres surplus at the top end. Remove parings from around the shoe during extrusion to prevent obstruction to movement of the sample.

3.3.2.5 Sever the sample at the level of the cutting edge of the shoe.

3.3.2.6 Detach the cell and shoe from the extruder and remove the cutting shoe. Support the underside of the specimen by spatula blades before lifting.

3.3.2.7 Trim the specimen at each end flush with the cell body flange.

3.3.2.8 Use a cylindrical spacer of appropriate thickness, and slightly smaller than the cell diameter, to push out the unwanted length of specimen; cut off this length.

3.3.2.9 Trim the cut end of the specimen (which will be the bottom face) flush with the upper edge of the cell. Remove any protruding particles carefully; fill the resulting void with fine material from the trimmings, and press in well.

3.3.2.10 Weigh the cell with the specimen to an accuracy of within 0.1 %. Measure the distance from the surface of the specimen to the top end of the cell body to 0.5 mm and calculate the initial specimen height (H_0).

3.3.2.11 Cover the de-aired cell base (prepared as in **3.2.6.6**) with a thin film of de-aerated water.

3.3.2.12 Place two thin steel spatulas under the bottom flange of the cell body to retain the specimen flush with the flange while it is lifted. Slide the specimen on to the flooded cell base without entrapping any air, and remove the spatulas. Bolt the body to the cell base by progressively tightening opposite pairs of bolts. Ensure that the body is properly sealed on the base sealing ring, and that it is tightened down uniformly. Close the flushing system valve.

3.3.2.13 Fill the top of the cell above the specimen with de-aerated water only if the soil is not susceptible to swelling or is not sensitive to a moisture content change under zero stress.

NOTE For a soil that is susceptible to swelling or sensitive to moisture content change the swelling pressure is determined by the procedure in **3.5.2.2**, by allowing water to percolate up from the base.

3.3.2.14 Take representative samples from the soil trimmings for determination of moisture content.

3.3.2.15 Assemble the cell top in accordance with **3.4**.

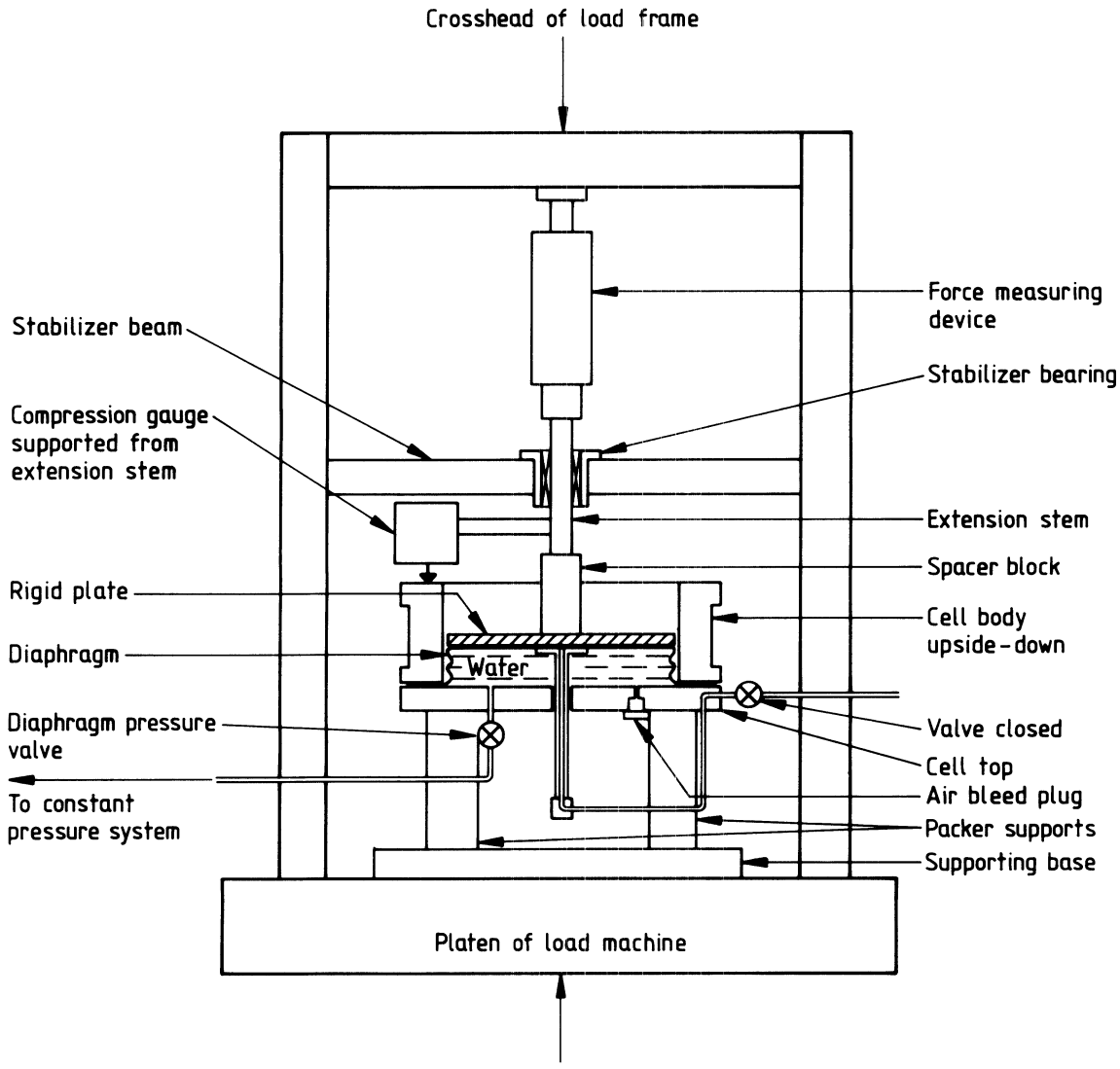


Figure 3 — Arrangement for load calibration of diaphragm

3.3.3 ***Preparation of specimen from block sample***

3.3.3.1 The procedure given in **3.3.2.2** to **3.3.3.8** enables a specimen to be fitted into the cell body from a block sample, or from a sample already extruded from a tube, or from a suitably trimmed exposure on site.

NOTE A sample taken on site should be trimmed flush to the cell flanges at each end, covered with a rubber sealing sheet and securely clamped to hold it in place protected from the atmosphere, before transporting to the laboratory.

3.3.3.2 Trim the surfaces of the specimen level and reasonably flat.

3.3.3.3 Place the cell, fitted with plastics liner if needed and the appropriate cutting shoe, on the levelled surface, cutting edge down.

3.3.3.4 With a sharp blade trim the soil a few centimetres ahead of the shoe to about 3 mm larger than its internal diameter.

3.3.3.5 Push the cell downwards, keeping its axis vertical, so that the cutting shoe pares away the outer 1.5 mm or so of the soil. With soft soils the weight of a 250 mm cell alone may be enough to advance it downwards. For stiff soils, jacking against a load frame may be necessary. A spirit level on the uppermost flange provides a guide to prevent tilting.

NOTE Correct alignment is easier to maintain if the apparatus referred to in **3.2.4.2.3** is used.

3.3.3.6 Continue **3.3.3.4** and **3.3.3.5** until the cell is completely filled, with a few millimetres surplus projecting at the top.

3.3.3.7 Lift off the cell with specimen, underpinning it with spatulas, take off the cutting shoe, and complete the trimming as in **3.3.2.7** to **3.3.2.14**.

3.3.3.8 Assemble the cell top in accordance with **3.4**.

3.3.4 *Preparation of soil for compacted specimens*

3.3.4.1 Soil for compaction into a large consolidation cell shall be prepared as described in **3.3.4.2** to **3.3.4.5**.

3.3.4.2 Remove any particles larger than one-sixth of the height of the specimen to be tested, by passing the soil through the appropriate sieve if necessary.

3.3.4.3 Bring the soil to the desired moisture content by thoroughly mixing with the appropriate amount of water, allowing for evaporation loss.

3.3.4.4 Take at least two representative specimens for determination of the moisture content.

3.3.4.5 Place the prepared soil in a sealed container, weigh to an accuracy of 0.1 % and store for at least 24 h before use.

3.3.5 *Compaction by specified compactive effort*

3.3.5.1 The prepared and weighed soil is compacted into the cell and made ready for test as described in **3.3.5.2** to **3.3.5.14**.

3.3.5.2 Attach the cell base to the body. The cell is first fitted with a peripheral drain if appropriate; the drainage material shall not be greased.

3.3.5.3 Close the valves between the cell and the pore pressure measuring system.

3.3.5.4 Place the cell assembly on a solid base, e.g. a concrete floor or plinth.

3.3.5.5 Place a quantity of prepared soil in the cell such that when compacted it occupies a little over one-half or one-third or one-fifth of the final specimen height, depending on the number of layers used.

3.3.5.6 Apply the requisite compactive effort equivalent to 2.5 kg compaction or 4.5 kg compaction (see **3.3** and **3.5** respectively of BS 1377-4:1990.

NOTE The method of compaction depends on the type of soil and the relevant conditions. Trial tests using different degrees of compaction may be necessary to achieve a uniform specimen of the required density.

3.3.5.7 Repeat **3.3.5.5** and **3.3.5.6** the appropriate number of times to produce a specimen of the required height.

3.3.5.8 Trim the top face of the compacted specimen to form a flat level surface, using a gauged depth trimming tool. Avoid tearing out hard particles. Return the trimmings to the remains of the prepared sample, and weigh the total remains to an accuracy of 0.1 %.

3.3.5.9 Determine the mass of soil used in the specimen by difference.

3.3.5.10 Determine the height of the specimen (H_0) to the nearest 0.5 mm by measuring down to the trimmed surface from the top of the cell body.

3.3.5.11 Take representative samples from the remaining soil for determination of moisture content.

3.3.5.12 If the soil is susceptible to swelling or is sensitive to a moisture content change it shall not be covered with water. (See note to **3.3.2.13**).

3.3.5.13 Seal the specimen and allow it to stand for at least 24 h before starting a test, to enable excess pore pressures to dissipate.

3.3.5.14 Assemble the cell top in accordance with **3.4**.

3.3.6 *Compaction to a specified density*

3.3.6.1 The procedure is similar to that given in **3.3.5** but is modified as described in **3.3.6.2** to **3.3.6.7**.

3.3.6.2 Assemble and connect the cell body and base as in **3.3.5.2** and **3.3.5.3**.

3.3.6.3 Calculate the mass of soil required to form a specimen of the desired height and volume from the specified density.

3.3.6.4 Weigh out this mass of soil from the prepared sample.

3.3.6.5 Compact the soil into the cell in layers, using a controlled degree of compaction, so that it forms a homogeneous specimen of the desired height (see note to **3.3.5.5**).

3.3.6.6 Trim, measure and prepare the specimen as in **3.3.5.8** to **3.3.5.13**.

NOTE The final measurements give the actual specimen dimensions and density, which may differ slightly from the desired values.

3.3.6.7 Assemble the cell top in accordance with **3.4**.

3.3.7 *Preparation of specimen under static pressure*

3.3.7.1 A specimen is prepared in the consolidation cell by static compression to give a specified dry density as described in **3.3.7.2** to **3.3.7.12**.

3.3.7.2 Attach the cell base, prepared as in **3.2.6.6**, to the body. First fit the cell with a peripheral drain if appropriate; the drainage material shall not be greased.

3.3.7.3 Close the valves between the cell and the pore pressure measuring system.

3.3.7.4 Place a weighed quantity of soil corresponding to one layer into the cell and spread it evenly, using a tamping rod if appropriate.

3.3.7.5 Place suitable spacer blocks on the soil and apply a static load until the required height of soil is formed.

NOTE The method used for compression depends on the type of soil and the relevant conditions. Trial tests using different amounts of soil and compression loads may be necessary to achieve a uniform specimen of the required density.

3.3.7.6 Repeat **3.3.7.4** and **3.3.7.5** for succeeding layers until the specimen is of the required height.

3.3.7.7 Level the surface of the specimen as in **3.3.5.8** and weigh any soil removed. Determine the mass of specimen by difference.

3.3.7.8 Verify the height of the specimen (H_0) to the nearest 0.5 mm by measuring down to the trimmed surface from the top of the cell body.

3.3.7.9 Take representative samples from the remaining soil for determination of moisture content.

3.3.7.10 If the soil is susceptible to swelling or is sensitive to a moisture content change it shall not be covered with water (see note to **3.3.2.13**).

3.3.7.11 Seal the specimen and allow it to stand for at least 24 h before starting a test, to enable excess pore pressures to dissipate.

3.3.7.12 Assemble the cell top in accordance with **3.4**.

3.4 Cell assembly

3.4.1 *General.* Before the cell can be finally assembled the operations given in one of **3.4.2** to **3.4.5** shall be carried out, depending on the type of test to be performed. These operations follow on from the preparation of the specimen (see **3.3**) and relate to **3.5** to **3.8** respectively.

In all cases the cell cover is then fitted as in **3.4.6** and initial observations are made and recorded as described in **3.4.7**.

3.4.2 *Consolidation with vertical drainage and pore pressure measurement*

3.4.2.1 *"Free strain" loading*

3.4.2.1.1 Place a saturated flexible porous disc centrally on the surface of the specimen, without entrapping air.

3.4.2.1.2 Pore pressure and drainage connection are as shown in Figure 2. The rim drain valve remains closed.

3.4.2.1.3 Cover the specimen and porous disc with de-aerated water, as appropriate.

3.4.2.2 *"Equal strain" loading*

3.4.2.2.1 Place a porous disc on top of the specimen, followed by the rigid loading plate. Avoid entrapping air. Ensure that the central hole of the plate aligns with the hole in the drainage spindle.

3.4.2.2.2 Pore pressure and drainage connections are as in **3.4.2.1**.

3.4.2.2.3 Cover the specimen and porous disc with de-aerated water, if appropriate.

3.4.3 *Consolidation with two-way vertical drainage*

3.4.3.1 The procedure is similar to that given in **3.4.2**, with the following variations.

3.4.3.2 Before transferring the specimen to the cell base (see **3.3.2.12**), place a saturated porous disc of the specimen diameter on the base, without entrapping air.

3.4.3.3 When tightening the cell body on to the base allow the thickness of the disc to displace the specimen upwards.

3.4.3.4 Allow for the thickness of the disc when measuring the specimen height, and the mass of the disc when weighing. Otherwise the setting-up procedure is the same as in **3.3.2**, and **3.4.2.1** or **3.4.2.2**.

3.4.3.5 The flushing system valve (see Figure 2) is connected to the same back pressure system as the back pressure valve, and becomes the bottom drainage valve. Pore pressures are not measured. The volume-change indicator measures the total volume of water draining out of the specimen from both faces. The rim drain valve remains closed.

3.4.3.6 Cover the specimen and porous disc with de-aerated water, if appropriate.

3.4.4 *Consolidation with outward radial drainage*

3.4.4.1 The procedure is similar to that given in **3.4.2**, with the variations given in **3.4.4.2** to **3.4.4.6**.

3.4.4.2 Fit a lining of porous plastics material against the cell wall, to act as a peripheral drain, before inserting the specimen.

3.4.4.3 Place an impervious membrane, such as a disc of latex rubber, on the surface of the specimen without entrapping air. For a "free strain" test the membrane shall be flexible.

3.4.4.4 For and "equal strain" test, place the circular steel plate on top of the membrane without entrapping air, and plug the central hole.

3.4.4.5 Connect the back pressure system to the rim drain valve (see Figure 4), through which drainage takes place. The back pressure valve is not used and remains closed, with the connection between it and the end of the hollow stem filled with de-aerated water. Pore pressure is measured at the centre of the base, as shown in Figure 4.

3.4.4.6 Cover the specimen and porous disc with de-aerated water, if appropriate.

3.4.5 ***Consolidation with inward radial drainage***

3.4.5.1 The procedure is similar to that given in **3.4.2** with the variations given in **3.4.5.2** to **3.4.5.10**.

3.4.5.2 Pore pressure is measured at a point offset from the centre, usually at a distance of 0.55 R from the centre, where R is the radius of the specimen. The central point is used for drainage, and the pore pressure valve is connected to the back pressure system.

3.4.5.3 The back pressure valve and the rim drain valve are not used and remain closed.

3.4.5.4 Immediately after trimming the surface of the specimen form a vertical hole in its centre by using a suitable mandrel.

NOTE The hole diameter should be as close as possible to 5 % of the specimen diameter, because the theoretical analysis for calculation of the coefficient of consolidation, c_{ri}, is based on a hole diameter ratio of 1.20.

3.4.5.5 Flush the hole with de-aerated water upwards from the central base port to ensure that there is no obstruction and no smeared material remaining on the porous insert.

3.4.5.6 Add clean de-aerated water to the hole to approximately two-thirds full.

3.4.5.7 Place the saturated sand (prepared as in **3.2.6.7.4**) steadily into the hole through a tube, so as to obtain a loose state of packing. Avoid jolting or vibrating the cell after placing.

3.4.5.8 When the hole is full check that water drains freely through the sand and out through the pore pressure valve, keeping the sand saturated. Trim the top surface of the specimen if necessary and cover with de-aerated water if appropriate.

3.4.5.9 For a "free strain" test place an impervious flexible disc on top of the specimen without entrapping air.

3.4.5.10 For an "equal strain" test place the circular steel plate on top of the specimen without entrapping air, and plug the central hole.

3.4.6 ***Fitting the cell cover***

3.4.6.1 After preparing the specimen for test in the cell by one of the methods given above fit the cell cover to the cell body over a sink or large tray, as described in **3.4.6.2** to **3.4.6.5**.

3.4.6.2 Support the cell cover over the cell body and partly fill the diaphragm with water so that it can be lowered into the cell without creasing.

NOTE For the large cells this operation is facilitated if the cell cover is temporarily supported while water is placed in the diaphragm, and then supported on spacer blocks on the cell body flange while the diaphragm is eased into the cell.

Allow displaced water to overflow from the top of the cell body, and seat the diaphragm on to the disc covering the specimen. Ensure that no air is trapped.

3.4.6.3 Bolt the cell cover to the body, tightening the bolts evenly ensuring that the flange of the diaphragm is properly seated between them.

NOTE When the specimen is not first covered with water because of its tendency to swell, air can be removed from behind the diaphragm by applying suction to the rim drain valve after bolting on the top cover, but this operation requires care to prevent disturbance to the specimen.

3.4.6.4 Fill the space above the diaphragm with water, displacing air through the air bleed, which is connected to a moderate vacuum to facilitate removal of all the air.

3.4.6.5 Apply a small seating pressure, P_{do} (not exceeding 10 kPa), to the diaphragm. Open the rim drain valve momentarily to release excess water from behind the diaphragm and to ensure that it remains seated on the disc covering the specimen.

3.4.7 ***Final adjustments***

3.4.7.1 Adjustments necessary before starting the test, and initial observations, are as described in **3.4.7.2** to **3.4.7.8**.

3.4.7.2 Ensure that the flushing system valve remains closed throughout the test, so as to isolate the pore pressure transducer from the flushing system.

3.4.7.3 Secure the compression dial gauge or transducer in position with the stem properly seated, allowing for a small upward movement.

3.4.7.4 Record the compression gauge reading as the datum value corresponding to the diaphragm seating pressure, p_{do}.

3.4.7.5 Record the initial steady pore water pressure, u_o, corresponding to p_{do}.

3.4.7.6 From the diaphragm pressure calibration data ascertain the pressure, p_o, applied to the specimen corresponding to the diaphragm seating pressure, p_{do}.

3.4.7.7 Set the back pressure system to the desired value, not less than u_o, keeping the appropriate drainage line valve closed.

3.4.7.8 Record the reading of the volume-change indicator on the back pressure line when equilibrium is established.

3.5 Procedure for consolidation test with one-way vertical drainage

3.5.1 *General.* This test allows for pore pressure to be measured at the bottom face of the specimen while drainage takes place from the top face. The specimen is set up as described in **3.4.2** with either "free strain" or "equal strain" loading. The procedure follows on from the adjustments and initial observations described in **3.4.7**, and consists of the following stages:

a) saturation and measurement of swelling pressure;

b) undrained loading (pore pressure build-up) (in a number of increments);

c) consolidation (pore pressure dissipation) (in a number of increments);

d) unloading;

e) dismantling.

3.5.2 ***Saturation***

3.5.2.1 *Objective.* The objective of the saturation stage is to ensure that all the voids are filled with water. This may be achieved by raising the pore water pressure in the specimen to a level high enough for the water to absorb into solution all the air originally in the voids. The degree of saturation is estimated by determining the ratio $\delta u/\delta\sigma$, where δu is the incremental change in pore pressure resulting from an incremental change in vertical stress of $\delta\sigma$ when no drainage is allowed (see note 2 of **3.3.1.2**). The criterion $\delta u/\delta\sigma = 0.95$ is usually accepted as an indication of sufficient saturation.

NOTE Values of the ratio $\delta u/\delta\sigma$ which can be expected when full saturation is reached or closely approached depend on the stiffness of a clay soil. In certain stiff fissured clays it may not be possible to obtain a ratio of 0.95, and a value of 0.90 which remains unchanged after three successive increments of diaphragm pressure and back pressure, as described in **3.5.2.3**, is then considered acceptable.

3.5.2.2 *Measurement of swelling pressure.* A soil that is susceptible to swelling shall not be allowed free access to water without provision for applying a vertical confining stress to prevent swell. Initial saturation is effected by allowing de-aerated water to enter at the base and to percolate upwards, while observing the compression gauge.

If this indicates an upward movement increase the seating pressure applied to the diaphragm to hold the reading at the initial value. When conditions become steady, record the diaphragm pressure.

NOTE 1 Considerably longer than 24 h might be needed to reach steady conditions in large specimens of low permeability soils.

The difference between the corresponding vertical stress applied to the surface of the specimen and the pressure of the water applied to the base is reported as the "swelling pressure".

Pockets of air remaining between the diaphragm and the cell wall may be removed by the application of a vacuum through the rim drain valve (see Figure 2), but this should be done with great care.

During the subsequent saturation stage the effective vertical stress applied to the specimen shall not at any time be less than the swelling pressure.

NOTE 2 The pressure differential between the vertical applied pressure and the base water pressure should be not less than the swelling pressure, nor large enough to cause premature consolidation of soft soils. A differential pressure of 10 kPa has been found to be suitable for many soils that are not susceptible to swelling.

3.5.2.3 *Saturation procedure (see form* 6.B *of* Appendix A.*)*

3.5.2.3.1 Increments of diaphragm and back pressure are applied alternately. The diaphragm pressure increment stages are carried out without allowing drainage into or out of the specimen, which enables values of the pore pressure ratio $\delta u/\delta\sigma$ to be determined at each level of total stress.

