δP to maintain the K_0 condition according to the relationship

$$\delta P = -\frac{A}{1000}\left(\frac{1}{K_0} - 1\right)\delta u \tag{20.24}$$

The minus sign means that a decrease in pore pressure requires an increase in load, and vice versa.

OUTLINE PROCEDURE

The drainage line valve is initially closed and a suitable cell pressure is applied, together with an axial load calculated from Equation (20.22). Consolidation is carried out as described in Section 20.2.1, except that as the pore pressure u decreases the applied axial load must be increased by an amount calculated from Equation (20.24). The load should be adjusted at frequent intervals in order to maintain the effective stress ratio σ'_h/σ'_v, close to the desired value.

This type of test, with or without the lateral strain indicator, can be carried out more conveniently with the aid of an automatic feed-back control system, as outlined in Chapter 25.

20.4 MEASUREMENT OF PERMEABILITY

20.4.1 Triaxial Permeability Test with Two Back Pressure Systems

APPARATUS

One constant pressure system is connected to the base of the sample, one to the top, in addition to the system used for applying the cell confining pressure, as shown in Fig. 20.8. The cell pressure must always be greater than the other pressures.

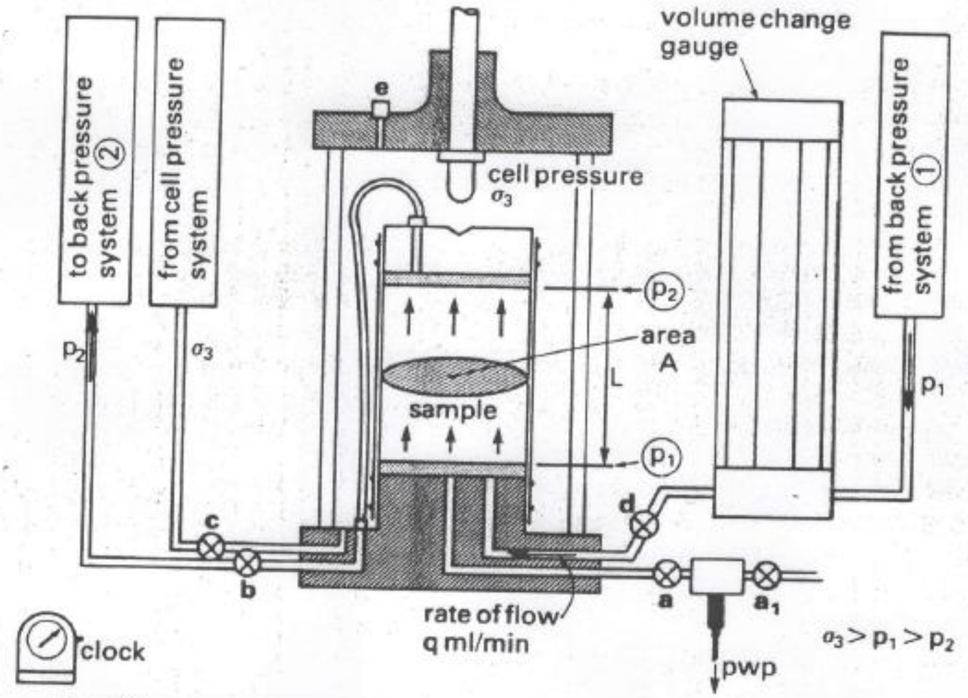


Fig. 20.8 Arrangement of apparatus for triaxial permeability test using two back pressure systems