The procedure is as described in **3.5.2.3.2** to **3.5.2.3.13**.

3.5.2.3.2 Record the initial pore water pressure (u_o) as soon as it has reached a steady value after applying the pressure p_o on the specimen corresponding to the diaphragm seating pressure p_{do}. Ensure that the back pressure valve (see Figure 2) is closed.

3.5.2.3.3 Increase the diaphragm pressure to give the required first stage pressure on the specimen (p_1).

NOTE 1 Cell pressure increments of 50 kPa for the first two stages, and 50 kPa or 100 kPa thereafter, have been found to be suitable for many soil types, provided that the desired effective consolidation pressure is greater than 100 kPa.

Observe the pore water pressure until it reaches a steady value (u_1).

NOTE 2 A graphical plot of pore pressure reading against time may be made to verify when the steady state condition is reached (see note 2 of **3.3.1.2**).

3.5.2.3.4 Calculate the value of ratio $\delta u/\delta\sigma$ from the equation

$$\frac{\delta u}{\delta\sigma} = \frac{u_1 - u_0}{p_1 - p_0}$$

3.5.2.3.5 Keeping the back pressure valve closed, increase the pressure in the back pressure line to a value equal to the vertical pressure p_1 less the selected differential pressure (see note 2 to **3.5.2.2**). Record the reading of back pressure line volume-change indicator (v_1) when it reaches a steady value, to allow for expansion of connecting lines.

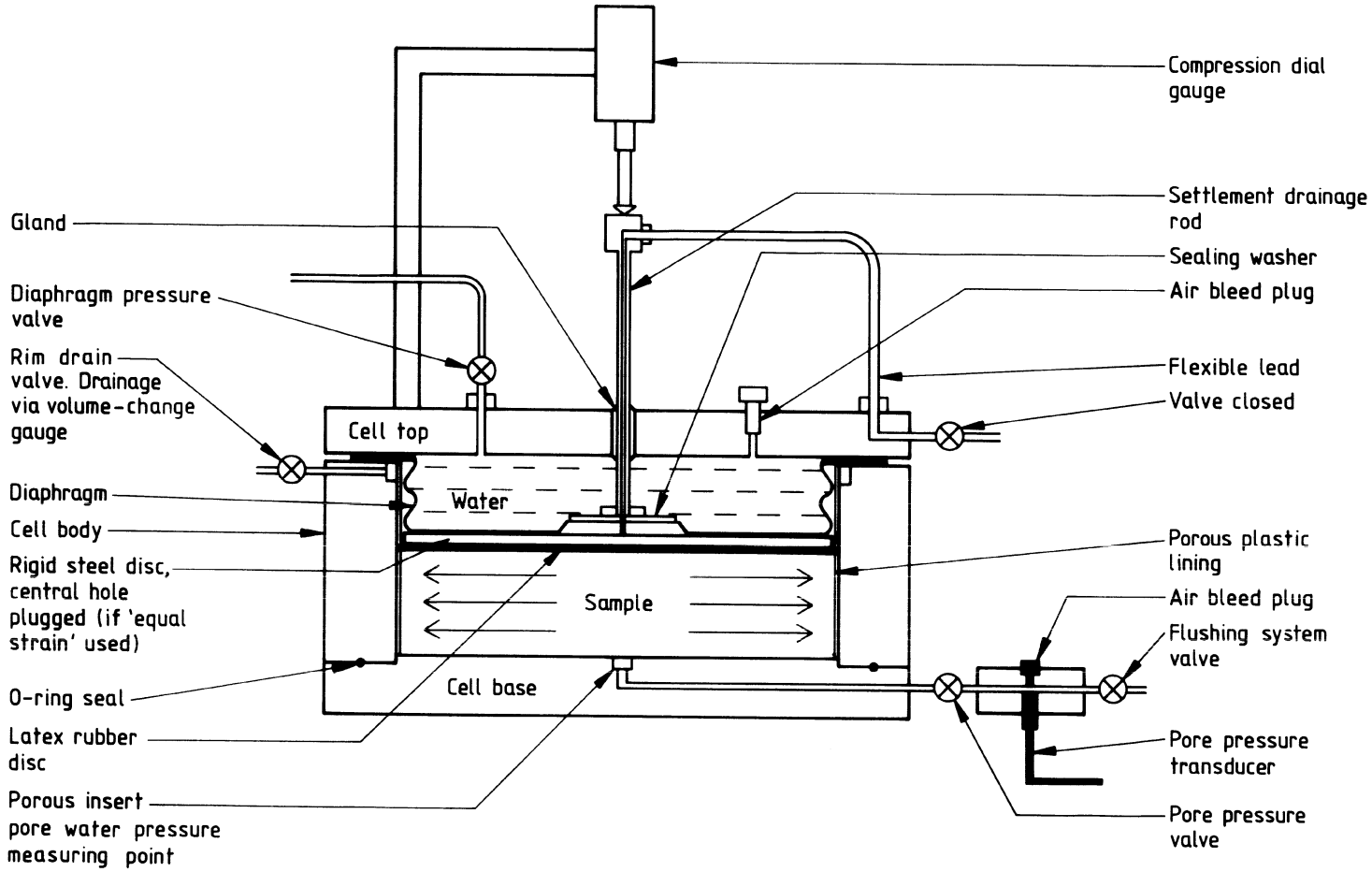


Figure 4 — Connections to hydraulic consolidation cell for consolidation test with radial drainage to periphery [test type (f)]

3.5.2.3.6 Open the back pressure valve to admit the back pressure into the specimen.

3.5.2.3.7 Observe the pore pressure and the volume-change indicator readings. When the pore water pressure becomes equal to the applied back pressure, and the volume-change indicator shows that movement of water into the specimen has virtually ceased, record these readings (u_2 and v_2 respectively) and close the back pressure valve.

NOTE Some considerable time might be needed before equilibrium is established.

3.5.2.3.8 Calculate the volume of water taken in by the specimen during this increment from the difference between v_1 and v_2.

3.5.2.3.9 Increase the diaphragm pressure by a further increment to give a pressure increase on the specimen of $\delta\sigma$. Observe the resulting change in pore pressure δu, as in **3.5.2.3.3** When equilibrium is established calculate the new value of $\delta u/\delta\sigma$.

3.5.2.3.10 Repeat the operations described in **3.5.2.3.5** to **3.5.2.3.9** until the pore pressure ratio $\delta u/\delta\sigma$ indicates that saturation is achieved.

3.5.2.3.11 The specimen is considered to be saturated when the value of $\delta u/\delta\sigma$ is equal to or greater than 0.95, or such other value appropriate to the soil type (see note to **3.5.2.1**).

3.5.2.3.12 Calculate the total volume of water taken up by the specimen into the air voids by totalling the differences obtained from **3.5.2.3.8**.

NOTE The volume of water taken up by the specimen from the back pressure line during saturation can be compared with the volumetric swell measured by the vertical movement gauge. The former usually exceeds the latter when air is initially present in the specimen voids.

3.5.2.3.13 A graph of $\delta u/\delta\sigma$ against diaphragm pressure at the end of each increment, or against pore pressure responses to cell pressure changes, may be plotted.

3.5.3 *Undrained loading*

3.5.3.1 Each increment of load is applied to the specimen with the drainage valve closed. The additional applied stress is carried by the consequent increase in pore water pressure which is monitored during this build-up stage.

Initially the diaphragm pressure valve (see Figure 2) is open to the diaphragm pressure system, and the pore pressure valve is open to enable the pore pressure to be observed. All other valves remain closed during this stage.

The procedure is as described in **3.5.3.2** to **3.5.3.6**.

3.5.3.2 Record the initial readings of pore pressure, the compression gauge and the pressure applied to the diaphragm.

3.5.3.3 Close the diaphragm pressure valve and set the diaphragm pressure line to the value needed to give the desired vertical stress on the specimen, taking into account the diaphragm calibration (see **3.2.5.2**).

3.5.3.4 Open the diaphragm pressure valve to admit the pressure to the diaphragm, and at the same instant start the timer.

3.5.3.5 Observe and record readings of the pore pressure transducer at suitable intervals of time for plotting a curve of pore pressure build-up against time.

3.5.3.6 Open and close the rim drain valve to allow escape of excess water from behind the diaphragm into a measuring cylinder.

NOTE 1 Clays of low permeability are unlikely to lose any pore water by consolidation during the 2 or 3 s while this valve is open. Greater care is needed with soils of higher permeability, for which the valve should be opened only momentarily. An alternative procedure is to drain the surplus water into the back pressure system by momentarily opening the valve and allowing for the volume thus removed.

The stage is complete when the pressure becomes steady (see note 2). Record the final pore pressure reading and the compression gauge reading.

NOTE 2 If the sample is saturated the increase in pore pressure should almost equal the pressure increment applied to the specimen.

3.5.4 *Consolidation (drained stage)*

3.5.4.1 Consolidation is effected by opening the drainage valve, which allows water to drain from the specimen while the applied stress is transferred to the soil "skeleton", i.e. the effective stress increases. Pore pressure changes, volume changes and settlement are monitored.

3.5.4.2 Record the diaphragm pressure and back pressure, and the initial readings of pore pressure, the compression gauge and the volume-change indicator corresponding to zero time.

3.5.4.3 Open the back pressure valve thus permitting drainage and at the same instant start the timer.

3.5.4.4 Record readings of pore pressure, the compression gauge and the volume-change indicator at suitable intervals of time after opening the drainage valve. Intervals of 0, ¼, ½, 1, 2, 4, 8, 15, 30, 60 min; 2, 4, 8, 24 h, are convenient for plotting on a log time base. Alternatively intervals of 0, ¼, ½, 1, 2¼, 4, 9, 16, 25, 36, 49, 64 min; 1½, 2, 4, 8, 24 h are more convenient for a square-root time plot.

For tests which continue beyond 24 h, additional readings shall be recorded at about 28 h and 32 h from the start, and thereafter at least twice a day, morning and evening.

(A test form suitable for recording these readings is shown in Appendix A, form 6.C.)

3.5.4.5 Hold the applied pressure constant until the pore pressure dissipation (calculated as in **3.5.8.2**) reaches at least 95 % (see note 1). Pore pressure dissipation of 100 % represents the end of primary consolidation (see note 2).

NOTE 1 If this requirement would result in a test of excessively long duration, an alternative criterion may be acceptable. The load stage should be extended to give as close to 100 % dissipation as practicable.

NOTE 2 If the coefficient of secondary compression is to be determined the loading stage should be continued beyond 100 % dissipation. Further readings of settlement are then observed until the slope of the linear log time/settlement plot is defined (see **3.6.5** of BS 1377-5:1990).

3.5.4.6 Close the back pressure valve to terminate the load stage. Record the final readings of pore pressure, settlement gauge and volume-change indicator.

3.5.4.7 Increase the diaphragm pressure to give the next vertical stress on the specimen, as described in **3.5.3.2** to **3.5.3.6**.

NOTE The sequence of loading should normally be such that the pressure increment is equal to the pressure already applied, i.e. a pressure increment ratio of 1. The sequence may differ from this to represent field conditions but it is desirable to maintain a constant pressure ratio in order to obtain consistent values of this coefficient of consolidation.

3.5.4.8 Allow consolidation as in **3.4.5.1** to **3.4.5.6**.

3.5.4.9 Repeat **3.5.4.7** and **3.5.4.8** for each value of applied stress in the desired loading sequence.

NOTE The number of loading stages should be not less than four, and should be enough to define the voids ratio/log pressure curve over a range of effective stress exceeding that which will occur in-situ due to overburden and the proposed construction.

3.5.5 *Unloading*

3.5.5.1 After completing the consolidation stage under the maximum applied pressure record the final readings and close the back pressure valve.

3.5.5.2 Unload the specimen in a sequence of decrements of diaphragm pressure (see note), similar in principle to the procedures described in **3.5.3** and **3.5.4**. However in each undrained stage the pore pressure decreases to a steady value, and in each drained stage the specimen swells and takes in water from the drainage line until the pore pressure virtually equalizes with the back pressure.

NOTE The number of stress decrements should not normally be less than half the number of stress increments applied, and a constant unloading stress ratio should be used. The final unloading should be to a stress equal to the initial seating pressure.

3.5.5.3 When equilibrium is established at an applied stress equal to the initial seating pressure, record the readings of pore pressure, compression gauge and volume-change indicator and close the pore pressure valve and the back pressure valve.

3.5.6 *Dismantling and final measurements*

3.5.6.1 Open the back pressure valve and the rim drain valve to the atmosphere to allow surplus water to escape, reduce the diaphragm pressure to zero, and remove the cell top and drainage disc (and loading plate if used). Remove any free water from the specimen surface.

3.5.6.2 Using a straightedge placed across the top edge of the cell body, measure down to the surface of the specimen at a number of points using a steel rule or depth gauge to an accuracy of 0.5 % to obtain a surface profile, from which the final volume of the specimen can be calculated.

3.5.6.3 Weigh the specimen in the cell body to an accuracy of 0.1 %.

3.5.6.4 Remove the specimen from the cell and take representative portions from two or more points for determination of final moisture content.

3.5.6.5 Break open a representative portion of the specimen on a vertical line for detailed examination and description of the soil. Record details of the soil fabric by sketches and, if required, by colour photographs.

3.5.7 *Graphical plots*

3.5.7.1 *Loading stage.* Plot the following graphs for each loading stage:

a) pore pressure against logarithmic time for each undrained loading phase;

b) settlement and volume-change against log time, or against square-root time, or both, during consolidation;

c) pore pressure dissipation, expressed as a percentage and derived as in **3.5.8.2** against log time.

Settlement and volume changes shall be plotted as cumulative values, each related to the reading under the initial seating load as datum.

3.5.7.2 *Unloading stage.* Plot the following graphs for each unloading stage:

a) pore pressure against logarithmic time for each undrained stage;

b) swell and volume change against log time or square-root time during the swelling phase;

c) percentage pore pressure equalization against log time.

NOTE The same axes as used for consolidation may be used for the graph in item b).

3.5.7.3 *End of test.* Plot the voids ratio at the end of each drained loading or unloading stage (calculated as described in **3.5.8.3**), if required, as ordinates against applied effective stress on a logarithmic scale as the abscissa (the e/log p' curve) (see form 6.F of Appendix A).

NOTE Values of the coefficient of consolidation, c_v (calculated as described in **3.5.8.5**), may also be plotted against log p'.

3.5.8 ***Calculations and analysis of data***

3.5.8.1 *Initial specimen data* (see form 6.A of Appendix A)

3.5.8.1.1 Calculate the initial density of the specimen, ρ(in Mg/m^3), from its initial measurements and mass.

3.5.8.1.2 Using the initial moisture content, w_o (in %), determined from trimmings, calculate the initial dry density, ρ_d (in Mg/m^3), from the equation

$$\rho_d = \frac{100\rho}{100 + w_o}$$

3.5.8.1.3 Calculate the initial voids ratio (e_o) if required from the equation

$$e_o = \frac{\rho_s}{\rho_d} - 1$$

where ρ_s is the particle density of the soil (measured or assumed) (in Mg/m^3).

3.5.8.1.4 Calculate the initial degree of saturation, S_o (in %), if required from the equation

$$S_o = \frac{w_o}{e_o} \times \frac{\rho_s}{\rho_w}$$

where ρ_w = 1.0 Mg/m^3.

3.5.8.2 *Pore pressure dissipation* (see form 6.C of Appendix A)

From every set of readings taken during each consolidation and swelling phase, calculate the percentage pore pressure dissipation, U (in %), from the equation

$$U = \frac{u_1 - u}{u_1 - u_2} \times 100$$

where

u_1 is the pore pressure at the start of the consolidation phase (in kPa);

u_2 is the pore pressure at the end of primary consolidation (in kPa);

u is the measured pore pressure at any intermediate instant (in kPa).

Plot pore pressure dissipation (U) against log time (in min).

3.5.8.3 *Voids ratio (if required)* (see form 6.D of Appendix A)

3.5.8.3.1 For tests with "equal strain" loading, changes in voids ratio can be related to changes in vertical settlement by the equation

$$\Delta e = \frac{1 + e_o}{H_o} \times \Delta H$$

where

Δe is the cumulative change in voids ratio at the end of the consolidation phase from the initial value e_o;

H_o is the initial height of the specimen (in mm);

ΔH is the cumulative change in height of the specimen at the end of a consolidation phase from the initial height (in mm).

The voids ratio (e) at the end of the consolidation phase is calculated from the equation

$$e = e_o - \Delta e$$

3.5.8.3.2 For tests with "free strain" loading (and optionally for "equal strain" loading), changes in voids ratio can be calculated from measured volume of water draining out of the specimen using the equation

$$\Delta e = \frac{1 + e_o}{V_o} \times \Delta V$$

where

e_o is as defined in **3.5.8.3.1**;

Δe is as defined in **3.5.8.3.1**;

V_o is the initial volume of the specimen (in cm^3);

ΔV is the cumulative change in volume of the specimen from the initial volume, assumed equal to the cumulative volume of water (in cm^3) that has drained out of the specimen due to consolidation only, up to the end of a consolidation phase.

This method is likely to be less accurate than that given in **3.5.8.3.1**. The voids ratio (e) at the end of the consolidation phase is calculated from the equation

$$e = e_o - \Delta e$$

3.5.8.3.3 For each consolidation phase calculate the incremental change of voids ratio (δe) from the equation

$$\delta e = e_1 - e_2$$

where

e_1 is the voids ratio at the beginning of the consolidation phase;

e_2 is the voids ratio at the end of that phase.

3.5.8.4 *Compressibility* (see form 6.D of Appendix A*)*

3.5.8.4.1 For tests with "equal strain" loading calculate the coefficient of volume compressibility, m_v (in m^3/MN), from the equation

$$m_v = \frac{\Delta H_2 - \Delta H_1}{H_o - \Delta H_1} \times \frac{1000}{P'_2 - P'_1}$$

where

ΔH_1 is the cumulative change in height of the specimen up to the end of the previous consolidation stage (in mm);

ΔH_2 is the cumulative change in height of the specimen up to the end of the consolidation stage being considered (in mm);

H_o is the initial height of the specimen (in mm);

P'_1 is the effective pressure applied to the specimen for the previous consolidation stage (in kPa);

P'_2 is the effective pressure applied to the specimen for the consolidation stage considered (in kPa).

3.5.8.4.2 For tests with "free strain" loading, calculate the coefficient of volume compressibility, m_v (in m^2/MN) for each consolidation stage from the equation

$$m_v = \frac{\Delta V_2 - \Delta V_1}{V_o - \Delta V_1} \times \frac{1000}{P'_2 - P'_1}$$

where

ΔV_1 is the cumulative change in volume of the specimen from the initial volume up to the end of the previous consolidation stage (in cm^3);

ΔV_2 is the cumulative change in volume of the specimen from the initial volume up to the end of the consolidation stage considered (in cm^3);

V_o is the initial volume of the specimen (in cm^3);

P'_1 is the effective pressure applied to the specimen for the previous consolidation (in kPa);

P'_2 is the effective pressure applied to the specimen for the consolidation stage considered (in kPa).

3.5.8.5 *Coefficient of consolidation* (see form 6.D of Appendix A*)*

3.5.8.5.1 *General*

The coefficient of consolidation, c_v, can be evaluated by using three empirical methods.

Method (a): From the pore pressure dissipation relationship;

Method (b): Curve fitting using the plot of settlement against log time;

Method (c): Curve fitting using the plot of settlement against square-root time.

Since the specimen is fully saturated similar curves based on the measured volume change, instead of settlement, may be used. Method (a) is based on pore pressure readings at a central point, whereas methods (b) and (c) depend on the "average" behaviour of the whole specimen. The theoretical time factors used for calculating c_v are different for the two types of measurement. Method (a) is preferred because it uses a value taken directly from the graph. The time factors are identical for "free strain" and "equal strain" loading.

3.5.8.5.2 *Method (a): pore pressure dissipation.* From the graph of pore pressure dissipation against log time for each loading stage, read off the time t_{50} (in min) corresponding to a dissipation of 50 %. Calculate c_v (in m^2/year) from the equation

$$c_v = \frac{0.20\overline{H}^2}{t_{50}}$$

where

$\overline{H}$ $= {}^1/_2(H_1 + H_2)$;

H_1 is the height of specimen at the start of the consolidation stage (in mm);

H_2 is the height of specimen at the end of the consolidation stage (in mm).

3.5.8.5.3 *Method (b): log time curve fitting.* On the initial (convex upwards) portion of the plot of settlement against log time locate the theoretical zero point (denoted by d_o) as follows (see Figure 5).

NOTE 1 In a test with "equal strain", either the volume change or the vertical compression graph may be used.

a) Mark off the difference in ordinates between any two points having times in the ratio of 1 : 4, and lay off an equal distance above the upper point. Repeat for two other points with times in the same ratio. The ordinate of the mean of the points so derived represents d_o.

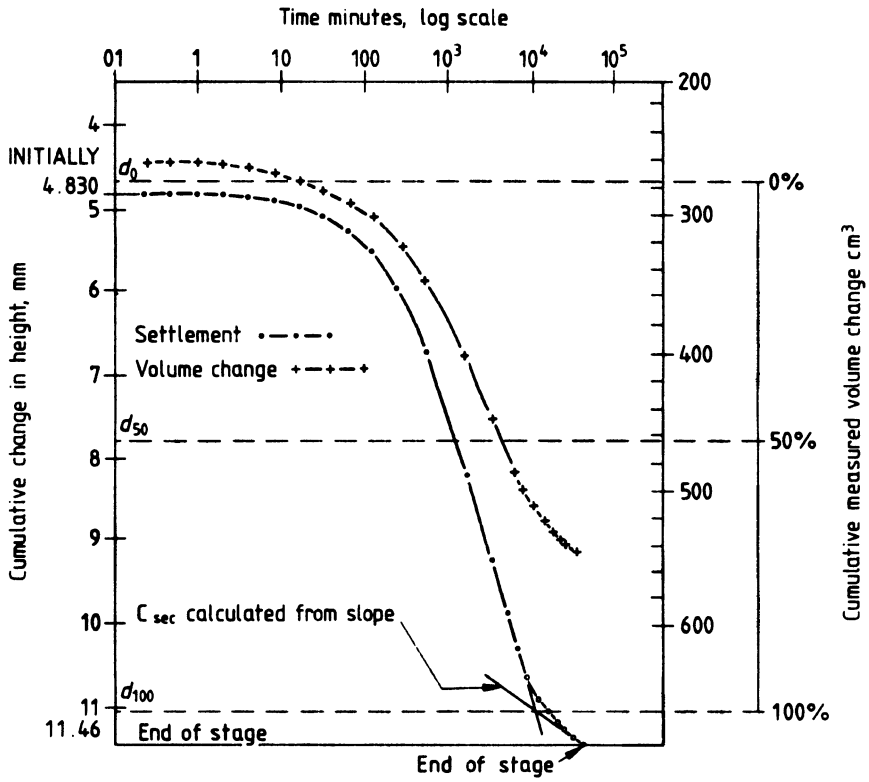


Figure 5 — Derivation of t_{50} from log time curves

NOTE 2 Because undrained loading can be applied, initial bedding effects are largely eliminated and the zero point derived in this way should be very close to the initial reading for the drained stage.

b) Draw the tangent at the point of inflection, i.e. where the slope is steepest, of the curve, and the tangent to the final linear portion. The point of intersection of these tangents represents theoretical 100 % primary consolidation (the d_{100} point). Alternatively take the d_{100} point corresponding to the time of 100 % pore pressure dissipation if that value is reached.

c) Locate the point of theoretical 50 % primary consolidation (d_{50}) by interpolation, and read off the corresponding time t_{50} (in min). Calculate the coefficient of consolidation, c_v (in m^2/year) from the equation

$$c_V = \frac{0.10\overline{H}^2}{t_{50}}$$

where

$\overline{H}$ is the average thickness of specimen during the load increment (in mm) as in **3.5.8.5.2**.

3.5.8.5.4 *Method (c): square-root time curve fitting* (see note 2 to **3.5.8.5.3**). On the plot of settlement against square-root time (see Figure 6) for each loading stage draw the straight line which best fits the approximately linear early portion (within about the first 50 % primary consolidation) and extend it to intersect the ordinate of zero time. This intersection represents the theoretical zero point denoted by d_o.

NOTE The temperature correction is given here to enable results from tests carried out at different temperature to be compared. The accuracy of c_v values derived by these methods does not justify the use of temperature corrections to correlate with in-situ conditions.

Draw a straight line through this point on which at all points abscissae are 1.15 times greater than those of the best fit line. The intersection of this line with the curve drawn through the plotted test data represents theoretical 90 % primary consolidation, denoted by d_{90}. By proportion obtain the abscissae representing 100 % and 50 % theoretical primary consolidation (d_{100} and d_{50}) and read off the value $\sqrt{t_{50}}$ from the graph.

Calculate the coefficient of consolidation, c_v (in m^2/year), from the same equation as in method (b).

Alternatively, read off the value of $\sqrt{t_{90}}$ from the graph and calculate c_v from the equation

$$c_v = \frac{0.446\overline{H}^2}{t_{90}}$$

A generalized form of the plot is shown in Figure 6, in which for this type of test $m = 1.15$ and $n = 0.5$.

3.5.8.5.5 *Temperature correction.* If the average laboratory temperature during a consolidation stage differs by more than ± 2 °C from 20 °C, the derived value of c_v shall be corrected to the 20 °C value by multiplying the appropriate correction factor obtained from Figure 7 (see note to **3.5.8.5.4**).

3.5.8.6 *Coefficient of secondary compression*

3.5.8.6.1 The coefficient of secondary compression, if required, is derived from the laboratory logarithm of time curve as described in **3.5.8.6.2** to **3.5.8.6.5**

3.5.8.6.2 Extend the linear portion of the secondary compression portion of the curve (see Figure 5) so that it covers one complete cycle of log time. It may be necessary to prolong the duration of the load increment to establish a linear relationship.

3.5.8.6.3 Read off the compression gauge readings at the beginning and end of the cycle, e.g. at 1 000 min and 10 000 min, and calculate the difference, $(\delta H)_s$ (in mm), between them.

3.5.8.6.4 Calculate the coefficient of secondary compression, Csec, from the equation

$$C_{sec} = \frac{(\delta H)_s}{H_o}$$

where

H_o is the initial height of the specimen.

3.5.8.6.5 Repeat **3.5.8.6.2** to **3.5.8.6.4** for each of the applied loading stages.

3.5.9 *Test report.* The test report shall affirm that the test was carried out in accordance with **3.5** of BS 1377-6:1990, and shall include the following, in addition to the relevant information listed in clause **9** of BS 1377-1:1990 (form 6.E of Appendix A is suitable for summarizing most of the data):

a) a statement that a hydraulic consolidation cell was used, and its nominal diameter;

b) remarks on the condition and quality of the sample;

c) remarks on any difficulties experienced during specimen preparation;

d) the initial dimensions of specimen;

e) the initial moisture content, bulk density and dry density;

f) the particle density, indicating whether measured or assumed;

g) the initial voids ratio and degree of saturation, if required;

h) the type of loading ("free strain" or "equal strain") and drainage conditions;

i) a statement that drainage took place from the top of the specimen with pore water pressure measurement at the centre of the base;

j) the swelling pressure (to two significant figures) (if applicable);

k) the method used for saturating the specimen, if applicable including pressure increments applied and differential pressure;

l) the volume of water taken into the specimen during saturation;

m) the diaphragm pressure, pore pressure and value of ratio $\delta u/\delta\sigma$ at the end of the saturation stage;

n) tabulated data for each loading stage, comprising:

1) back pressure used;

2) diaphragm pressure;

3) effective stress at termination of consolidation stage;

4) settlement and pore pressure increase due to undrained loading;

5) voids ratio (if required) and percentage dissipation of pore pressure at the end of consolidation;

6) values of the coefficient m_v and c_v (to two significant figures);

o) the method used for deriving c_v;

p) plotted curves for each consolidation stage, comprising:

1) pore pressure dissipation (%) against log time;

2) volume change and settlement against log time or square-root time;

q) curve of voids ratio or vertical compression as ordinate against effective stress at the end of each consolidation or swelling stage, to a log scale, as abscissa (see form 6.F of Appendix A);

r) the final density and overall moisture content of specimen;

s) moisture contents representing specified zones or layers (identified by a sketch) within the specimen, where appropriate;

t) colour photographs illustrating features of the soil fabric (if required);

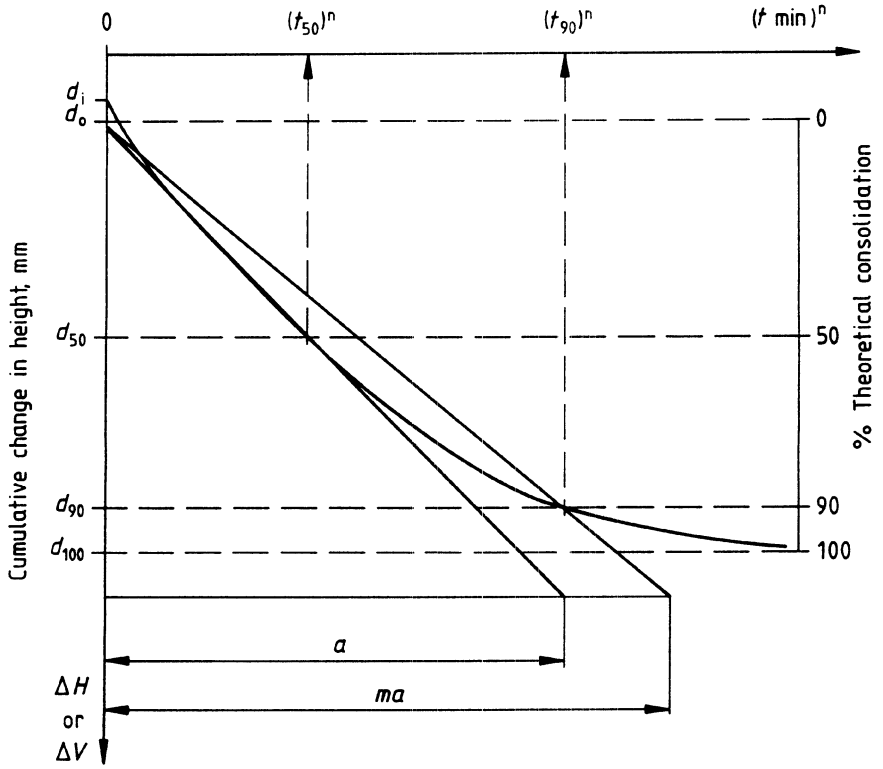


Figure 6 — Derivation of t_{50} and t_{90} from power function curves

u) the in-situ total and effective stresses at the depth from which the sample was taken, if known.

3.6 Procedure for consolidation test with two-way vertical drainage

3.6.1 *General.* In this test drainage takes place from both the top and bottom faces of the specimen, but pore water pressure is not measured. The top and bottom drainage valves are both connected to the back pressure system. The test specimen is prepared as described in **3.4.3**, with either "free strain" or "equal strain" loading, the latter giving conditions equivalent to those of the oedometer consolidation test described in clause **3** of BS 1377-5:1990.

The test stages are the same as those listed in **3.5.1**. Procedures are similar to those described in **3.5.2** to **3.5.9**, with the variations given in **3.6.2** to **3.6.6**.

3.6.2 *Saturation.* If during the saturation stage the bottom drainage valve (see Figure 2) remains closed the conditions are similar to those referred to in **3.5.1**. Apply saturation as described in **3.5.2**.

3.6.3 *Undrained loading.* When a load increment is applied by increasing the diaphragm pressure, leave the bottom drainage valve and the back pressure valve (Figure 2) closed so that pore water pressure build-up can be observed and recorded as described in **3.5.3**.

3.6.4 *Consolidation (drained stage).* Effect consolidation by opening both the top and bottom drainage valves at the same time as the timer is started. Proceed as in **3.5.4** except that pore pressure changes cannot be observed.

During each stage of consolidation, plot curves of vertical compression or volume change or both against log time and square-root time. Continue consolidation until the curves indicate that at least 95 % primary consolidation has been achieved. Terminate a stage by closing both drainage valves. Apply further increments of load as described in **3.5.4.9**.

3.6.5 *Unloading.* Unload the specimen in decrements, as described in **3.5.5**, except that pore water pressure can be observed only during the undrained unloading stage. Judge the equilibrium condition at the end of a drained swelling stage from volume-change readings of water entering the specimen.

3.6.6 *Dismantling and final measurements.* Proceed as in **3.5.6**.

NOTE In **3.5.6.1** drainage of excess water should take place from the flushing system valve as well as the back pressure valve.

3.6.7 *Graphical plots*

3.6.7.1 *During each loading stage.* Proceed as in **3.5.7.1**, except that item c) is not applicable.

3.6.7.2 *During each unloading stage.* Proceed as in **3.5.7.2**, except that item c) is not applicable.

3.6.7.3 *End of test.* Proceed as in **3.5.7.3**.

3.6.8 *Calculations and analysis of data*

3.6.8.1 Carry out calculations in accordance with **3.5.8.1** and **3.5.8.3** to **3.5.8.6**. In calculating values of *c*v (see **3.5.8.5**), use only methods (b) or (c) with the following modifications.

NOTE The theoretical time factors are identical for "free strain" and "equal strain" loading.

3.6.8.2 *Method (b): log time curve fitting.* Calculate c_v from the equation

$$c_v = \frac{0.026\,\overline{H}^2}{t_{50}}$$

3.6.8.3 *Method (c): square-root time curve fitting.* Calculate c_v from t_{50} as in method (b) above, or from t_{90} using the equation

$$c_v = \frac{0.111\,\overline{H}^2}{t_{90}}$$

3.6.8.4 *Temperature correction*

Apply a temperature correction to the calculated value of c_v, if appropriate, as in **3.5.8.5.5**.

3.6.9 *Test report.* The test report shall affirm that the test was carried out in acccordance with **3.6** of BS 1377-6:1990. It shall include the information as listed in **3.5.9**, except for data relating to pore pressure measurements.

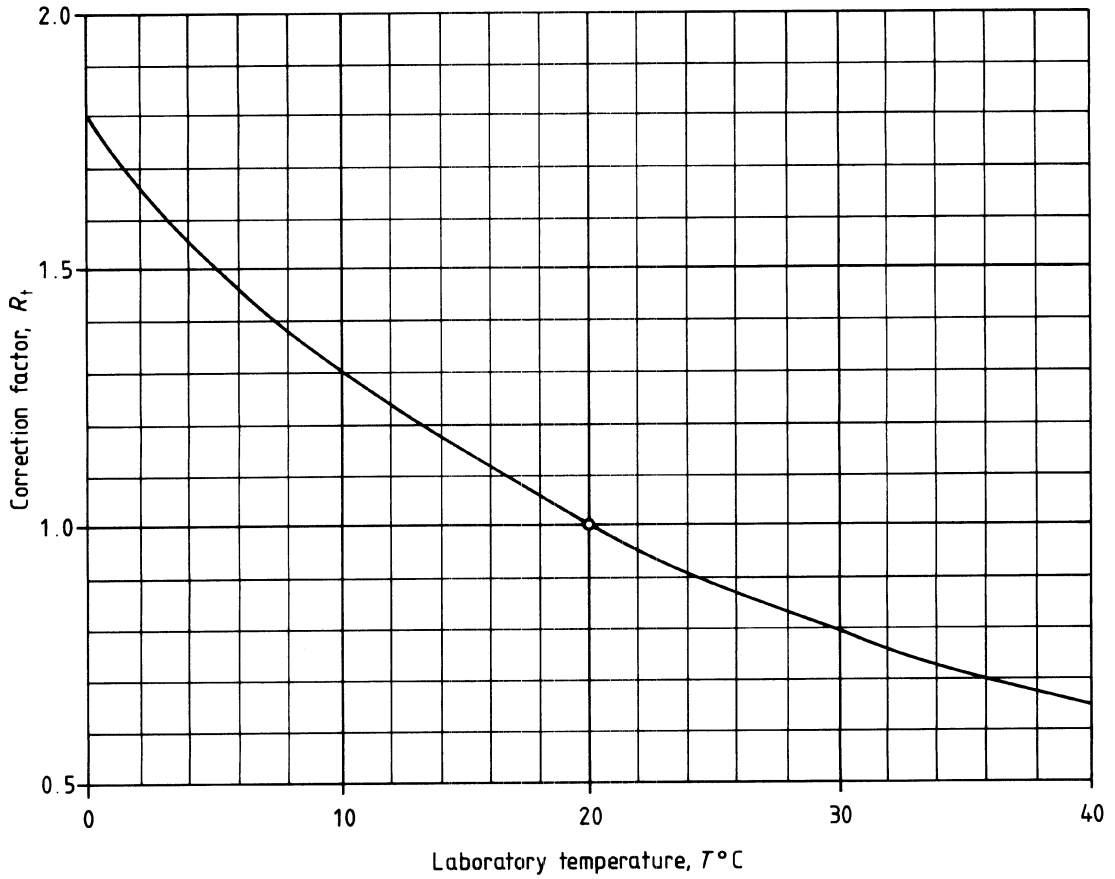


Figure 7 — Temperature correction curve

3.7 Procedure for consolidation test with drainage radially outwards

3.7.1 *General.* In this test drainage takes place to the curved periphery of the specimen, i.e. the drainage path in the specimen is horizontal, radially outwards. Pore water pressure is measured at the centre of the bottom face, and it is assumed that at any instant the pore water pressure distribution along any vertical line is uniform.

The test specimen is prepared as described in **3.3**, with a drainage layer of porous plastic material fitted to the cell wall. The cell is assembled as described in **3.4.4** with either "free strain" or "equal strain" loading. Connections to the cell are as shown in Figure 4. The drainage line is controlled by the rim drain valve. The line between the specimen surface and the back pressure valve shall be completely filled with de-aerated water, and this valve then remains closed.

3.7.2 *Saturation.* Carry out the saturation procedure as described in **3.5.2** except that the back pressure is applied through the rim drain valve (see note 2 of **3.3.1.2**).

3.7.3 *Undrained loading.* Apply increments of loading and observe the build-up of pore water pressure, as in **3.5.3**. In **3.5.3.6** excess water can be allowed to escape from behind the diaphragm by momentarily opening the rim drain valve and measuring the volume of water thus removed so that it is not included in the drainage measurements.

NOTE In laminated soils, true pore pressure equilibrium might take longer than is apparent, as indicated in note 2 of **3.3.1.2**.

3.7.4 *Consolidation (drained stage).* Initiate consolidation by opening the rim drain valve. Otherwise proceed and record data as in **3.5.4** for each stage of consolidation.

NOTE With laminated soils consolidation of less permeable layers might continue after the observed pore water pressure indicates 100 % dissipation. The duration of consolidation can then be monitored only by observation of settlement and volume-change readings.

3.7.5 *Unloading.* Carry out decremental unloading as in **3.5.5** except that the rim drain valve is used instead of the back pressure valve.

3.7.6 *Dismantling and final measurements.* Proceed as in **3.5.6**. Discard porous plastics material used as the peripheral drain.

3.7.7 *Graphical plots*

3.7.7.1 *Loading stage.* Plot graphs for each loading stage as described in **3.5.7.1**, except for the square-root time method of item b) when "free strain" loading is used. In this case plot settlement and volume change against $t^{0.465}$ instead of $t^{0.5}$, where t is the elapsed time in minutes from the start of each consolidation stage.

3.7.7.2 *Unloading stage.* Plot graphs for each unloading stage as in **3.5.7.2**, except for item b) when "free strain" loading is used. In this case $t^{0.465}$ shall be used instead of $t^{0.5}$.

3.7.7.3 *End of test.* Proceed as in section **3.5.7.3**.

3.7.8 *Calculations and analysis of data*

3.7.8.1 *General.* Carry out calculations of initial specimen data, pore pressure dissipation, voids ratios and coefficient of volume compressibility as in **3.5.8.1** to **3.5.8.4**.

The coefficient of consolidation, c_{ro}, can be evaluated by methods similar in principle to those described in **3.5.8.5**. However, details depend on the type of plot and whether "equal strain" or "free strain" loading was applied. Variations to take account of these differences are indicated below.

3.7.8.2 *Method (a): pore pressure dissipation.* Calculate c_{ro} (m^2/year) from one of the following equations, as applicable:

a) "free strain" loading:

$$c_{ro} = \frac{0.026D^2}{t_{50}}$$

b) "equal strain" loading:

$$c_{ro} = \frac{0.023D^2}{t_{50}}$$

where

t_{50} is the time corresponding to a pore water pressure dissipation of 50 % (in min);

D is the specimen diameter (in mm).

3.7.8.3 *Method (b): log time curve fitting.* Calculate C_{ro} (m^2/year) from one of the following equations, as applicable:

a) "free strain" loading;

$$c_{ro} = \frac{0.0083D^2}{t_{50}}$$

b) "equal strain" loading;

$$c_{ro} = \frac{0.011D^2}{t_{50}}$$

3.7.8.4 *Method (c): "free strain" loading (special power curve fitting).* From the graph of volume change against $t^{0.465}$ obtain the point corresponding to zero theoretical primary consolidation (represented by d_o) in the same way as in **3.5.8.5.4**. Draw the straight line through the d_o point which at all points has abscissae 1.22 times greater than those of the best fit line. The intersection of this line with the experimental curve represents theoretical 90 % consolidation (d_{90}). Read off the values of $(t_{50})_{0.465}$ and $(t_{90})_{0.465}$ from the graph as in **3.5.8.5.4**. The procedure is illustrated in Figure 6, where for this type of test $m = 1.22$ and $n = 0.465$.

Calculate the value of c_{ro} (m2/year) from either of the equations:

a) $c_{ro} = \dfrac{0.0083D^2}{t_{50}}$

b) $c_{ro} = \dfrac{0.044D^2}{t_{90}}$

3.7.8.5 *Method (d): "equal strain" loading (square-root time curve fitting).* Derive t_{50} and t_{90} as in **3.5.8.5** using square-root time as the abscissa for the plot, except that the line drawn through the d_o point has abscissae 1.17 (instead of 1.15) times those of the best fit line. In Figure 6, for this type of test $m = 1.17$ and $n = 0.5$.

Calculate c_{ro} (m^2/year) from either of the equations:

a) $c_{ro} = \dfrac{0.011D^2}{t_{50}}$

b) $c_{ro} = \dfrac{0.038D^2}{t_{90}}$

3.7.8.6 *Temperature correction.* A temperature correction shall be applied to the calculated value of c_{ro}, if appropriate, as in **3.5.8.5.5**.

3.7.9 *Test report.* The test report shall affirm that the test was carried out in accordance with **3.7** of BS 1377-6:1990 and shall include the following, in addition to the relevant information listed in clause **9** of BS 1377-1:1990:

a) a statement that a hydraulic consolidation cell was used, and its nominal diameter;

b) remarks on the condition and quality of the sample;

c) remarks on any difficulties experienced during specimen preparation;

d) the initial dimensions of specimen;

e) the initial moisture content, bulk density and dry density;

f) the particle density, indicating whether measured or assumed;

g) the initial voids ratio and degree of saturation, if required;

h) the type of loading ("free strain" or "equal strain") and drainage conditions, indicating thickness of the peripheral drainage material;

i) a statement that drainage took place from the periphery of the specimen with pore water pressure measurement at the base, and the location of the pore pressure measurement point;

j) the swelling pressure (to two significant figures) if applicable;

k) the method used for saturating the specimen, if applicable, including pressure increments applied and differential pressure;

l) the volume of water taken into the specimen during saturation;

m) the diaphragm pressure, pore pressure and value of pore pressure ratio $\delta u/\delta\sigma$ at the end of the saturation stage;

n) tabulated data for each loading stage, comprising:

1) back pressure used;

2) diaphragm pressure;

3) effective stress at termination of consolidation stage;

4) settlement and pore pressure increase due to undrained loading;

5) voids ratio, if required, and percentage dissipation of pore pressure at the end of consolidation;

6) values of the coefficient m_v and c_{ro} (to two significant figures);

o) the method used for deriving c_{ro};

p) plotted curves for each consolidation stage, comprising:

1) pore pressure dissipation (%) against log time;

2) volume change and settlement against log time or time raised to the power of 0.5 or 0.465, as appropriate;

q) curve of voids ratio or vertical compression as ordinate against effective stress at the end of each consolidation or swelling stage, to a log scale, as abscissa (see form 6.F of Appendix A);

r) final density and overall moisture content of specimen;

s) moisture contents representing specified zones or layers (identified by a sketch) within the specimen, where appropriate;

t) colour photographs illustrating features of the soil fabric (if required);

u) the in-situ total and effective stresses at the depth from which the sample was taken if known.

3.8 Procedure for consolidation test with drainage radially inwards

3.8.1 *General.* In this test drainage takes place to a central drainage well of fine sand or other suitable material of high permeability relative to the specimen. The drainage path is horizontal, radially inwards. Pore water pressure can be measured at one or more points offset from centre, usually at one point spaced at $0.55R$ from the centre (where R is the specimen radius). It is assumed that the pore water pressure distribution along any vertical line is uniform.

The test specimen is prepared by one of the methods described in **3.3**. The central drainage well is formed and installed, and the specimen is made ready, as described in **3.4.5**. The cell cover is fitted as in **3.4.6**.

The pore pressure transducer is connected to an off-centre pore pressure measuring port in the cell base. Drainage takes place from the central base drainage port which is connected to the back pressure system as described in **3.5.4.2**. The other lines from the specimen are completely filled with de-aerated water, and their valves remain closed.

3.8.2 *Saturation.* Carry out the saturation procedure as described in **3.5.2** except that the back pressure is applied through the central base drainage port.

NOTE The time required to achieve saturation of the whole specimen will be greater than indicated by pore pressure readings at the point $0.55R$ from the centre. This is in addition to the longer period required for saturation of the less permeable zones of laminated soils (see note 2 of **3.3.1.2**).

3.8.3 *Undrained loading.* Apply increments of loading and observe the build-up of pore water pressure as in **3.5.3** except that pore water pressure is measured off-centre.

3.8.4 *Consolidation (drained stage).* Initiate consolidation by opening the central base drainage valve. Measure pore water pressure offset from centre. Otherwise proceed and record data as described in **3.5.4** for each stage of consolidation.

NOTE With laminated soils consolidation of the less permeable layers might continue after observed pore water pressure indicates 100 % dissipation. In addition the excess pore water pressure at the periphery will always exceed that measured at the usual offset point ($0.55R$). Additional measurements of pore water pressure at $0.1R$ and $0.9R$ from the centre, where possible, would enable a better distribution of pore water pressure to be obtained.

3.8.5 *Unloading.* Carry out decremental unloading as in **3.5.5** but with base drainage.

3.8.6 *Dismantling and final measurements.* Proceed as in **3.5.6**. The central drainage material shall be discarded and not re-used.

3.8.7 *Graphical plots.* Plot graphs during each loading and unloading stage, and at the end of test, as described in **3.5.7**.

3.8.8 ***Calculations and analysis of data***

3.8.8.1 *General.* Carry out calculations of initial specimen data, pore pressure dissipation, voids ratios and coefficient of volume compressibility as in **3.5.8.1** to **3.5.8.4**.

Evaluate the coefficient of consolidation, c_{ri}, by three methods similar in principle to those described in **3.5.8.5**. The difference between the theoretical time factors for "free strain" and "equal strain" loading conditions is negligible.

NOTE These calculations assume that the pore pressure has been measured at $0.55R$ from the centre and that $D/d = 20$, where D is the specimen diameter (in mm) and d is the diameter of the drainage well (in mm).

3.8.8.2 *Method (a): pore pressure dissipation.* Calculate c_{ri} (m^2/year) from the following equation:

$$c_{ri} = \frac{0.10D^2}{t_{50}}$$

where

t_{50} is the time corresponding to a pore water dissipation of 50 % (in min);

D is the specimen diameter (in mm).

3.8.8.3 *Method (b): log time curve fitting.* Calculate c_{ri} (m^2/year) from the same equation as in **3.8.8.2**.

3.8.8.4 *Method (c): square-root time curve fitting.* Derive t_{50} and t_{90} by the procedure described in **3.7.8.5**. In Figure 6, for this type of test with either "free strain" or "equal strain", $m = 1.17$ and $n = 0.5$.

Calculate c_{ri} (m^2/year) from either of the equations

a) $$c_{ri} = \frac{0.10D^2}{t_{50}}$$

b) $$c_{ri} = \frac{0.34D^2}{t_{90}}$$

3.8.8.5 *Temperature correction.* Apply a temperature correction to the calculated value of c_{ri}, if appropriate, as in **3.5.8.5.5**.

3.8.9 *Test report.* The test report shall affirm that the test was carried out in accordance with **3.8** of BS 1377-6:1990. It shall include the following, in addition to the relevant information in clause **9** of BS 1377-1:1990:

a) statement that a hydraulic consolidation cell was used, and its nominal diameter;

b) remarks on the condition and quality of the sample;

c) remarks on any difficulties experienced during specimen preparation;

d) initial dimensions of specimen;

e) initial moisture content, bulk density and dry density;

f) particle density, indicating whether measured or assumed;

g) initial voids ratio and degree of saturation, if required;

h) statement that drainage took place from the centre of the specimen with pore pressure measurement at the base, and the location of the pore pressure measurement point or points;

i) type of loading ("free strain" or "equal strain") and drainage conditions, indicating the diameter of the central drainage well;

j) swelling pressure (to two significant figures) if applicable;

k) methods used for the saturation of the specimen, if applicable, including pressure increments applied and differential pressure;

l) volume of water taken into the specimen during saturation;

m) diaphragm pressure, pore pressure and value of the ratio $\delta u/\delta\sigma$ at the end of the saturation stage;

n) tabulated data for each loading stage, comprising:

1) back pressure used;

2) diaphragm pressure;

3) effective stress at termination of consolidation stage;

4) settlement and pore pressure increase due to undrained loading;

5) voids ratio, if required, and percentage dissipation of pore pressure at the end of consolidation;

6) values of the coefficients m_v and C_{ri} (to two significant figures);

o) method used for deriving C_{ri};

p) plotted curves for each consolidation stage, comprising:

1) pore pressure dissipation (%) against log time;

2) volume change and settlement against log time or square-root time;

r) curve of voids ratio or vertical compression as ordinates against effective stress at the end of each consolidation or swelling stage, to a log scale, as abscissa (see form 6.F of Appendix A);

s) final density and overall moisture content of specimen;

t) moisture contents representing specified zones or layers (identified by a sketch) within the specimen, where appropriate;

u) colour photographs illustrating features of the soil fabric (if required);

v) the in-situ total and effective stresses at the depth from which the sample was taken, if known;

w) method for forming central drainage well;

x) grading characteristics of material used in central drainage well, and method of placing.

4 Determination of permeability in a hydraulic consolidation cell

4.1 General

4.1.1 *Principle.* This method covers the measurement of the coefficient of permeability of a laterally confined specimen of soil under a known vertical effective stress, and under the application of a back pressure. The volume of water passing through the soil in a known time, and under a constant hydraulic gradient, is measured. The direction of flow may be either vertical (parallel to the specimen axis) or horizontal (radially outwards or inwards).

The method is suitable for soils of low and intermediate permeability.

4.1.2 *Test specimens.* The specimen is in the form of a cylinder laterally confined in a consolidation cell of the type described in clause **3**.

The test may be carried out on specimens prepared from undisturbed samples of cohesive soil taken from the natural ground, or on disturbed samples recompacted in the laboratory.

4.1.3 *Types of test.* Two types of permeability test are described. The first (**4.8.3**) is for the determination of permeability in the vertical direction, in which water is made to flow vertically downwards through the specimen. The second (**4.8.4**) is for the determination of horizontal permeability in which water is made to flow radially, either outwards from the centre to the periphery or inwards to the centre.

4.1.4 *Test conditions.* The following test conditions shall be specified before starting a test:

a) size of test specimen;

b) loading conditions;

c) drainage conditions and direction of flow of water;

d) effective stress at which each permeability measurement is to be carried out;

e) whether void ratios are to be calculated.

The requirements of Part 1 of this standard, where appropriate, shall apply to the test methods described in this clause.

4.1.5 ***Environmental requirements and safety***

4.1.5.1 *Temperature.* These tests shall be carried out in a laboratory in which the temperature is maintained constant to within ± 2 °C, in accordance with **6.1** of BS 1377-1:1990. All apparatus shall be protected from direct sunlight, from local sources of heat and from draughts.

4.1.5.2 *Hazard warning*

NOTE Users of this equipment should be conversant with regulations for pressure vessels.

Consolidation cells and ancillary equipment shall not be used at pressures above their safe working pressures.

4.2 Apparatus for preparation of specimens

The apparatus required for the preparation and measurement of undisturbed specimens, and of compacted specimens prepared in the laboratory, is the same as that given in **3.2.4**.

4.3 Apparatus for permeability test

4.3.1 *Hydraulic consolidation cell.* The hydraulic consolidation cell and its accessories and instrumentation are described in **3.2.1** to **3.2.3**.

4.3.2 ***Ancillary equipment for permeability tests in the cell***

4.3.2.1 *Three independent pressure systems,* as specified in **3.2.3.1** for applying and maintaining the desired pressures for the following:

a) diaphragm loading;

b) inlet drainage line;

c) outlet drainage line.

NOTE When it is not necessary to maintain a high back pressure at the outlet end of the specimen the outlet drainage line can be connected to an elevated water reservoir fitted with an overflow to maintain a constant water level.

For vertical permeability tests the inlet and outlet drainage lines are connected to the back pressure valves and the pore pressure valve of Figure 2 respectively. For radial permeability tests the lines are connected to the rim drain valve and the pore pressure valve depending on the direction of flow.

4.3.2.2 *A calibrated pressure gauge,* for independent calibrated measurements of the pressure in each pressure system, as specified in **3.2.3.1**, except that the gauge shall be connected to the three pressure systems. Alternatively, independent calibrated gauges may be used, each connected to its own pressure system.

For the measurement of a small pressure difference between the inlet and outlet drainage lines a suitably calibrated differential pressure gauge or pressure transducer shall be used. Pressure differences shall be readable to 0.5 kPa.

4.3.2.3 *Two calibrated volume-change indicators* (burette or transducer type), one on each of the drainage lines connected to the specimen, as specified in **3.2.3.3**.

4.3.2.4 *Timing device,* readable to 1 s.

4.3.2.5 *A plentiful supply of de-aerated tap water,* at room temperature.

4.3.2.6 *Silicone grease or petroleum jelly.*

4.3.2.7 For vertical permeability tests:

a) *two porous discs,* as specified in **3.2.1.2.8**;

b) *a rigid loading plate* as specified in **3.2.1.2.9**.

4.3.2.8 For horizontal permeability tests.

a) *A sheet of porous plastics material,* 1.5 mm thick for forming a peripheral drain around the wall of the cell body. The inside face of the material shall be smooth.

b) *Mandrel for forming a central drainage hole.*

NOTE The hole diameter should be as close as possible to 5 % of the specimen diameter because the theoretical analysis for the calculation of c_{vi} is based on a hole/diameter ratio of 1 : 20.

c) *Uniform fine sand,* for the central drainage well.

4.3.2.9 *A calibrated thermometer,* readable to 0.5 °C.

4.4 Calibration of apparatus

4.4.1 *Measurements.* Determine the dimensions of the cell and accessories as in **3.2.5.1**.

4.4.2 *Calibration of diaphragm.* Calibrate the force exerted by the diaphragm as in **3.2.5.2**.

4.4.3 ***Head losses***

4.4.3.1 *General.* Determine the head losses in pipelines and other restrictions, for various rates of flow of water, as follows.

4.4.3.2 For tests with vertical flow, assemble and connect the cell as described in **4.7.2**, except that the cell is filled with water instead of a soil sample and spacer blocks separate the two discs of porous material.

4.4.3.3 For tests with radial flow, assemble and connect up the cell as described in **4.7.3**, except that the cell is filled with fine uniform gravel and the central drainage well of fine sand is wrapped in mesh fine enough to retain the finest particles.

4.4.3.4 Apply a suitable seating pressure to the diaphragm.

4.4.3.5 Adjust the pressure in the inlet and outlet drain pressure systems p_1 (kPa) and p_2 (kPa) respectively to give a small difference, measured with a differential pressure gauge or manometer. Both pressures should be significantly less than the diaphragm pressure.

4.4.3.6 Open the appropriate inlet and outlet valves and start the timer. Record readings of the volume change gauges on both lines at regular intervals of time.

4.4.3.7 Plot a graph of the cumulative flow of water, Q (mL), as recorded from each volume change gauge, as ordinates, against time (in min) as abscissae. Continue until the relationship is linear and the two lines are parallel.

4.4.3.8 From the linear relationship between Q and time determine the slope, which gives the mean rate of flow, q (mL/min).

4.4.3.9 Repeat steps **4.4.3.5** to **4.4.3.8** at least three more times over a range of rates of flow, q, which covers the likely rates of flow to be encountered in a series of tests.

4.4.3.10 Plot the results as a graph of pressure difference, $(p_1 - p_2)$ (denoted by p_c) as ordinate, against rate of flow, q, as abscissa. This is the calibration graph referred to in **4.9.1.2** and **4.9.2.2**.

4.5 Preparation and checking of apparatus

Prepare and check the cell and ancillary items as described in **3.2.6**.

4.6 Preparation of test specimen

Prepare the test specimen by one of the methods described in **3.3**, as appropriate to the type of specimen and method of test.

4.7 Assembly of cell

4.7.1 *General.* Assemble the cell with specimen generally as described in **3.4.1**. The rigid loading plate is normally placed on top of the specimen to maintain a uniform thickness of soil. Detailed requirements for the two types of test are described in **4.7.2** to **4.7.4**.

4.7.2 *Test with vertical flow*

4.7.2.1 Assemble the cell as described in **3.4.3** (with reference to **3.4.2.2**). The top and bottom faces of the specimen are in contact with a porous disc.

4.7.2.2 Connect the inlet pressure line to the back pressure valve, and the outlet pressure line to the pore pressure valve, without entrapping air, in order to give flow vertically downwards through the specimen.

4.7.3 *Tests with radial flow*

4.7.3.1 Assemble the cell as described in **3.4.4** (with reference to **3.4.2.2.1** and **3.4.2.2.3**). The periphery of the specimen is in contact with the porous plastic material.

4.7.3.2 Install the central drain as described in **3.4.5.4** to **3.4.5.8**.

4.7.3.3 Place the rigid circular steel plate on top of the specimen and plug the central hole. Do not permit drainage from the top and bottom faces of the specimen.

4.7.3.4 For outwards flow of water, connect the inlet pressure line to the pore pressure valve and the outlet to the rim drain valve, without entrapping air.

4.7.3.5 For inward flow of water, reverse the above connections.

4.7.4 *Final assembly and adjustments*

4.7.4.1 Fit the cell cover to the cell body as described in **3.4.6**.

4.7.4.2 Make final adjustments and initial observations as described in **3.4.7.3** and **3.4.7.8**.

4.8 Test procedures

4.8.1 *Saturation.* Saturate the specimen by the procedure given in **3.5.2**. When applying an increment of diaphragm pressure to determine the value of the ratio $\delta u/\delta\sigma$, ensure that the pore pressure valve is closed.

4.8.2 *Consolidation*

4.8.2.1 Consolidate the specimen to achieve the desired effective stress, as described in **4.8.2.2** to **4.8.2.4**.

4.8.2.2 For a vertical flow test, follow the procedures of **3.6.3** and **3.6.4** Evaluate the results if necessary as in **3.6.7** and **3.6.8**.

4.8.2.3 For a radial flow test with outward flow, follow the procedures in **3.7.3** and **3.7.4**. Evaluate the results if necessary as in **3.7.7** and **3.7.8**.

4.8.2.4 For a radial flow test with inward flow follow the procedures in **3.8.3** and **3.8.4**. Evaluate the results if necessary as in **3.8.7** and **3.8.8**.

4.8.3 *Measurement of vertical permeability* (see form 6.G of Appendix A)

4.8.3.1 Carry out a permeability test with flow vertically downwards on the consolidated specimen as described in **4.8.3.2** to **4.8.3.10**.

4.8.3.2 With the pore pressure valve and the back pressure valve closed adjust the pressure in the outlet drain line connected to the pore pressure valve, p_2 (in kPa), to equate with the back pressure, p_1 (in kPa), already applied to the top of the specimen via the back pressure valve. Open the pore pressure valve. The rim drain valve remains closed.

4.8.3.3 Increase the pressure p_1 to a value such that the pressure difference $(p_1 - p_2)$ is equal to the desired pressure difference across the specimen for the permeability test (see note). The difference between the diaphragm pressure p_d (kPa) and p_1 should normally be not less than $(p_1 - p_2)$.

NOTE The pressure difference should be such as to produce a reasonable rate of flow through the specimen. A very high hydraulic gradient (i = 20 or more) may be necessary in clay soils to achieve any measurable flow. The gradient should be increased carefully, while observing the rate of flow, to avoid disturbance due to piping or internal erosion.

4.8.3.4 Record the readings of the volume-change indicators in the inlet and outlet pressure lines when they reach steady values.

4.8.3.5 Open the back pressure valve and start the timer. Record readings of both volume-change gauges at suitable regular intervals of time. The mean effective vertical stress σ_v (in kPa) for the test is given by the equation

$$\sigma_v = p_d - \frac{p_1 + p_2}{2}$$

4.8.3.6 Plot a graph of the cumulative volume of water flowing through the specimen, Q (in mL), as recorded from each volume change gauge, as ordinates, against time (in rain) as abscissa. Continue the test until the relationship is linear and the two lines are parallel.

4.8.3.7 Record the temperature in the vicinity of the consolidation cell to ± 0.5 °C.

4.8.3.8 Stop the test by closing the pore pressure valve and the back pressure valve.

4.8.3.9 If an additional test at a lower effective stress is required, repeat **4.8.3.2** to **4.8.3.8** with the values of p_1 and p_2 increased as appropriate.

4.8.3.10 If an additional test at a higher effective stress is required, consolidate the specimen as in **4.8.2**, using the appropriate pressures, and repeat **4.8.3.2** to **4.8.3.8**.

4.8.4 ***Measurement of horizontal permeability*** (see form 6.G of Appendix A)

4.8.4.1 Carry out a permeability test with horizontal flow radially outwards on the consolidated specimen as described in **4.8.4.2** to **4.8.4.10**. For flow radially inwards the procedure is similar but with the inlet and outlet connections interchanged.

4.8.4.2 The back pressure valve remains closed. With the pore pressure valve and the rim drain valve closed adjust the pressure in the outlet drain line connected to the pore pressure valve, p_2 (in kPa), to equate with the back pressure, p_1 (in kPa), already applied to the top of the specimen via the rim drain valve. Open the pore pressure valve.

4.8.4.3 Increase the pressure p_1 to a value such that the pressure difference $(p_1 - p_2)$ is equal to the desired pressure difference across the specimen for the permeability test (see note to **4.8.3.3**). The difference between the diaphragm pressure p_d (in kPa) and p_1 should normally be not less than $(p_1 - p_2)$.

4.8.4.4 Record the readings of the volume-change indicators in the inlet and outlet pressure lines when they reach steady values.

4.8.4.5 Open the rim drain valve and start the timer. Record readings of both volume-change indicators at suitable regular intervals of time. The mean effective vertical stress, σ_v (kPa), for the test is equal to $p_d - \frac{p_1 + p_2}{2}$

4.8.4.6 Plot a graph of the cumulative volume of water flowing through the specimen, Q (in mL), as recorded from each volume change indicator, as ordinates, against time (in min) as abscissae. Continue to test until the relationship is linear and the two lines are parallel.

4.8.4.7 Record the temperature in the vicinity of the consolidation cell to ± 0.5 °C.

4.8.4.8 Stop the test by closing the pore pressure valve and the rim drain valve.

4.8.4.9 If an additional test at a lower effective stress is required, repeat **4.8.4.2** to **4.8.4.8** with the values of p_1 and p_2 increased as appropriate.

4.8.4.10 If an additional test at a higher effective stress is required, consolidate the specimen as in **4.8.2**, using the appropriate pressures, and repeat **4.8.4.2** to **4.8.4.8**.

4.9 Calculations

4.9.1 ***Vertical permeability***

4.9.1.1 Calculate the circular area of cross section of the soil specimen, A (in mm^2).

4.9.1.2 From the graphs plotted in **4.8.3.6** or **4.8.4.6**, determine the mean slope of the linear portion, which is equal to the mean rate of flow, q (in mL/min), during steady flow conditions in the test.

4.9.1.3 From the calibration graph derived as in **4.4.3.9**, determine the pressure difference, p_c (in kPa), corresponding to the rate of flow q in the test.

4.9.1.4 Calculate the coefficient of permeability, k_v (in m/s), at 20 °C, from the equation

$$k_v = \frac{1.63\ q\ L}{A\{(p_1 - p_2) - p_c\}} \times R_t \times 10^{-4}$$

where

q is the mean rate of flow of water through the specimen (in mL/min);

L is the length of the specimen (in mm);

$(p_1 - p_2)$ is the difference between the pressures applied to the inlet and outlet pressure lines (in kPa);

p_c is the pressure loss in the system (in kPa) for the rate of flow q, obtained from the calibration graph;

R_t is the temperature correction factor for the viscosity of water, derived from Figure 7;

A is the cross section area of the specimen (in mm^2).

4.9.2 *Horizontal permeability*

4.9.2.1 From the graphs plotted in **4.8.3.6** determine the mean slope of the linear portion, which is equal to the mean rate of flow, q (in mL/min), during steady flow conditions in the test.

4.9.2.2 From the calibration graph derived as in **4.4.3.10**, determine the pressure difference, p_c (in kPa), corresponding to the rate of flow q in the test.

4.9.2.3 Calculate the coefficient of permeability in the horizontal direction, k_H (in m/s), at 20 °C from the equation

$$k_H = \frac{0.26q}{L\{(p_1 - p_2) - p_c\}} \log_e\left(\frac{D}{d}\right) \times R_t \times 10^{-4}$$

where

q is the mean rate of flow of water through the soil specimen (in mL/min);

L is the length of the specimen (in mm);

D is the diameter of the specimen (in mm);

d is the diameter to the central drain (in mm);

$(p_1 - p_2)$ is the difference between the pressures applied to the inlet and outlet pressure lines (in kPa);

p_c is the pressure loss in the system (in kPa) for the rate of flow q, obtained from the calibration graph;

R_t is the temperature correction factor for the viscosity of water, derived from Figure 7.

4.10 Reporting results

The test report shall affirm that the test was carried out in accordance with clause **4** of BS 1377-6:1990. It shall include the following, in addition to the relevant information listed in clause **9** of BS 1377-1:1990.

a) statement that the permeability was measured under constant head conditions in a hydraulic consolidation cell, with flow in the vertical direction, or in the horizontal direction (radially) and whether inward or outward, as appropriate;

b) dimensions of test specimen, and whether undisturbed or remoulded;

c) if remoulded, the method of preparation;

d) density, moisture content and dry density of the test specimen;

e) method of saturation;

f) value of the pore pressure ratio $\delta u/\delta\sigma$ achieved;

g) data from the consolidation stage or stages, if appropriate;

h) coefficient of vertical or horizontal permeability, k_v or k_H (m/s) as appropriate, at 20 °C, to two significant figures;

i) diameter of central drain, method of forming the well, and a description of the material used, if appropriate;

j) vertical stress applied to the specimen and the mean pore water pressure at which the permeability was measured;

k) pressure difference, or hydraulic gradient, across the specimen during the test.

5 Determination of isotropic consolidation properties using a triaxial cell

5.1 General

5.1.1 *Principle.* These procedures cover the determination of the magnitude and rate of consolidation of soil specimens when subjected to isotropic stress conditions in a triaxial cell. Test specimens are normally about 100 mm diameter and 100 mm high, but specimens of other dimensions from 38 mm diameter upwards may be used.

Values of m_{vi} and c_{vi} derived from this isotropic test are not the same as the values of m_v and c_v obtained from a one-dimensional test.

5.1.2 *Type of test.* In this test the soil specimen is subjected to increments of equal all-round confining pressure, i.e. $\sigma_1 = \sigma_2 = \sigma_3$. Each pressure increment is held constant until virtually all the excess pore pressure due to that increment has dissipated. During this process water drains out from one end of the specimen, and its volume is measured. At the same time the pore water pressure at the other (undrained) end is monitored. These measurements are used for the determination of the relationship between voids ratio and effective isotropic stress for three-dimensional consolidation, and for the calculation of volumetric coefficients of consolidation and compressibility.

The usual arrangement is for drainage to take place vertically upwards to the top face, while pore pressure is measured at the base.

5.1.3 *Test conditions.* The following test conditions shall be specified before starting a test:

a) size of test specimen;

b) drainage conditions;

c) whether void ratios are to be calculated and plotted;

d) sequence of effective pressure increments and decrements;

e) criterion for terminating each primary consolidation and swelling stage;

f) whether secondary compression characteristics are required.

The requirements of BS 1377-1, where appropriate, shall apply to the test methods described in this clause.

5.1.4 ***Environmental requirements and safety***

5.1.4.1 *Temperature.* These tests shall be carried out in a laboratory in which the temperature is maintained constant to within ± 2 °C, in accordance with **6.1** of BS 1377-1:1990. All apparatus shall be protected from direct sunlight, from local sources of heat and from draughts.

5.1.4.2 *Hazard warning*

NOTE Users of this equipment should be conversant with regulations for pressure vessels.

Triaxial cells and ancillary equipment shall not be used at pressures above their safe working pressures.

5.2 Apparatus

5.2.1 *Apparatus for preparation of specimens.* Apparatus required for the preparation of test specimens of various types is given in **8.2** of BS 1377-1:1990.

5.2.2 *The triaxial cell and accessories*

NOTE The main features of the apparatus are the same as for the triaxial test apparatus described in **3.2** and **3.3** of BS 1377-8:1990.

5.2.2.1 *Triaxial cell* of dimensions appropriate to the size of the test specimen, suitable for use with de-aerated water at internal working pressures required to perform the test. A gas shall not be used for pressurizing the cell.

NOTE De-aerated tap water as specified in **5.2** of BS 1377-1:1990 of this standard is normally used as the cell fluid. Distilled or de-ionized water should not be used because of their corrosive effects on certain types of seals.

The main features of the cell are shown diagrammatically in Figure 8 and are as follows.

a) *Cell top plate* of corrosion-resistant material fitted with an air bleed plug.

b) *Cylindrical cell body,* which shall be removable for inserting the specimen, and shall be adequately sealed to the top plate and base plate.

NOTE The cylinder should preferably be made of a transparent material, or fitted with viewing ports, so that the specimen can be observed during the test.

The cell shall not be used at pressures exceeding its design working pressure.

c) *Cell base* of corrosion-resistant rigid material, incorporating connection ports as shown in Figure 8. Each port shall be fitted with either a valve, or a blanking plug if it is not required for the test. The ports are connected as follows (the corresponding valve designations are indicated in brackets):

1) from the base pedestal to the pore pressure measuring device (the pore pressure valve);

2) from the top cap drainage line to the back pressure system (the back pressure valve);

3) from the cell chamber to the cell pressurizing system (the cell pressure valve);

4) a second connection from the base pedestal (the base drainage valve);

5) from the pore pressure measuring device mounting block to the flushing system (the flushing system valve).

The base pedestal shall have a plane horizontal circular surface of a diameter equal to that of the specimen. The cylindrical sides shall be smooth and free from scratches.

5.2.2.2 *Specimen top cap,* of light weight impermeable corrosion-resistant material. The cap shall be perforated by a drainage hole which can be connected to the back pressure inlet in the cell base by a length of flexible tubing of not more than 2.5 mm internal diameter. The tubing shall be impermeable to water and shall have an expansion coefficient due to internal pressure not exceeding 0.001 mL per metre length for every 1 kPa increase in pressure. The cylindrical surface of the cap shall be smooth and free from scratches.

Alternatively a cell normally used for triaxial compression tests, as described in **3.2** a) of BS 1377-8:1990, may be used provided that the piston is rigidly restrained against the upward force from the cell pressure.

5.2.2.3 *On-off valves.* Valves fitted to the cell base shall be capable of withstanding the maximum working pressure without leakage. They shall produce negligible volume displacement during operation.

NOTE Ball valves with PTFE seals have been found to comply with this requirement.

5.2.2.4 *Tubular membrane,* of high-density latex to enclose the specimen and provide protection against leakage from the cell fluid. The unstretched internal diameter shall not be less than 90 % of the specimen in diameter nor greater than the specimen diameter. The length shall be about 50 mm greater than the specimen length. The membrane thickness shall not exceed 1 % of the specimen diameter.

NOTE Membranes of natural latex rubber are generally used. For specimens up to 50 mm diameter a thickness of 0.2 mm is suitable. For larger specimens a greater thickness is used. Two or more membranes separated by silicone grease may be fitted where there is danger of puncturing by angular particles, or for tests of long duration.

An unused leak-free membrane shall be used for every test. The membrane shall be soaked in de-aerated water overnight before use.

5.2.2.5 *Four rubber O-rings,* for sealing the membrane on to the top cap and base pedestal. Two are required at each end. The O-rings shall be of an unstretched diameter of between 80 % and 90 % of the specimen diameter. They shall be free from flaws and necking when stretched.

5.2.2.6 *Membrane stretcher,* to suit the size of the specimen.

5.2.2.7 *O-ring stretcher,* to facilitate placing of O-rings on the base pedestal and top cap. To allow for the top drainage lead lead an openable cylindrical ring is required.

5.2.2.8 *Rigid porous disc for placing between the top end of the specimen and the top cap.* The diameter of the disc shall be the same as that of the specimen, and its surface shall be plane and smooth. Its permeability shall be substantially greater than that of the soil, and it shall withstand the maximum vertical pressure likely to be imposed.

NOTE Discs of porous ceramic, or sintered bronze, have been found to be satisfactory.

The disc shall be checked before each use to ensure that it is not clogged by soil particles. It shall be boiled for at least 10 min in distilled water before use and kept immersed in de-aerated water until required.

5.2.2.9 *Rigid porous disc at the base of the specimen.* Either a disc similar to that described in **5.2.2.8** may be placed between the bottom end of the specimen and the cell pedestal; or a porous disc of smaller diameter may be bonded into a central recess in the cell pedestal. It shall be checked and prepared as for **5.2.2.8**.

5.2.3 *Pressure systems and ancillary apparatus*

5.2.3.1 *Two independent systems for applying and maintaining the desired pressure* in the cell fluid and in the specimen drainage line (referred to as the cell pressure system and back pressure system respectively). They shall be capable of maintaining the pressure constant to within ± 0.5 %.

NOTE Pressure systems dependent on self-compensating mercury pots (see warning in **5.3.2** of BS 1377-1:1990), air pressure regulators, dead-weight pressure cells and oil pressure regulators have been successfully used. Their capacity to supply or take in water should be large enough to compensate for cell leakage and drainage to or from the specimen.

If air-water systems are used a diaphragm shall separate air from water.

5.2.3.2 *A calibrated pressure gauge,* for independent measurements of cell pressure and back pressure, complying with **4.2.1.7** of BS 1377-1:1990. Calibration data shall be clearly displayed. The gauge shall be permanently connected to the two pressure systems.

Alternatively, two independent calibrated gauges may be used, each permanently connected to its own pressure system.

5.2.3.3 *A calibrated pore water pressure measuring device,* consisting of an electric pressure transducer mounted in a de-airing block fitted with an air bleed plug. One side of the block shall be fitted to the pore pressure valve on the cell base and the other side to the flushing system valve (see Figure 8). The whole assembly when closed shall allow no movement of water into or out of the port leading to the cell base pedestal. The pore pressure assembly shall allow a negligible amount of water to move into or out of the specimen.

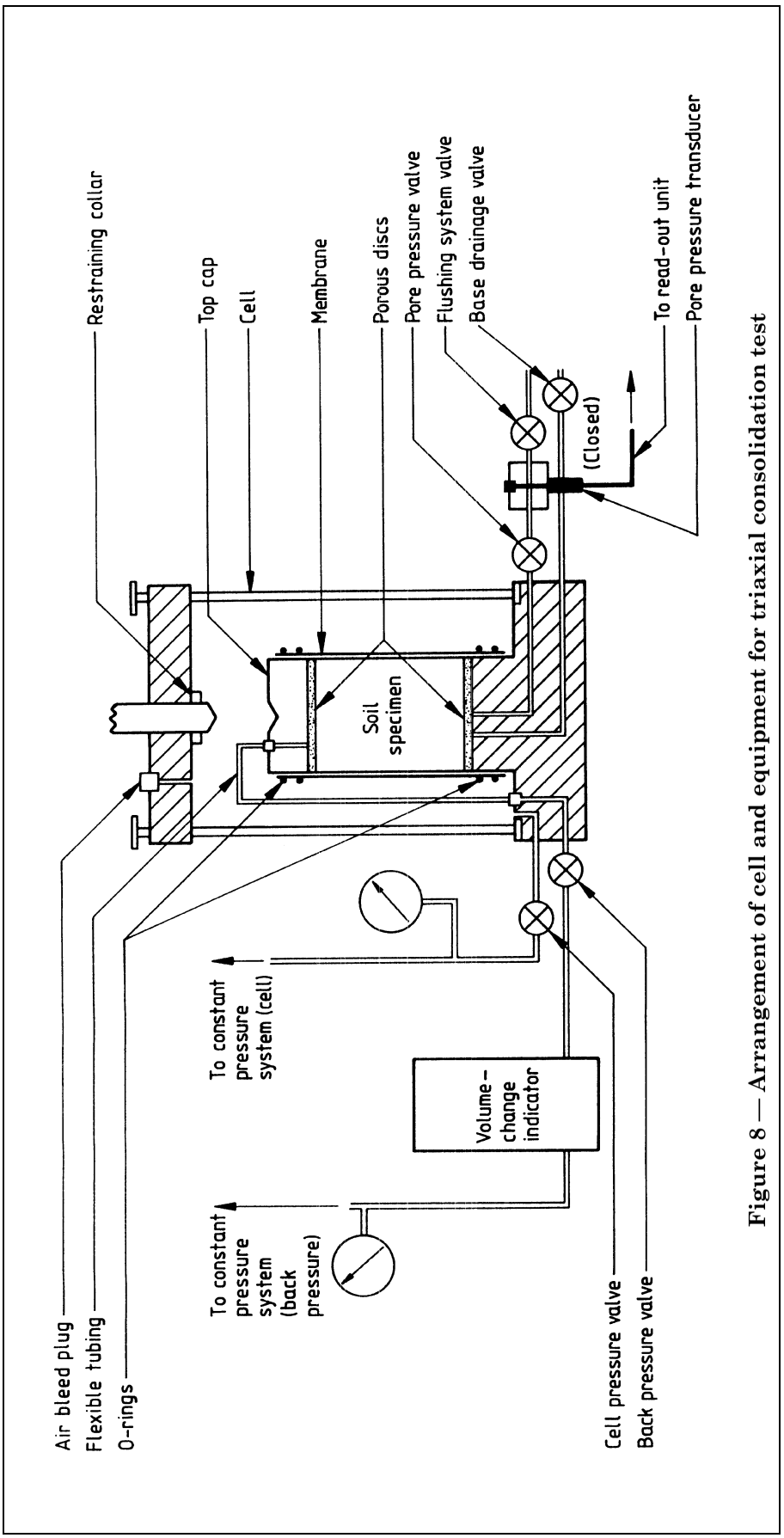


Figure 8 — Arrangement of cell and equipment for triaxial consolidation test

5.2.3.4 *A calibrated volume change indicator* (burette or transducer type) complying with **4.2.1.8** of BS 1377-1:1990, connected into the back pressure line.

NOTE A pressurized paraffin burette device is suitable if the scale markings can be read to the required degree of accuracy. A transducerized volume-change unit of appropriate range and sensitivity is convenient when an electronic readout or recording system is available.

In precise work, or where the differential pressure is small, account should be taken of pressure variations which occur due to movement of the interface between the water and the lower density paraffin in the burettes.

5.2.3.5 *Tubing* suitable for connecting the components of each pressure system to the cell. The expansion coefficient of the tubing due to internal pressure shall not exceed 0.001 mL per metre length for every 1 kPa increase in pressure.

5.2.3.6 *Timing device,* readable to 1 s.

5.2.3.7 *A supply of de-aerated tap water,* as specified in **5.2** of BS 1377-1:1990.

5.2.3.8 *Silicone grease or petroleum jelly.*

5.2.3.9 *A calibrated thermometer,* readable to 0.5 °C.

5.2.4 *Preparation and checking of apparatus*

5.2.4.1 *General*. Apparatus used for triaxial consolidation tests shall be subjected to rigorous inspection and check testing before use. The checks described in **5.2.4.2** to **5.2.4.6** shall be carried out on the cell pressure, back pressure and pore pressure systems at the stated frequency. Checks on these systems are of two kinds: complete checks and routine checks.

Complete checks (**5.2.4.2**, **5.2.4.3**, **5.2.4.5**) shall be carried out:

a) when any item of new equipment is introduced into a system;

b) if an integral part of a system has been removed, stripped down, overhauled or repaired;

c) at intervals not exceeding three months.

Routine checks (**5.2.4.4**, **5.2.4.6**) shall be carried out immediately before starting a test.

Before checking, the pressure systems and connecting lines shall be filled with freshly de-aerated water complying with **5.2** of BS 1377-1:1990.

NOTE A screw-type hand pump (control cylinder) may be used as an aid to flushing and checking the pressure systems.

The procedures described in **5.2.4.7** shall be carried out on porous materials immediately before each test.

5.2.4.2 *Cell pressure system (complete check).* A pressure test of the cell pressure system and the triaxial cell shall be made to ensure that the pressure required for a test can be maintained at all times during the test.

5.2.4.3 *Back pressure system (complete check)*

5.2.4.3.1 Flush freshly de-aerated water through the back pressure connecting line from the volume-change indicator and through the specimen drainage line (whether on the top cap or the base pedestal). In this operation work the indicator at least twice to its limits of travel, allowing water to pass out of the top cap or base pedestal and replacing it with freshly de-aerated water from the pressure system.

5.2.4.3.2 Seal the drainage line port with a watertight plug.

5.2.4.3.3 Pressurize the back pressure system to 750 kPa with the drainage line valve open, and record the volume change indicator reading when steady.

5.2.4.3.4 Leave the system pressurized for at least 12 h and record the volume change indicator reading again.

5.2.4.3.5 If the difference between the two readings, after deducting the volume change due to expansion of the tubing, does not exceed 0.1 mL the system can be considered to be leak free and ready for a test.

5.2.4.3.6 If the corrected difference exceeds 0.1 mL the leaks shall be investigated and rectified so that when **5.2.4.3.1** and **5.2.4.3.4** are repeated the requirement in **5.2.4.3.5** is achieved.

5.2.4.4 *Back pressure system (routine check)*

5.2.4.4.1 The following check can be carried out at the same time as the pore pressure system check given in **5.2.4.6**.

5.2.4.4.2 Flush the back pressure line and drainage connections as in **5.2.4.3.1**. Close the drainage line valve.

5.2.4.4.3 Increase the pressure in the back pressure system to 750 kPa, and record the volume change indicator reading after 5 min.

5.2.4.4.4 Proceed as in **5.2.4.3.4** to **5.2.4.3.6**.

5.2.4.5 *Pore pressure system (complete check)*

5.2.4.5.1 Open the valve between the transducer mounting block and the flushing system. Pass freshly de-aerated water through mounting block and cell base and out through the base pedestal port, to ensure that the entire system is filled with de-aerated water.

5.2.4.5.2 Place and secure the cell body on to the cell base, taking care not to pinch the drainage line to the top cap.

5.2.4.5.3 Open the air bleed on the cell top and fill the cell, via the transducer mounting block, with de-aerated water from the flushing system.

5.2.4.5.4 Remove the bleed plug in the transducer mounting block and close the pore pressure valve on the cell base.

5.2.4.5.5 Inject a solution of soft soap into the bleed plug hole. Open the pore pressure valve to allow water from the cell to flow out of that hole, then open the flushing system valve so that water also flows from the de-aerated supply.

5.2.4.5.6 Screw the bleed plug back into the transducer mounting block while water continues to emerge, and allow the cell to refill, then close the bleed plug on the cell.

5.2.4.5.7 Open the base pedestal drainage valve and allow about 500 mL of de-aerated water to pass through the pedestal to waste.

NOTE This is to ensure that any further air, or water containing air, in the transducer mounting block is removed.

5.2.4.5.8 Pressurize the system to 700 kPa and again allow about 500 mL of water to pass out of the base pedestal drainage valve.

5.2.4.5.9 Leave the system pressurized for at least 12 h.

5.2.4.5.10 After this period, check for leaks and if none are found allow about 500 mL of water to pass out of the base pedestal drainage valve.

NOTE A more positive means of detecting leaks than by visual observation is to connect the system to a sensitive volume change indicator.

If leaks are evident they shall be rectified and the above procedure repeated.

5.2.4.5.11 When checks confirm that the system is free of leaks, close the flushing system valve on the transducer mounting block. Drain water from the cell via the cell pressure valve, with the cell air bleed open after the pressure has been released.

5.2.4.5.12 Remove the cell body. Seal the pore pressure measurement port on the base pedestal with a watertight plug, without entrapping air.

5.2.4.5.13 Open the flushing system valve and apply the maximum pressure achievable (within the limitations of the pressure system and the pore pressure transducer) to the base pedestal.

5.2.4.5.14 Close the flushing system valve on the transducer mounting block and record the pore pressure reading.

5.2.4.5.15 If the pore pressure reading remains constant over a minimum 12 h period the pore pressure connections can be assumed to be air and leak free.

5.2.4.5.16 If there is a decrease in the pressure reading this indicates that there is a defect in the system, which shall be rectified. The complete pore pressure system check described above shall be repeated until the system is proved to be free of entrapped air and leaks.

5.2.4.6 *Pore pressure system (routine check)*

5.2.4.6.1 Follow the procedures described in **5.2.4.5.1** to **5.2.4.5.11**.

5.2.4.6.2 Remove the cell body. Keep the base pedestal covered with de-aerated water by fitting a cut-down membrane, secured with O-rings, until the test specimen is ready for setting up.

5.2.4.7 *Porous discs.* Inspect the porous discs to ensure that water drains freely through them. Discs that are clogged by soil particles shall be rejected.

NOTE Removal of soil particles from the pores of the disc can be aided by immersion in an ultrasonic water bath.

Before use, boil the discs for at least 30 min in distilled water. Then keep them under de-aerated water in a beaker until required.
Remove excess surface water immediately before placing, but ensure that the pores of the disc remain saturated.

5.3 Preparation and setting up of specimen

5.3.1 *Specimen preparation.* The specimen shall be prepared for test in accordance with one of the procedures given in clause **8** of BS 1377-1:1990.

The following measurements shall be made on the prepared test specimen with sufficient accuracy to enable the bulk density to be calculated to an accuracy of ± 1 %:

a) height (H_o) in mm;
b) diameter (D_o) in mm;
c) mass (m_o) in g.

(See form 6.H of Appendix A.)

5.3.2 ***Setting up the specimen***

5.3.2.1 The procedure for mounting the prepared specimen in the triaxial cell is described in **5.3.2.2** to **5.3.2.12**.

5.3.2.2 If a separate base porous disc is used, slide the saturated disc on to a layer of water on the triaxial base pedestal without entrapping air. Remove any surplus water standing on the disc, ensuring that the pores remain saturated.

Place the specimen on the disc without delay and without entrapping air.

5.3.2.3 If a base pedestal with a bonded-in porous disc is used, ensure that the porous disc is saturated without any free water standing above it. Place the specimen on the base, pedestal without delay and without entrapping air.

5.3.2.4 Place a saturated porous disc, with excess water removed, on top of the specimen.

5.3.2.5 Place the soaked rubber membrane, after allowing surplus water to drain off, around the specimen using the membrane stretcher. Seal the membrane to the base pedestal using two rubber O-rings.

NOTE A smear of silicone grease on the curved surfaces of the pedestal and top cap improves the seal. Grease should not be allowed to come into contact with the porous discs.

Remove the air pockets from between the membrane and the specimen by light stroking upwards. No further water shall be inserted between the specimen and the membrane.

5.3.2.6 Fit two O-rings around the drainage lead connected to the top loading cap.

5.3.2.7 Open the back pressure valve (Figure 8) momentarily to moisten the top cap and fit it on to the porous disc without entrapping air. Seal the membrane on to the top cap with the two O-rings, using the split-ring stretcher (see note to **5.3.2.5**).

5.3.2.8 Ensure that the specimen axis is in vertical alignment, and that the drainage line from the top cap will not interfere with fitting the cell body.

5.3.2.9 Assemble the cell body with the loading piston (if present) well clear of the specimen top cap.

5.3.2.10 Fill the triaxial cell with de-aerated water, ensuring that all the air is displaced through the bleed hole (Figure 8).

5.3.2.11 Keep the bleed plug open until the cell is to be pressurized, in order to maintain the pressure at atmospheric.

5.3.2.12 Apply the first cell pressure increment as soon as possible, as required by the saturation procedure (see **5.4**).

5.4 Saturation

5.4.1 *General.* The objective of the saturation stage is to ensure that all the voids are filled with water. This is often achieved by raising the pore water pressure in the specimen to a level high enough for the water to absorb into solution all the air originally in the voids.

The pore pressure can be increased either:

a) by applying water pressure (the back pressure) to the specimen, and at the same time increasing the cell pressure in order to maintain a small positive effective stress; or

b) by increasing the cell pressure only.

The degree of saturation is estimated by determining the ratio $\delta u/\delta\sigma$ (the pore pressure coefficient B), where δu is the incremental change in pore pressure resulting from an incremental change in cell pressure of $\delta\sigma_3$ when no drainage is allowed. The criterion $B = 0.95$ is usually accepted as an indication of sufficient saturation.

NOTE Values of B which can be expected when full saturation is reached or closely approached depend on the stiffness of a clay soil. In certain stiff fissured clays it may not be possible to obtain a ratio of 0.95, and a value of 0.90 which remains unchanged after three successive increments of cell pressure and back pressure, as described in **5.4.3.5** to **5.4.3.9** is then considered acceptable.

The saturation process has to take into account the two following conflicting conditions.

1) The applied effective stresses should not be so high as to excessively pre-stress or over-consolidate the specimen.

2) The effective stress should not fall below the level required to prevent swelling of soils that have a significant swelling potential (unless this property is to be investigated and steps are taken to make appropriate measurements).

In some instances, especially with specimens that are initially fully saturated, a saturation stage may not be necessary.

Two saturation procedures are described:

i) saturation by applying alternate increments of cell pressure and back pressure (see **5.4.3**);

NOTE This procedure may also be followed by increasing the cell pressure and back pressure simultaneously.

ii) saturation at constant moisture content (see **5.4.4**).

NOTE This procedure is necessary when swelling of the specimen would significantly affect measured pore pressure changes. The time required is appreciably longer than when a back pressure is used.

5.4.2 *Basic requirements* The following conditions apply to any saturation procedure except where stated otherwise.

a) Water applied to the specimen from the back pressure system shall be de-aerated in accordance with **5.2** of BS 1377-1:1990.

b) The magnitude of a cell pressure increment shall not exceed 50 kPa, or 50 % of the effective stress to which the specimen is to be consolidated in the first consolidation stage, unless otherwise specified.

NOTE 1 Cell pressure increments of 50 kPa until a B value of about 0.8 has been achieved, and 100 kPa thereafter, have been found to be suitable for many soil types, provided that the desired effective consolidation pressure is greater than 100 kPa.

c) The difference between the cell pressure and applied back pressure (the "differential pressure") shall be not greater than the effective stress referred to in **5.4.2** b) or 35 kPa, whichever is less, and shall not be less than 5 kPa.

NOTE 2 A differential pressure of 10 kPa has been found to be suitable for many soils for which swelling is not significant at this level of effective stress.

d) For a soil with swelling potential the differential pressure shall not normally be less than the effective stress considered necessary to prevent swelling, or 5 kPa, whichever is greater.

NOTE 3 When observing changes in pore pressure or volume, it may be convenient to plot the readings against time to verify when the steady state condition is reached.

NOTE 4 Back pressure can be applied to the specimen at the top end, or at both ends. For the latter the back pressure valve and the drainage valve are both connected to the back pressure system.

5.4.3 *Saturation by increments of cell pressure and back pressure*

5.4.3.1 In this method increments of cell pressure and back pressure are applied alternately. The cell pressure increment stages are carried out without allowing drainage into or out of the specimen, which enables values of the pore pressure coefficient B to be determined at each level of total stress.

The procedure is as described in **5.4.3.2** to **5.4.3.13**. (See form 6.J of Appendix A.)

5.4.3.2 Ensure that the back pressure valve and the flushing system valve (and the base drainage valve if fitted) (Figure 8) are closed. Apply the first increment of cell pressure immediately after setting up [see **5.4.2** b)].

5.4.3.3 Observe the pore water pressure until it reaches an equilibrium value, determined as indicated in Note 3 of **5.4.2**, and record it. If the pore pressure decreases appreciably (possibly after an initial increase) proceed to **5.4.3.4** without waiting for equilibrium, in order to ensure that the pore pressure does not reach zero.

5.4.3.4 Increase the cell pressure by 50 kPa and repeat **5.4.3.3**. If a steady value of pore pressure is reached record it, and calculate the change in pore pressure (δu kPa) resulting from this increment. Calculate the value of the pore pressure coefficient B from the equation

$$B = \frac{\delta u}{50}$$

If this is equal to or greater than 0.95 the specimen can be considered to be saturated and the consolidation stage (**5.5.2**) can be started. Otherwise proceed as follows.

5.4.3.5 Keeping the back pressure valve and the flushing system valve closed, increase the pressure in the back pressure line to a value equal to the cell pressure less the selected differential pressure. [**5.4.2** c) and **5.4.2** d).] (If the pore water pressure at this stage is greater than the intended back pressure a further increment, or increments, of cell pressure shall be applied until the corresponding back pressure exceeds the equilibrium pore water pressure, or until the B value equals or exceeds 0.95.)

Record the reading of the back pressure line volume-change indicator (v_1) when it reaches a steady value, to allow for expansion of connecting lines.

5.4.3.6 Open the back pressure valve (and the base drainage valve if pressurizing from both ends) to admit the back pressure into the specimen.

5.4.3.7 Observe the pore water pressure and the volume-change indicator readings. When the pore water pressure becomes equal to the applied back pressure (if pressurizing the top end only), and the volume-change indicator shows that movement of water into the specimen has virtually ceased, record these readings (u_2 and v_2 respectively) and close the back pressure valve (and the base drainage valve if appropriate). Monitor the pore pressure until equilibrium is established.

5.4.3.8 If required, calculate the volume of water taken in by the specimen during this increment from the difference between readings v_1 and v_2.

5.4.3.9 Increase the cell pressure by a further suitable increment, $\delta\sigma_3$. Observe the resulting change in pore pressure, δu, as in **5.4.3.3**. When equilibrium is established calculate the value of the pore pressure coefficient B from the equation

$$B = \frac{\delta u}{\delta \sigma_3}$$

5.4.3.10 Repeat the operations described in **5.4.3.5** to **5.4.3.9** until the pore pressure coefficient B indicates that saturation is achieved.

5.4.3.11 The specimen is considered to be saturated when the pore pressure remains stable after 12 h and the value of B is equal to or greater than 0.95 (see note to **5.4.1**).

5.4.3.12 If required calculate the total volume of water taken up by the specimen into the air voids by totalling the differences obtained from **5.4.3.8**.

5.4.3.13 A graph of B value against cell pressure at the end of each increment, or against pore pressure responses to cell pressure changes, may be plotted.

5.4.4 ***Saturation at constant moisture content***

5.4.4.1 No water is allowed to enter or leave the specimen during this procedure, in which saturation is achieved by raising only the cell pressure.

The procedure is as described in **5.4.4.2** to **5.4.4.5**.

5.4.4.2 Increase the cell pressure to a nominal level such as 50 kPa or 100 kPa.

5.4.4.3 Allow the pore pressure to reach equilibrium (see **5.4.3.7**).

5.4.4.4 Apply additional equal increments of cell pressure, record the resulting values of pore water pressure, as in **5.4.4.2** to **5.4.4.3** and calculate the corresponding B values.

5.4.4.5 The specimen is considered to be saturated when **5.4.3.11** is satisfied.

5.5 Procedure for triaxial consolidation with vertical drainage

5.5.1 *General.* A test normally comprises three or more stages of consolidation. Each stage of consolidation is carried out in two phases, an undrained phase and a drained phase. In the undrained phase the cell confining pressure is increased so that it exceeds the back pressure by an amount equal to the desired effective stress for consolidation causing the pore pressure to build up and eventually reach a steady value. In the drained phase this excess pore pressure is allowed to dissipate against the back pressure until the pressures virtually equalize. The volume of water draining out of the specimen during this process, and the pore water pressure, are recorded at suitable time intervals for obtaining the consolidation curves.

The effective stress from one stage to the next is usually increased by a factor of 2; for example a series of effective stresses
of 50, 100, 200, 400, etc. kPa would be suitable. It is usually convenient to maintain the back pressure at a constant value throughout the series. The back pressure should not normally be reduced below the level of pore pressure in the final step of the saturation stage, or 300 kPa, whichever is the greater.

5.5.2 ***Consolidation procedure***

5.5.2.1 After completion of the saturation stage keep the drainage valve closed and record the final pore pressure and volume-change indicator readings. The consolidation procedure is as described in **5.5.2.2** to **5.5.2.9**. (See form 6.K of Appendix A.)

5.5.2.2 Increase the pressure σ_c, in the cell pressure line with the cell pressure valve closed, and adjust the back pressure line, u_b, if necessary, to give a difference equal to the required effective consolidation pressure, σ_c^1, such that $\sigma_c^1 = \sigma_c - u$.

5.5.2.3 Open the cell pressure valve (Figure 8) to admit the pressure to the cell, and observe the pore pressure until a steady value (u_i) is reached. It may be convenient to record and plot readings of pore pressure against time to establish when equilibrium is reached.

The excess pore pressure to be dissipated is equal to $(u_i - u_b)$.

5.5.2.4 Record the reading of the volume-change indicator. At a convenient moment (zero time) start the consolidation stage by opening the back pressure valve.

5.5.2.5 Record readings of pore pressure and of the volume-change indicator at suitable intervals of time.

NOTE Suitable intervals for convenience of plotting the readings against log time are 0, ¼, ½, 1, 2, 4, 8, 15, 30, 60 min and for plotting square-root time are 0, ¼, ½, 1, 2¼, 4, 9, 12¼, 16, 25, 36, 64 min; in both cases followed by readings at 2, 4, 8, 16, 24 h.

5.5.2.6 Allow consolidation to continue until at least 95 % of the excess pore pressure has been dissipated, i.e. until

$$U \geqslant 95$$

in the equation

$$U = \frac{u_i - u}{u_i - u_b} \times 100$$

where u is the pore pressure reading at a given time t.

5.5.2.7 When consolidation is judged to be complete, record the reading of the volume-change indicator and calculate the total change in volume, ΔV_c, during the consolidation stage. Close the back pressure valve. Record the pore pressure u_f.

5.5.2.8 Repeat **5.5.2.2** to **5.5.2.7** for each subsequent effective consolidation pressure.

5.5.2.9 If the swelling characteristics of the specimen are required, reduce the cell confining pressure in a series of decrements and record readings of volume change and pore pressure for each stage in a similar manner to the consolidation **5.5.2.2** to **5.5.2.8**.

5.5.3 ***End of test procedure***

5.5.3.1 When the final consolidation or swelling stage is completed, remove the specimen from the triaxial cell pedestal as quickly as possible so that the absorption of water from the porous discs is kept to a minimum.

The sequence of operations is as described in **5.5.3.2** to **5.5.3.8**.

5.5.3.2 Ensure that the back pressure valve and the pore pressure line valve are closed (Figure 8).

5.5.3.3 Reduce the cell pressure to zero and drain the cell.

5.5.3.4 Dismantle the cell and remove the specimen.

5.5.3.5 Remove the top cap, rubber membrane and porous discs.

5.5.3.6 Measure the specimen to determine its mean diameter and height to an accuracy of 0.5 %.

5.5.3.7 Weigh the specimen to an accuracy of 0.1 % and calculate its final density.

5.5.3.8 Dry the whole specimen to constant mass, and determine its moisture content, using the procedure of **3.2** of BS 1377-2:1990. A large specimen should be broken up before placing in the oven.

5.6 Calculations, plotting and analysis

5.6.1 ***General initial data***

(See form 6.H of Appendix A.)

5.6.1.1 Calculate the initial moisture content, w_o (in %), from the equation

$$w_o = \frac{m_o - m_d}{md} \times 100$$

where

m_o is the initial mass of the specimen (in g);

m_d is the final dry mass of the specimen (in g).

5.6.1.2 Calculate the initial dry density, ρ_d (in Mg/m^3) from the equation

$$\rho_d = \frac{m_d \times 1000}{AH_o}$$

where

A is the cross-sectional area of the specimen (in mm^2);

H_o is the initial height of the specimen (in mm).

5.6.1.3 Calculate the initial bulk density, ρ (in Mg/m^3), from the equation

$$\rho = \frac{m_o \times 1000}{AH_o}$$

5.6.1.4 Calculate the initial voids ratio, e_o, if required, from the equation

$$e_o = \frac{\rho_s}{\rho_d} - 1$$

where

ρ_s is the particle density (in Mg/m^3).

5.6.1.5 Calculate the initial degree of saturation, S_o, if required, as a percentage from the equation

$$S_o = \frac{w_o}{e_o} \times \frac{\rho_s}{\rho_w}$$

where

ρ_w = 1.0 Mg/m^3.

5.6.2 ***Saturation data***

5.6.2.1 If saturation was achieved by the application of increments of back pressure, plot the calculated value of the pore pressure coefficient B (where $B = \delta u/\delta\sigma$) against pore pressure or cell pressure.

5.6.2.2 During the saturation stage, if it is assumed that water entering the specimen only replaces air in the voids there is no change in the volume or height or diameter of the specimen.

5.6.3 ***Consolidation data***

(See form 6.L of Appendix A.)

5.6.3.1 For each undrained phase calculate the value of the pore pressure coefficient B from the equation in **5.6.2.1**.

5.6.3.2 Plot the pore pressure at the end of each undrained phase and each drained phase against cell confining pressure.

5.6.3.3 For each drained phase plot:

a) change in volume (ΔV_c) against square-root time;

b) pore pressure dissipation (U) % against time to a logarithmic scale (see Figure 9).

5.6.3.4 From each graph given by **5.6.3.3** b) read off the time, t_{50} (minutes) corresponding to 50 % pore pressure dissipation.

5.6.3.5 Calculate the height of specimen H(in mm) at the end of each consolidation stage from the equation

$$H = H_o\left(1 - \frac{1}{3}\frac{\Delta V}{V_o}\right)$$

where

H_o is the initial height of the specimen immediately after saturation (assumed equal to the initial height) (in mm);

V_o is the initial volume of the specimen (in cm^3);

ΔV is the cumulative change in volume of the specimen from the start of the first consolidation stage (in cm^3).

5.6.3.6 Calculate the voids ratio, e, if required, at the end of each consolidation stage from the equation

$$e = e_o - (1 + e_o)\frac{\Delta V}{V_o}$$

5.6.3.7 Calculate the coefficient of volume compressibility for isotropic consolidation, m_{vi} (m^2/MN), for each stage from the equation

$$m_{vi} = \frac{\Delta V_2 - \Delta V_1}{V_o - \Delta V_1} \times \frac{1000}{p'_2 - p'_1}$$

where

ΔV_1 is the cumulative change in volume of the specimen from the initial volume up to the end of the previous consolidation stage (in cm^3);

ΔV_2 is the cumulative change in volume of the specimen from the initial volume up to the end of the consolidation stage considered (in cm^3);

V_o is the initial volume of the specimen (in cm^3);

p_1 is the effective pressure applied to the specimen for the previous consolidation stage (in kPa);

p_2 is the effective pressure applied to the specimen for the consolidation stage considered (in kPa).

5.6.3.8 Calculate the value of the coefficient of consolidation for isotropic consolidation, c_{vi} (in m^2/year), for each stage from the equation

$$c_{vi} = \frac{0.2\ \overline{H}^2}{t_{50}}$$

where

$\overline{H}$ is the average height of the specimen during the stage, i.e. $H = \frac{H_1 + H_2}{2}$ (in mm);

t_{50} is the value determined from the graph in **5.6.3.4** (in min);

H_1 is the height of the specimen at the beginning of the stage (i.e. at the end of the previous stage) (in mm);

H_2 is the height of the specimen at the end of the stage considered (in mm).

5.6.3.9 If appropriate apply a temperature correction to the calculated value of c_{vi}, as described in **3.5.8.5.5**.

5.6.3.10 Plot the calculated values of voids ratio, or change in volume, against effective pressure to a logarithmic scale (the e/log p' plot), including the initial voids ratio e_o, or initial volume, corresponding to the effective pressure immediately after saturation. (See form 6.N of Appendix A.)

5.7 Test report

The test report shall affirm that the test was carried out in accordance with clause **5** of BS 1377-6:1990. It shall include the following, in addition to the relevant information listed in clause **9** of BS 1377-1:1990 (form 6.M of Appendix A is suitable for summarizing most of the data):

a) statement of the method used, i.e. isotropic consolidation in a triaxial cell;

b) remarks on the condition and quality of the sample, and any difficulties experienced during specimen preparation;

c) initial dimensions of the specimen;

d) initial moisture content, bulk density and dry density;

e) particle density indicating whether measured or assumed;

f) initial voids ratio and degree of saturation, if required;

g) method used for saturating the specimen if applicable, including pressure increments and differential pressure applied;

h) volume of water taken into the specimen during saturation;

i) cell pressure, pore pressure and value of pore pressure coefficient B at the end of saturation;

j) tabulated data for each pressure stage comprising:

1) cell pressure;

2) back pressure;

3) effective stress at start and termination of each stage;

4) pore pressure increase and B value due to each undrained loading phase;

5) voids ratio, if required, and percentage pore pressure dissipation at the end of each consolidation phase;

6) volume change during each consolidation phase;

7) calculated values of the coefficient of volume compressibility, m_{vi} (in m^2/MN), and the coefficient of consolidation, c_{vi} (in m^2/year), to two significant figures, for isotropic consolidation;

k) plotted curves for each consolidation stage, comprising pore pressure dissipation (in %) against log time, volume change against log time or square-root time, or both;

l) curve of voids ratio or change in volume as ordinate against effective stress at the end of each consolidation or swelling stage, to a log scale, as abscissa;

m) final bulk density and overall moisture content of the specimen.

6 Determination of permeability in a triaxial cell

6.1 General

6.1.1 *Principle.* This method covers the measurement of the coefficient of permeability of a cylindrical specimen of soil in the triaxial apparatus under known conditions of effective stress, and under the application of a back pressure. The volume of water passing through the soil in a known time, and under a constant hydraulic gradient, is measured.

The method is suitable for soils of low and intermediate permeability.

6.1.2 *Test specimens.* Test specimens are normally about 100 mm diameter and 100 mm high, but specimens of other dimensions from 38 mm diameter upwards may be used.

NOTE A permeability test may also be carried out on a specimen set up for a triaxial compression test described in BS 1377-8. The test would normally be carried out after consolidation to the desired state of effective stress (see clause **6** of BS 1377-8:1990). After the permeability measurements, the pore pressure should be allowed to equalize throughout the specimen before proceeding with the compression stage.

6.1.3 *Test conditions.* The following test conditions shall be specified before starting the test:

a) size of test specimen;

b) direction of flow of water;

c) method of saturation;

d) effective stress at which each permeability measurement is to be carried out;

e) whether void ratios are to be calculated.

The requirements of BS 1377-1, where appropriate, shall apply to the test methods described in this clause.

6.1.4 *Environmental requirements and safety*

6.1.4.1 *Temperature.* These tests shall be carried out in a laboratory in which the temperature is maintained constant to within ± 2 °C, in compliance with **6.1** of BS 1377-1:1990. All apparatus shall be protected from direct sunlight, from local sources of heat and from draughts.

6.1.4.2 *Hazard warning*

NOTE Users of this equipment should be conversant with regulations for pressure vessels.

Triaxial cells and ancillary equipment shall not be used at pressures above their safe working pressures.

6.2 Apparatus for preparation of specimens

The apparatus required for the preparation of test specimens of various types is given in **8.2** of BS 1377-1:1990.

6.3 Apparatus for permeability test

NOTE The general arrangement of the test apparatus is shown in Figure 10.

6.3.1 *Triaxial cell,* similar to that specified in **5.2.2.1**. However for this test the base drainage valve and back pressure system are connected to the base pedestal, to provide a water outlet from the specimen.

6.3.2 Items as specified in **5.2.2.2** to **5.2.2.7**.

6.3.3 *Rigid porous disc,* similar to that specified in **5.2.2.7** for placing between the base pedestal and the bottom end of the specimen.

6.3.4 *Three independent systems,* as specified in **5.2.3.1**, for applying and maintaining the desired pressures in:

a) the cell fluid;

b) the drainage line to the top of the specimen;

c) the drainage line to the base of the specimen.

Items a), b) and c) are referred to as the cell pressure system, the top drain pressure system and the base drain pressure system respectively. The general arrangement is shown in Figure 10.

6.3.5 *A calibrated pressure gauge,* for independent calibrated measurement of the pressure in each pressure system, as specified in **5.2.3.2** except that the gauge shall be connected to the three pressure systems. Alternatively, independent calibrated gauges may be used, each connected to its own pressure system.

6.3.6 *A pore water pressure measuring device,* as specified in **5.2.3.3**.

6.3.7 *Two calibrated volume change indicators* (burette or transducer type), one on each of the drainage lines connected to the specimen, complying with **4.2.1.8** of BS 1377-1:1990.

NOTE 1 Use of two volume-change indicators is specified as a means of ensuring that the volume of water leaving the specimen is equal to that entering it. If it has been confirmed that the specimen is fully saturated, and that there are no leaks in the system, only one volume-change gauge, on the flow inlet line, need be used.

NOTE 2 A pressurized paraffin burette device is suitable if the scale markings can be read to the required degree of accuracy. In precise work, or where the differential pressure is small, account should be taken of pressure variations which occur due to movement of the interface between the water and the lower density paraffin in the burettes. A transducerized volume-change unit of appropriate range and sensitivity is convenient when an electronic readout or recording system is available.

6.3.8 *Timing device,* readable to 1 s.

6.3.9 *A plentiful supply of de-aerated tap water,* as specified in **5.2** of BS 1377-1:1990.

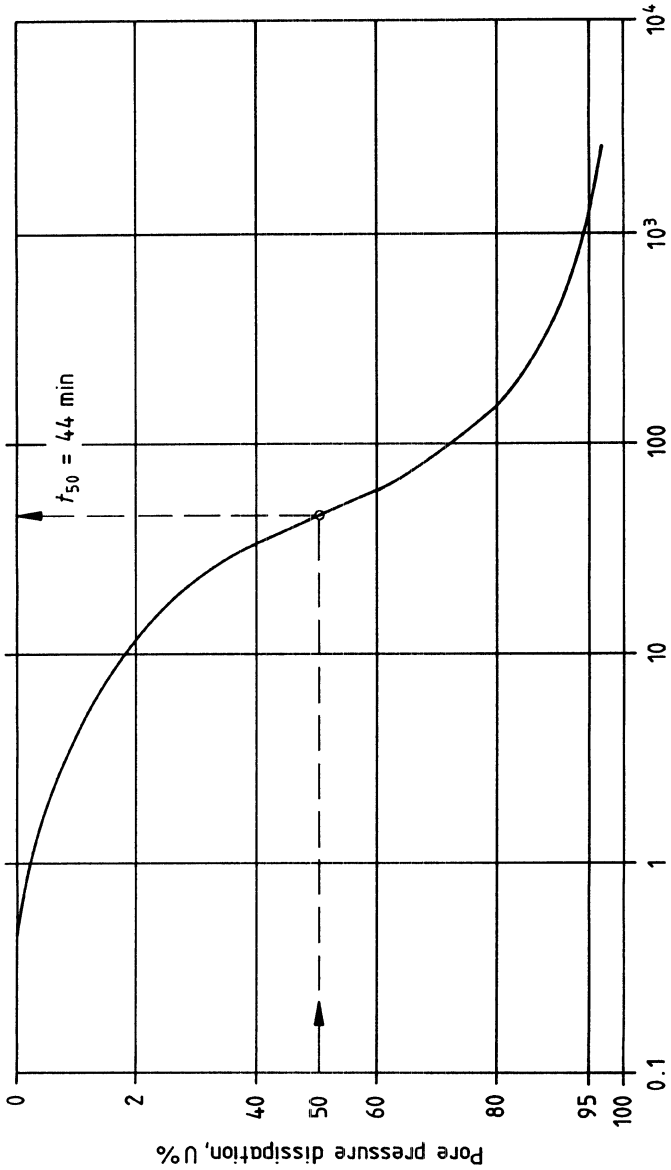


Figure 9 — Derivation of t_{50} from plot of pore pressure dissipation against log time

6.3.10 *Silicone grease or petroleum jelly*

6.3.11 *A calibrated thermometer,* readable to 0.5 °C.

6.4 Preparation and checking of apparatus

6.4.1 *General.* Prepare and check pressure systems as described in **5.2.4**. In addition, prepare and check the base drain pressure system in a manner similar to that for the top drain (back pressure) system (**5.2.4.3** and **5.2.4.4**). Keep the base pedestal covered with de-aerated water until ready for setting up the specimen.

6.4.2 *Porous discs.* Check and saturate the porous discs as in **5.2.4.7**.

6.4.3 *Calibration for head loss*

6.4.3.1 Prepare the apparatus as in **6.4.1** to **6.4.2**, ensuring that both drainage lines are free of air and leakage.

6.4.3.2 Place the two saturated discs, one on top of the other, on the cell base pedestal.

6.4.3.3 Enclose the discs in a rubber membrane and set up the apparatus as described in **6.5** except that no specimen is present. Increase the cell pressure to a suitable value. Close the back pressure valve and the base drainage valve (see Figure 10).

6.4.3.4 Adjust the pressure in the top and base drain pressure systems (p_1 (kPa) and p_2 (kPa) respectively) to give a small difference, measured with a differential pressure gauge or pressure transducer. Both pressures should be significantly less than the cell confining pressure.

6.4.3.5 Open the back pressure valve and the base drainage valve and start the timer. Record readings of both volume change gauges at regular intervals of time.

6.4.3.6 Plot a graph of the cumulative flow of water, Q(mL), as recorded from each volume change gauge, as ordinates, against times (in min) as abscissa. Continue until the relationship is approximately linear and the two lines are parallel.

6.4.3.7 From the relationship between cumulative flow and time determine the slope which gives the mean rate of flow, q (mL/min).

6.4.3.8 Repeat **6.4.3.4** to **6.4.3.7** at least three more times over a range of rates of flow, q, which covers the likely rates of flow to be encountered in a series of tests.

6.4.3.9 Plot the results as a graph of pressure difference, $(p_1 - p_2)$ (referred to as p_c) as ordinate against rate of flow, q, as abscissa. This is the calibration graph referred to in **6.9.3**.

6.5 Preparation and setting up of specimen

Prepare and set up the test specimen as described in **5.3**.

6.6 Saturation

Saturate the specimen by one of the procedures given in **5.4**.

6.7 Consolidation

Consolidate the specimen to achieve the desired effective stress using the procedure given in **5.5.2.2** to **5.5.2.7**.

6.8 Procedure for measurement of permeability

(See form 6.P of Appendix A.)

6.8.1 The test procedure for downward flow of water through the consolidated specimen is as described in **6.8.2** to **6.8.10**.

6.8.2 With the back pressure valve and the base drainage valve (Figure 10) closed, adjust the pressure in the base drain system, p_2 (in kPa), to equate with the back pressure, p_1 (in kPa), already applied to the top of the specimen. Open the base drainage valve.

6.8.3 Increase the pressure p_1 to a value such that the pressure difference $(p_1 - p_2)$ is equal to the desired pressure difference across the specimen for the permeability test.

NOTE 1 The pressure difference should be such as to produce a reasonable rate of flow through the specimen. A very high hydraulic gradient (i = 20 or more) is often necessary in clay soils to achieve any measurable flow. The gradient should be increased carefully, while observing the rate of flow, to avoid disturbance due to piping or erosion.

NOTE 2 The difference between the cell confining pressure σ_3 (in kPa) and p_1 should normally be not less than $(p_1 - p_2)$.

6.8.4 Record the readings of the top and base line volume-change indicators when they reach steady values.

6.8.5 Open the back pressure valve and start the timer. Record readings of both volume change indicators at suitable regular intervals of time. The mean effective stress σ'_3, (in kPa) for the test is equal to $\sigma_3 - \frac{p_1 + p_2}{2}$

NOTE If a greater hydraulic gradient is required at the same mean effective stress, increase p_1 and decrease p_2 by equal amounts. The pressure p_2 should not be reduced enough to allow air bubbles to come out of solution. Some time may be needed to re-establish equilibrium.

6.8.6 Plot a graph of the cumulative flow of water, Q (in mL), as recorded from each volume change indicator, as ordinates, against time (in min) as abscissae. Continue the test until the relationship is linear and the two lines are parallel.

6.8.7 Record the temperature in the vicinity of the triaxial cell to ± 0.5 °C.

6.8.8 Stop the test by closing the back pressure valve and the base drainage valve.

6.8.9 If an additional test at a lower effective stress is required, repeat **6.8.2** to **6.8.8** with the values of p_1 and p_2 increased as appropriate.

6.8.10 If an additional test at a higher effective stress is required, consolidate the specimen as in **6.7**, using the appropriate pressures, and repeat **6.8.2** to **6.8.8**.

6.9 Calculations

6.9.1 Calculate the circular area of cross section of the soil specimen, A (in mm^2).

6.9.2 From the graphs plotted in **6.8.6**, determine the mean slope of the linear portion, which is equal to the mean rate of mean rate of flow, q (in mL/min), during steady flow conditions in the test.

6.9.3 From the calibration graph derived as in **6.4.3.9**, determine the pressure difference, p_c (in kPa), corresponding to the rate of flow q in the test.

6.9.4 Calculate the coefficient of permeability in the vertical direction, k_v (in m/s), at 20 °C from the equation

$$k_v = \frac{1.63\ q\ L}{A\{(p_1 - p_2) - p_c\}} \times R_t \times 10^{-4}$$

where

q is the mean rate of flow of water through the soil specimen (in mL/min);

L is the length of the specimen (in mm);

$(p_1 - p_2)$ is the difference between the pressure applied to the top and base pressure lines (in kPa);

p_c is the pressure loss in the system (in kPa) for the rate of flow q, obtained from the calibration graph;

R_t is the temperature correction factor for the viscosity of water, derived from Figure 7.

6.10 Reporting results

The test report shall affirm that the test was carried out in accordance with clause **6** of BS 1377-6:1990. It shall contain the following, in addition to the relevant information listed in clause **9** of BS 1377-1:1990.

a) statement that the permeability was measured under constant head conditions in a triaxial cell;

b) dimensions of test specimen, and whether undisturbed or remoulded;

c) if remoulded, the method of preparation;

d) initial bulk density, moisture content and dry density of the test specimen;

e) method of saturation;

f) value of the pore pressure coefficient, B, achieved;

g) data from consolidation stage or stages, as detailed in **5.6.3**, if appropriate;

h) final bulk density and overall moisture content of the specimen;

i) coefficient of permeability, k_v (in m/s), at 20 °C, to two significant figures;

j) mean effective stress at which the permeability was measured;

k) pressure difference, or hydraulic gradient, across the specimen during the test.

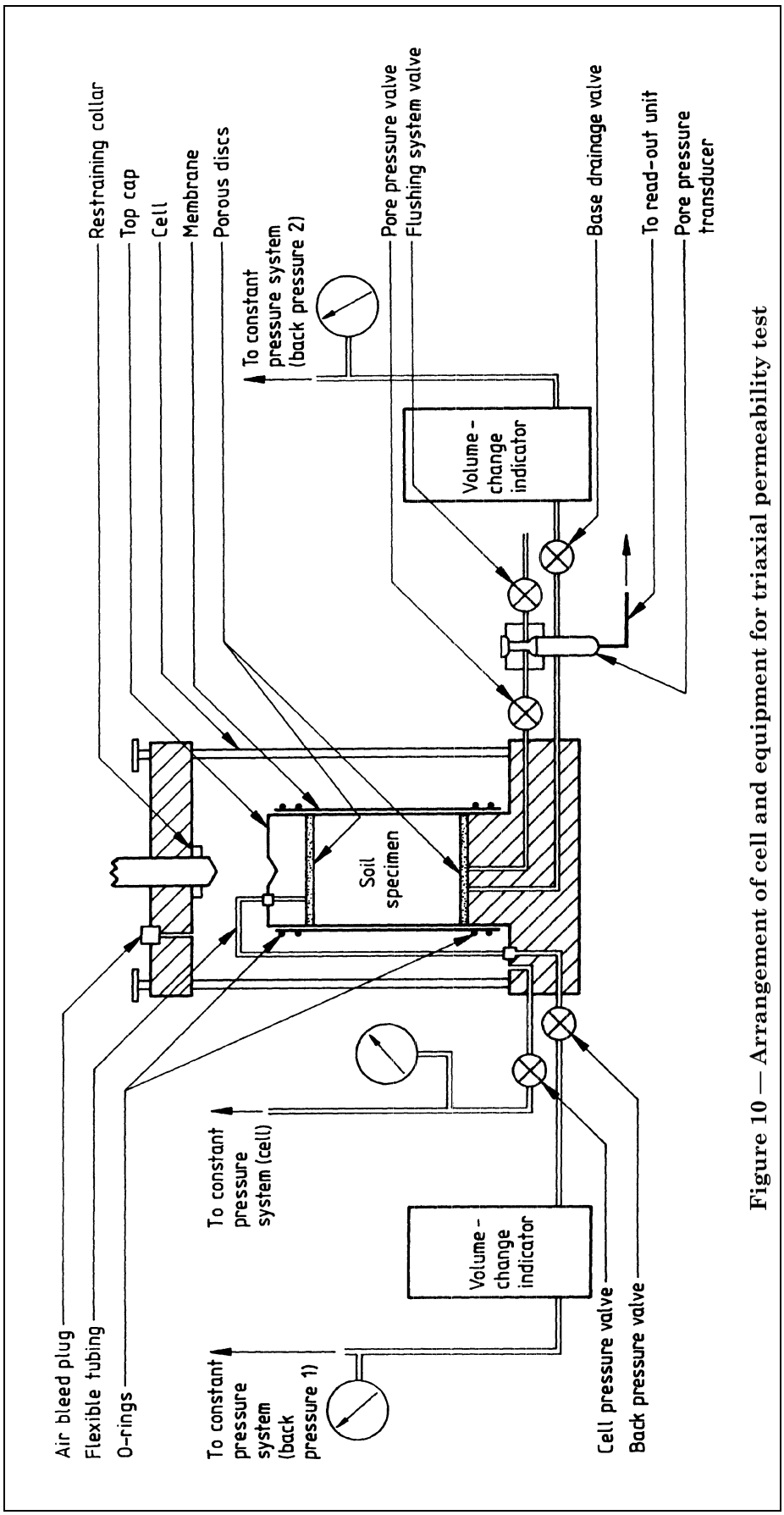


Figure 10 — Arrangement of cell and equipment for triaxial permeability test

Appendix A Typical test data and calculation forms

These test sheets are given as examples; other suitable forms may be used.

Form 6.A Hydraulic cell consolidation test: specimen data

Form 6.B Hydraulic cell consolidation test: saturation

Form 6.C Hydraulic cell consolidation test: consolidation readings

Form 6.D Hydraulic cell consolidation test: calculations

Form 6.E Hydraulic cell consolidation test: summary

Form 6.F Hydraulic cell consolidation test: log pressure/void ratio curve

Form 6.G Hydraulic cell permeability test

Form 6.H Triaxial cell consolidation: specimen data

Form 6.J Triaxial cell consolidation: saturation

Form 6.K Triaxial cell consolidation: consolidation readings

Form 6.L Triaxial cell consolidation: calculations

Form 6.M Triaxial cell consolidation: summary

Form 6.N Triaxial cell consolidation: log pressure/void ratio curve

Form 6.P Triaxial cell permeability test

Form 6.A. Hydraulic cell consolidation test: specimen data

Location		Job ref:	
		Borehole/ pit ref:	
Soil description		Sample no:	
		Depth	m
		Date	

Test method BS 1377 : Part 6 : 1990 : **3.5, 3.6, 3.7, 3.8***

Drainage conditions : Vertical – one way/two way*
Radial – outwards/inwards*

Loading conditions: Free strain/equal strain*

Pore pressure measurement location

Type of specimen undisturbed/compacted – dynamically/statically*

Preparation procedure

CELL DETAILS

Internal diameter	mm		Cell no.		
Thickness of peripheral drain*	mm		Mass of cell + baseplate	g	
Internal height	mm		Mass of peripheral drain*	g	
Thickness of top drainage disc*	mm		Mass of top discs	g	
Thickness of loading plate*	mm				

TEST SPECIMEN

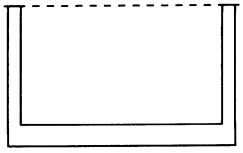
Diameter	D mm		Area	A mm^2		
Top of cell to specimen	mm		Volume	V_o cm^3		
Height of cell	mm		Mass	m_o g		
Initial specimen height H_0			Density	ρ Mg/m^3		
Compacted specimen *	Prepared soil	g		Moisture content	w_o %	
	Surplus soil	g		Dry density	ρ_o Mg/m^3	
	Mass of specimen	g		Particle density measured/assumed*	ρ_s Mg/m^3	
Initial degree of saturation S %			Initial void ratio	e_o		

WEIGHTINGS

		Initially			After test		
Reference		Specimen in cell			Specimen in cell		
Container no.							
Specimen + container	g						
Container	g						
Specimen	g	m_o			m_f		
Dry specimen + container	g						
Dry specimen	g						
Moisture	g						
Moisture content	%						
Average moisture content			w_o			w_f	

SPECIMEN AFTER TEST

Profile



Mean height	mm
Volume	cm^3
Mass	m_f g
Density	Mg/m^3
Moisture content	w_f %

Operator	Checked	Approved

*Delete as appropriate

Form 6.B. Hydraulic cell consolidation test: saturation

Location		Job ref:	
		Borehole/ pit ref:	
Soil description		Sample no:	
		Depth	m
		Date	
Test method BS 1377 : Part 6 : 1990 : **3.5, 3.6, 3.7, 3.8**			
Drainage conditions			
Pore pressure measurement location		Cell no.	
		Pressure system no.	

INITIAL CONDITIONS			
Diaphragm seating pressure p_{do} kPa		Compression gauge	
Pressure on specimen kPa		Back pressure kPa	
Pore pressure u_o kPa		Volume change indicator mL	
SWELLING PRESSURE*			
Diaphragm pressure to resist swell kPa			
Pressure on specimen kPa			
Back pressure kPa			
Effective swelling pressure kPa			

SATURATION

Diaphragm pressure	Pressure on specimen		Back pressure	Pore pressure			Volume change indicator		
	value	increment		reading	difference	$\frac{\delta u}{\delta \sigma}$	before	after	difference
p	σ	$\delta\sigma$		u	δu				
kPa	kPa	kPa	kPa	kPa	kPa		mL	mL	mL
								Total water taken up* mL	

	Operator	Checked	Approved

*Delete as appropriate

Form 6.C. Hydraulic cell consolidation test: consolidation readings

Location		Job ref:	
		Borehole/ pit ref:	
Soil description		Sample no:	
		Depth	m
		Date	
Test method BS 1377 : Part 6 : 1990 : **3.5, 3.6, 3.7, 3.8***			
Drainage conditions		Cell no.	
Pore pressure measurement location		Pressure System no.	
UNDRAINED LOADING		Stage no.	
Load increment/decrement*		Effective stress	kPa

	Initially	After pore pressure build-up		Pore pressure build-up	
				Time min	Pore pressure kPa
Diaphragm pressure kPa		p_d			
Stress on specimen kPa		σ			
Pore pressure kPa		u_i			
Effective stress kPa		σ'			
Compression gauge					
Effective stress after consolidation kPa					
Back pressure for consolidation kPa		u_b			
Excess pore pressure $(u_1 - u_b)$ kPa					
CONSOLIDATION	Average temperature °C				

Date	Clock time	Elapsed time	$\sqrt{t}$ or $t^{0.465}$*	Pore pressure			Compression gauge		Volume change	
				value	difference	dissipation	reading	difference	reading	difference
		t		u	$(u_i - u)$	U		ΔH		ΔV
		min		kPa	kPa	%		mm	mL	mL
		0	0		0	0		0		0

	Operator	Checked	Approved

*Delete as appropriate

Form 6.D. Hydraulic cell consolidation test: calculations

Location	Job ref:	
	Borehole/ pit ref:	
Soil description	Sample no:	
	Depth	m
	Date	

Test method BS 1377 : Part 6 : 1990 : **3.5, 3.6, 3.7, 3.8***

Drainage conditions	Pore pressure measurement location	Cell no.
Loading conditions		Pressure system no.

Specimen diameter D mm			m_v calculated from change in height/volume*	
Initial height H_o mm			c_v calculated from pore pressure dissipation log time plot * square-root time plot special power curve plot	Factor for coefficient of consolidation
Initial voids ratio e_o				

Stage no.	Effective stress kPa		Cumulative compression	Consolidated height	Cumulative volume change	Voids ratio change		Voids ratio	Incremental change		Coef-ficient	Time	Mean height	Coefficient
	value	increment				cumulative	increment		height	volume				
	σ'	$\delta\sigma'$	$\triangle H$	H	$\triangle V$	$\triangle e$	δe	e	δH	δV	m_v	t_{50}/t_{90}	$\overline{H}$	c_v
			mm	mm	cm^3				mm	mm^3	m^2/MN	min	mm	m^2/year

	Operator	Checked	Approved

*Delete as appropriate

Form 6.E. Hydraulic cell consolidation test: summary

Location	Job ref:	
	Borehole/ pit ref:	
Soil description	Sample no:	
	Depth	m
	Date	

Test method BS 1377 : Part 6 : 1990 : **3.5, 3.6, 3.7, 3.8**

Sample condition and quality	Nominal cell diameter mm
Type of specimen Undisturbed/Compacted – dynamic/static*	
Preparation procedure remarks	
Drainage conditions	
Type of loading	
Pore pressure measurement location	
Saturation procedure pressure increments kPa pressure differential kPa*	
Method of deriving c_v	

INITIAL SPECIMEN

Diameter mm		Particle density measured/assumed* Mg/m³	
Height mm		Voids ratio	
Density Mg/m³		Degree of saturation %	
Moisture content %			
Dry density Mg/m³			
In-situ stresses : Total kPa		Effective kPa	

SATURATION

Swelling pressure kPa		Final –	Diaphragm pressure kPa
			Pore pressure kPa
Volume of water taken in mL			Ratio $\frac{\delta u}{\delta \sigma}$

CONSOLIDATION STAGES

Stage no.	Diaphragm pressure kPa	Back pressure kPa	Final effective stress kPa	Undrained loading: height change mm	Undrained loading: pwp change kPa	End of consolidation: voids ratio	End of consolidation: dissipation %	m_v m²/MN	c_v* c_{ro}/c_{ri} m²/year

AFTER TEST

Density Mg/m³	
Moisture content %	

Local moisture contents %

Operator	Checked	Approved

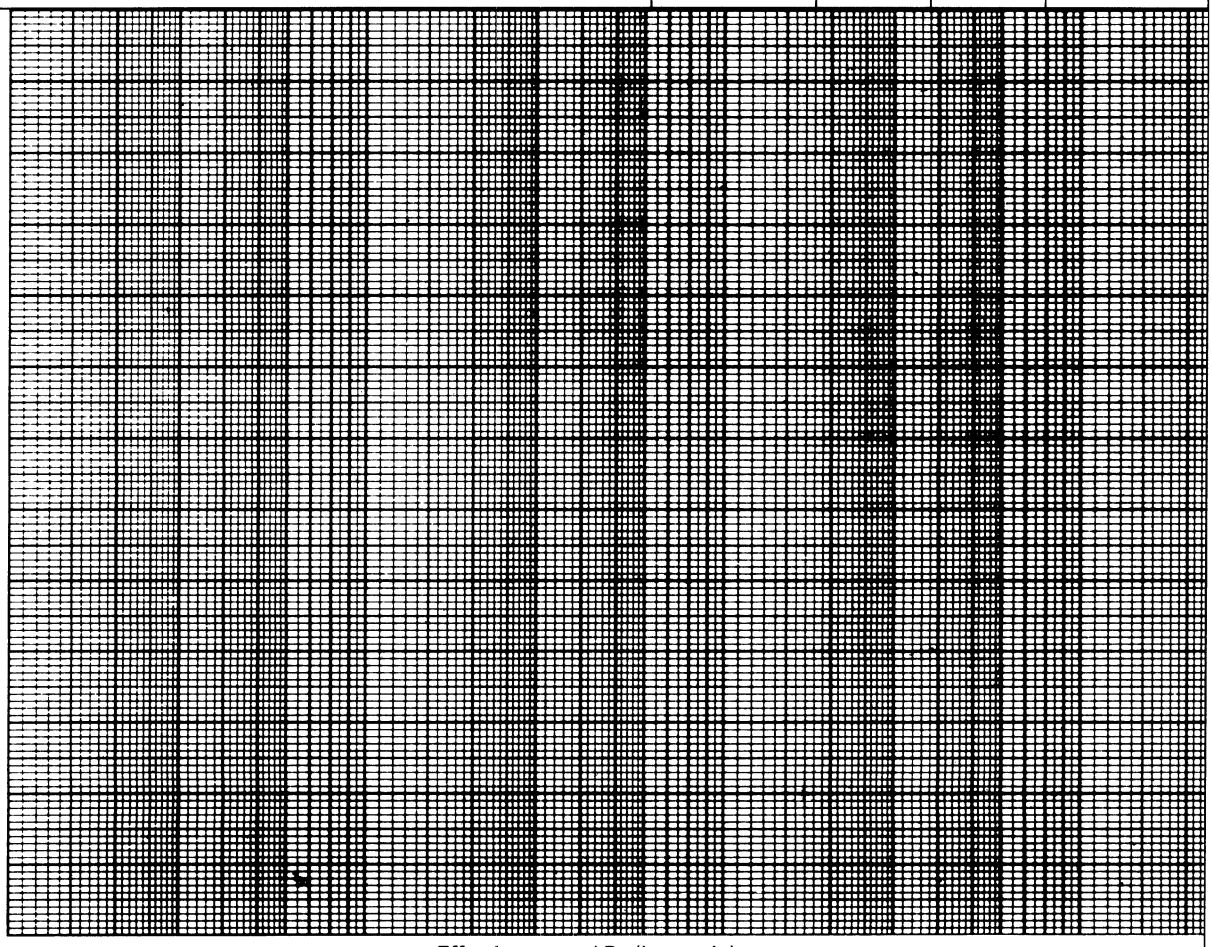
*Delete as appropriate

Form 6.F. Hydraulic cell consolidation test: log pressure/voids ratio curve

	Job ref:	
	Borehole/ pit ref:	
	Sample no:	
	Depth	m
	Date	

Test method BS 1377 : Part 6 : 1990: **3.5, 3.6, 3.7, 3.8***	Nominal diameter
Type of loading	
Sketch indicating drainage and pore pressure location	

INITIAL SPECIMEN				Effective stress kPa	Final voids ratio	m_v m²/MN	c_v* c_{ro}/c_{ri} m²/year
Diameter	mm	Density	Mg/m³				
Height	mm	Moisture content	%				
Voids ratio		Particle density measured/assumed*	Mg/m³				
Saturation	%						
Depth below surface			m				
Swelling pressure			kPa				
Remarks							



	Operator	Checked	Approved

* Delete as appropriate

Form 6.G. Hydraulic cell permeability test

Location		Job ref:	
		Borehole/ pit ref:	
Soil description		Sample no:	
		Depth	m
		Date	
Test method BS 1377 : Part 6 : 1990: **4.8.3, 4.8.4***			
Flow conditions*: Vertical – upwards/downwards. Horizontal -- inwards/outwards			

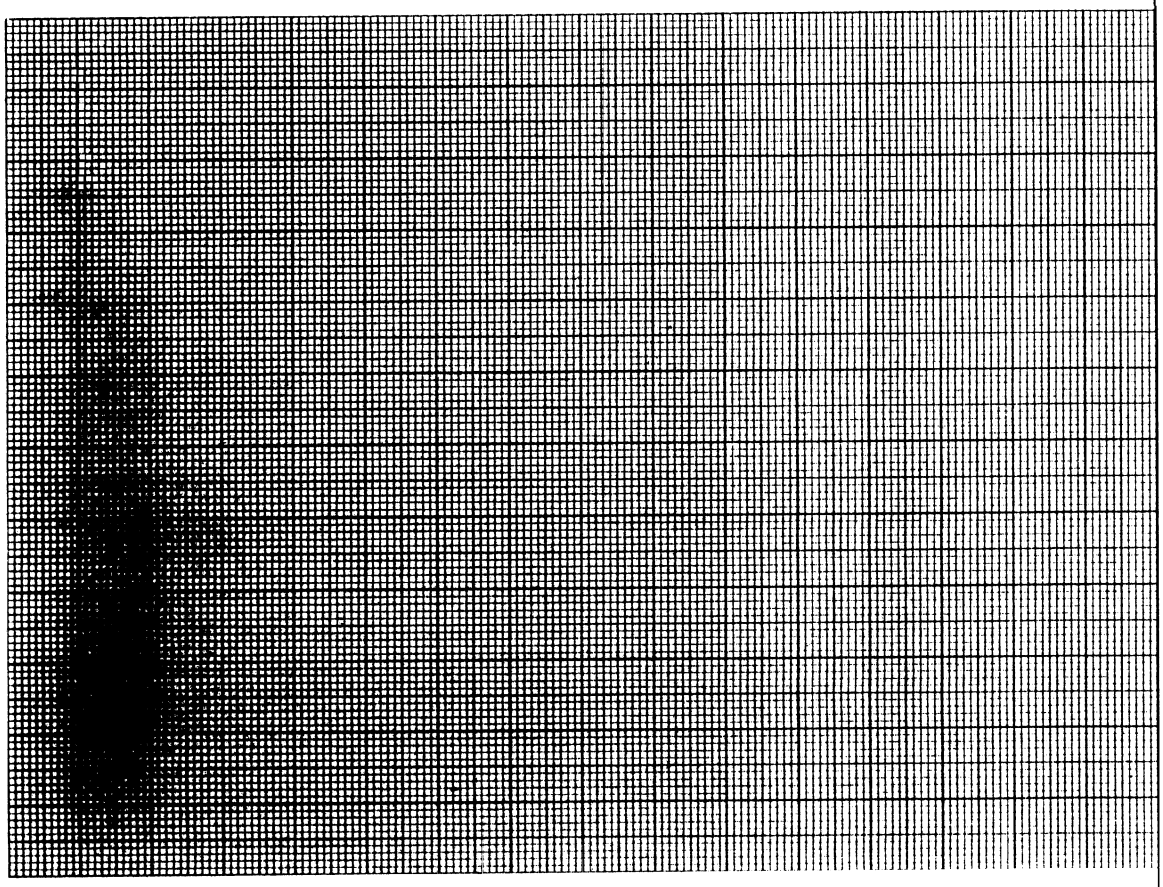
TEST SPECIMEN					
Diameter	D mm		Nominal effective stress	σ'_v kPa	
Area	A mm^2		Diaphragm pressure	p_d kPa	
Length	L mm		Pressure on specimen	σ kPa	
Density	ρ Mg/m^3		Back pressure	p_2 kPa	
Moisture content	%		Pressure difference required	$(p_1 - p_2)$ kPa	
Dry density	ρ Mg/m^3		Inlet pressure	p_1 kPa	
Method of saturation			Mean effective stress $\sigma' = \sigma - \frac{1}{2}(p_1 + p_2)$	kPa	
Final B value			Hydraulic gradient		

FLOW READINGS

Clock time	Elapsed time	Volume change indicators					
		inlet		outlet		Test temperature	°C
		reading	difference Q_1	reading	difference Q_2	Correction factor R_t	
	t min		mL		mL	Remarks	
	0		0		0		

Form 6.G. Hydraulic cell permeability test (*concluded*)

PLOT OF RATE OF FLOW



From graph, mean slope q = mL/min	
Corresponding pressure correction p_c = kPa	

CALCULATIONS

Vertical flow* $k_v = \frac{1.63\ q\ L\ R_t}{A((p_1 - p_2) - p_c)} \times 10^{-4}$ m/s

Horizontal flow* $k_H = \frac{0.26\ q\ R_t}{L((p_1 - p_2) - p_c)} \log_e \left(\frac{D}{d}\right) \times 10^{-4}$ m/s

	Accepted permeability m/s		
	Operator	Checked	Approved

* Delete as appropriate

Form 6.H. Triaxial cell consolidation: specimen data

Location		Job ref:	
		Borehole/ pit ref:	
Soil description		Sample no:	
		Depth	m
		Date	
Test method BS 1377 : Part 6 : 1990: **5**		Date	
Type of specimen undisturbed/compacted*		Nominal diameter	
Preparation procedure			
INITIAL SPECIMEN			
Length mm	Diameter mm		
		Mass m_o g	
		Moisture content w_o %	
		Dry mass m_d g	
		Area A_o mm^2	
		Volume V_o cm^3	
		Density ρ Mg/m^3	
mean L_o	D_o	Dry density ρ_d Mg/m^3	
		Particle density measured/assumed* ρ_s Mg/m^3	
Initial degree of saturation S_o %		Initial void ratio e_o	

WEIGHINGS

	Soil trimmings	Test specimen	
		initially	after test
Container no.			
Specimen + container g			
Container g			
Specimen g		m_o	m_f
Dry specimen + container g			
Dry specimen g		m_d	m_d
Moisture g			
Moisture content %		w_o	w_f

SKETCH OF SPECIMEN

	Operator	Checked	Approved

* Delete as appropriate

Form 6.J. Triaxial cell consolidation: saturation

Location	Job ref:	
	Borehole/ pit ref:	
Soil description	Sample no:	
	Depth	m
	Date	

Test method BS 1377 : Part 6 : 1990: **5.4.3/5.4.4***	Date	
Pressure system no.	Cell no.	Nominal diameter mm

Cell pressure kPa		Back pressure	Pore water pressure kPa		B value	Volume change indicator mL		
value	increment		reading	difference	$\frac{\delta u}{\delta \sigma_3}$	before	after	difference
σ_3	$\delta\sigma_3$	kPa	u	δu		V_1	V_2	

	Total water taken up *mL		
	Operator	Checked	Approved

* Delete as appropriate

Form 6.K. Triaxial cell consolidation: consolidation readings

Location				Job ref:	
				Borehole/ pit ref:	
Soil description				Sample no:	
				Depth	m
				Date	
Test method BS 1377 : Part 6 : 1990: **5.5.2**				Date	
Date started	Completed	Stage no.			
Pressure system no.	Cell no.	Nominal effective stress			kPa
Required effective stress	σ' kPa	PORE PRESSURE BUILD-UP			
Cell pressure	σ_c kPa	Time min	Pore pressure kPa		
Back pressure	u_b kPa				
Pore pressure after build-up	u_i kPa				
Excess pore pressure	$(u_i - u_b)$ kPa				
Initial diameter	D_o mm				
Length	L_o mm				
Area	A_o mm^2				
Volume	V_o mm^3				
Average test temperature	°C				

CONSOLIDATION DATA

Date	Clock time	Elapsed time t min	$\sqrt{t}$	Volume change indicator reading mL	Volume change indicator difference mL	Pore pressure reading u kPa	Pore pressure difference $(u_i - u)$ kPa	Dissipation U %
Final difference = ΔV = total consolidation volume change								

	Operator	Checked	Approved

Form 6.L. Triaxial cell consolidation: calculations

Location		Job ref:	
		Borehole/ pit ref:	
Soil description		Sample no:	
		Depth	m
		Date	
Test method BS 1377 : Part 6 : 1990: **5.5**			
Initial specimen diameter	D_o mm		Cell no.
height	H_o mm		Pressure system no.
volume	V_o cm^3		Test temperature °C
void ratio	e_o		

Stage no.		1	2	3	4
Effective stress applied	σ' kPa				
increment	$\delta\sigma'$ kPa				
B value (undrained stage)					
Volume change: cumulative	ΔV mL				
increment	δV mL				
$\frac{\Delta V}{V_o}$					
Height $H = H_o\left(1 - \frac{1}{3}\frac{\Delta V}{V_o}\right)$	mm				
Void ratio $e = e_o - (1 + e_o)\frac{\Delta V}{V_o}$					
Coeff. of vol. compressibility (m_{vi})	m^2/MN				
Time t_{50}	min				
Mean height	$\overline{H}$ mm				
Coeff. of consolidation c_{vi}	m^2/year				
Temperature correction factor					
Corrected coefficient	m^2/year				

$$m_{vi} = \frac{\delta V}{V_o - \Delta V} \times \frac{1000}{\delta\sigma'} \text{ m}^2/\text{MN}$$

$$c_{vi} = \frac{0.38\,\overline{H}^2}{t_{50}} \text{ m}^2/\text{year}$$

	Operator	Checked	Approved

Form 6.M. Triaxial cell consolidation: summary

Location	Job ref:	
	Borehole/ pit ref:	
Soil description	Sample no:	
	Depth	m
	Date	
Test method BS 1377 : Part 6 : 1990: 5 Isotropic consolidation in triaxial cell	Date	
Sample and condition and quality		
Type of specimen Undisturbed/compacted*		
Preparation procedure remarks		
Saturation procedure pressure increments kPa pressure differential kPa*		

INITIAL SPECIMEN			
Diameter mm		Particle density measured/assumed * Mg/m³	
Height mm			
Density Mg/m³		Voids ratio	
Moisture content %		Degree of saturation %	
Dry density Mg/m³			
In-situ stresses : total kPa effective kPa			

SATURATION				
Swelling pressure kPa		After saturation	Cell pressure kPa	
Volume of water taken in mL			Pore pressure kPa	
			B value	

CONSOLIDATION STAGES

Stage no.	Cell press. kPa	Back press. kPa	Effective stress start kPa	Effective stress end kPa	Undrained stage pwp incr. kPa	Undrained stage *B* Value	End of consol. *e*	End of consol. *U* %	Incr. vol. change δV cm³	m_{vl} m²/MN	c_{vl} m²/year

AFTER TEST	
Density Mg/m³	
Moisture content %	

	Operator	Checked	Approved

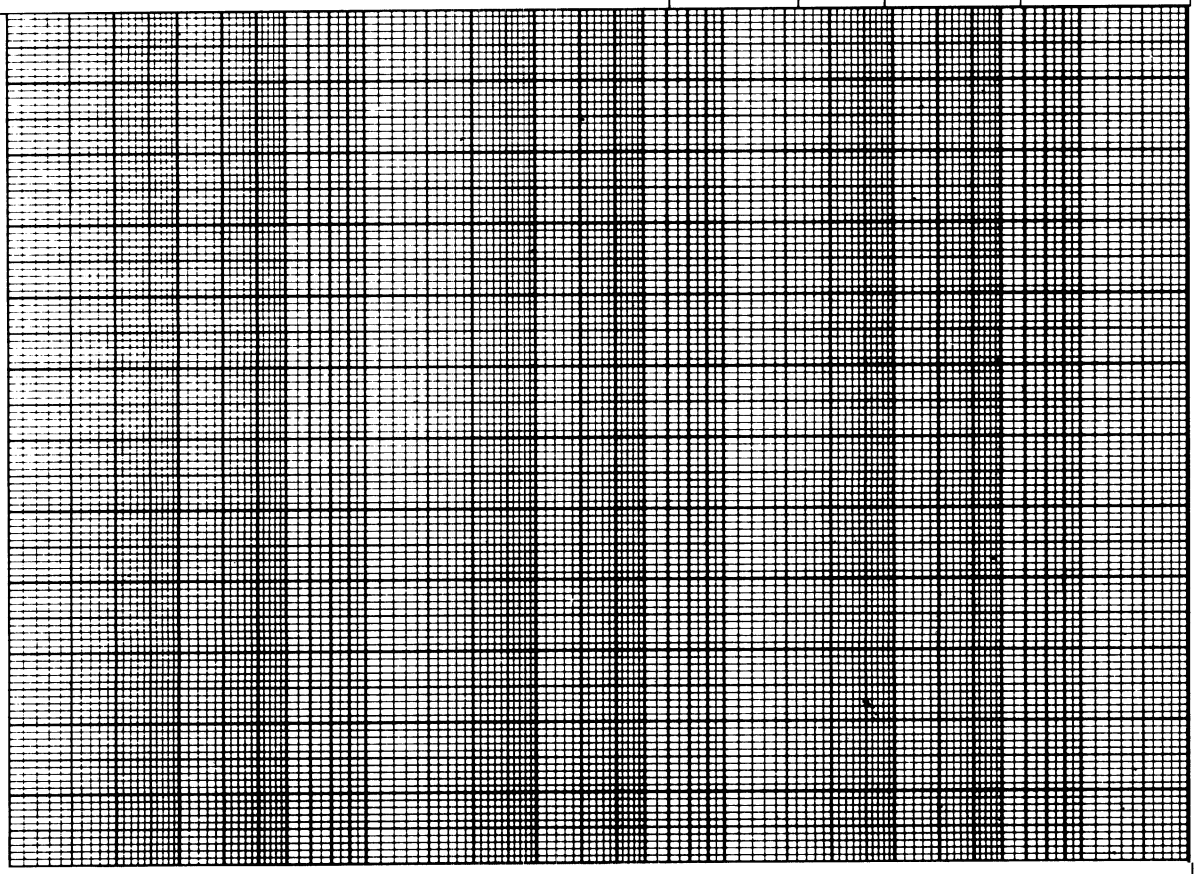
* Delete as appropriate

Form 6.N. Triaxial cell consolidation: log pressure/voids ratio curve

Location		Job ref:	
		Borehole/ pit ref:	
Soil description		Sample no:	
		Depth	m
		Date	
Test method BS 1377 : Part 6 : 1990: **5** Isotropic consolidation in triaxial cell		Nominal diameter	mm
Type of specimen			

INITIAL SPECIMEN

Diameter	mm		Density	Mg/m³		Effective stress kPa	Final voids ratio	m_{vi} m²/MN	c_{vi} m²/year
Height	mm		Moisture content	%					
Voids ratio									
Saturation	%		Particle density measured/assumed*	Mg/m³					
Depth below surface				m					
Swelling pressure				kPa					
Remarks									



	Operator	Checked	Approved

* Delete as appropriate

Form 6.P. Triaxial cell permeability test

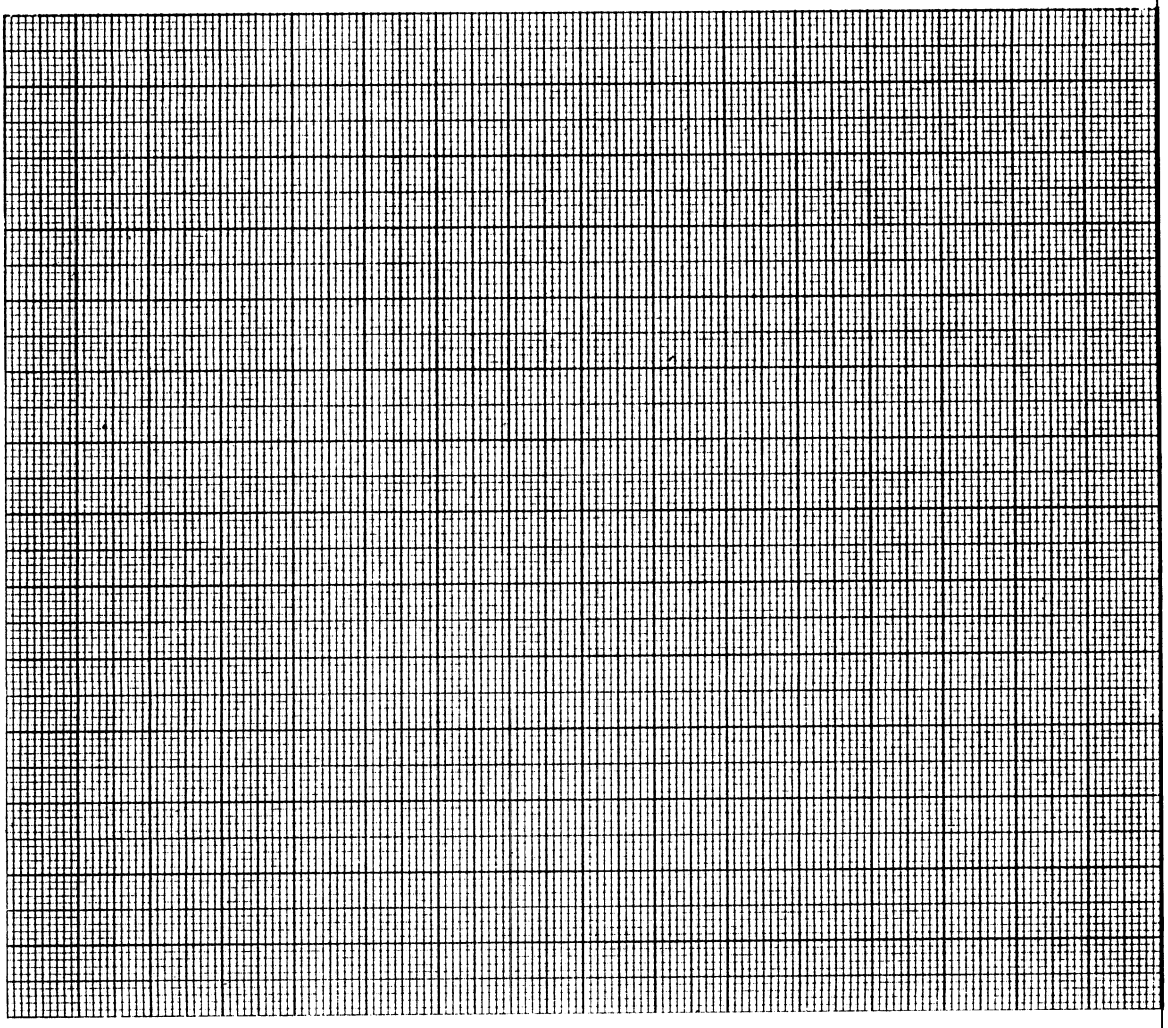
Location		Job ref:	
		Borehole/ pit ref:	
Soil description		Sample no:	
		Depth	m
		Date	
Test method BS 1377 : Part 6 : 1990: **6** Constant head permeability test in triaxial cell			
Type of specimen Undisturbed/compacted*			
Method of preparation			
Flow conditions Vertical upwards/downwards*			
TEST SPECIMEN			
Diameter D mm		Nominal effective stress kPa	
Area A mm^2		Cell pressure σ_3 kPa	
Length L mm		Back pressure p_2 kPa	
Density ρ Mg/m^3		Pressure difference $(p_1 - p_2)$ kPa	
Moisture content %		Inlet pressure p_1 kPa	
Dry density ρ_d Mg/m^3		Mean effective stress kPa $\sigma_3' = \sigma_3 - \frac{1}{2}(p_1 + p_2)$	
Method of saturation		Hydraulic gradient	
Final B value			

FLOW READINGS

Clock time	Elapsed time	Volume change indicators				Test temperature	°C
		inlet		outlet		Correction factor R_t	
		reading	difference	reading	difference		
	t min		Q_1 mL		Q_2 mL	Remarks	
	0		0		0		

Form 6.P. Triaxial cell permeability test (*concluded*)

PLOT OF RATE OF FLOW



From graph, mean slope q =	mL/min	
Corresponding pressure correction p_c =	kPa	

CALCULATIONS

Coefficient of permeability $k = \dfrac{1.63\ q\ L\ R_t}{A((p_1 - p_2) - p_c)} \times 10^{-4}$ m/s

SPECIMEN AFTER TEST

Density	Mg/m^3	
Moisture content	%	

Accepted permeability m/s

Operator	Checked	Approved

* Delete as appropriate

Publication referred to

BS 1377, *Methods of test for soils for civil engineering purposes.*
BS 1377-1, *General requirements and sample preparation.*
BS 1377-5, *Compressibility, permeability and durability tests.*

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