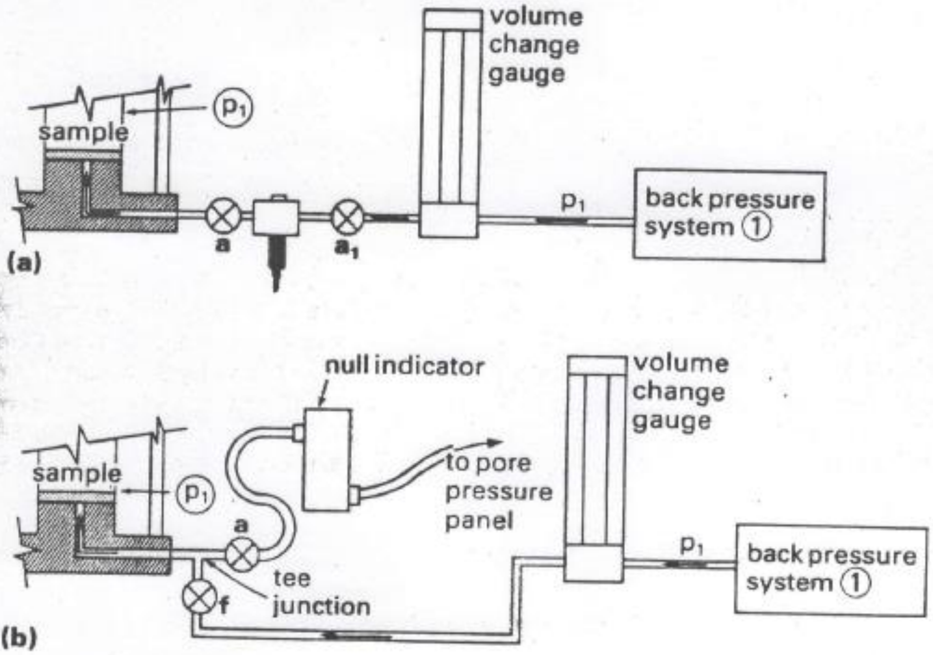


Fig. 20.9 Connections to triaxial cell with one outlet from base pedestal for permeability test: (a) using pore pressure transducer, (b) using manual null indicator

If the triaxial cell is fitted with two outlets from the base pedestal, one outlet is connected to the pore pressure system via valve a as usual, and the other is connected to one of the back pressure systems via valve d, as shown in Fig. 20.8. The port between valve d and the base pedestal should be flushed, de-aired and filled with de-aired water in the same way as the pore pressure connection.

If there is only one outlet from the base pedestal, and a pore pressure transducer is used, the additional pressure system is connected to valve a_1 as shown in Fig. 20.9 (a). If pore pressure is measured with a mercury null indicator on the only base pedestal outlet, a tee-junction on the cell enables the base pressure system to be connected as in Fig. (b) via valve f, and valve a remains closed after de-airing.

Wherever possible a volume-change gauge should be incorporated in both the inflow and the outflow pressure systems. When the rates of flow observed through the two gauges are practically equal, steady state flow conditions can be assumed. When only one volume-change gauge is available, it should be fitted in the pressure system connected to the sample inlet, so that water entering the gauge will be freshly de-aired water from the source of pressure. If fitted on the sample outlet line, any bubbles of gas remaining in the sample would find their way into the volume-change gauge, giving uncertain readings and necessitating tedious de-airing of the burettes afterwards.

If mercury-pot constant pressure systems are used, the volume of flow, if not too small, can be measured by means of a scale fitted to the pots (Bishop and Henkel (1962), Section III 5, Fig. 101).

PROCEDURE

(1) Flush and de-air the pore pressure and back pressure systems, and their connections to the sample, in the usual way, and then close all valves.

(2) Prepare and measure the sample, and set it up in the normal way between two saturated coarse porous discs.

(3) Saturate the sample by one of the methods given in Section 18.6.1 to ensure that virtually all the air in the voids is driven into solution.

(4) Consolidate the sample using top drainage only to the required effective stress until the pore pressure measured at the base equalises with the back pressure, or until outward drainage of water has ceased. Valve b (Fig. 20.8) is kept open.

(5) Adjust the pressure (p_1) in the base pressure system to a value somewhat greater than the back pressure (p_2) at the top of the sample, but less than the cell pressure σ_3. The pressure difference ($p_1 - p_2$) to be applied depends on the pressure required to give a reasonable rate of flow through the sample. A difference of 20 kPa, sometimes much more, may be needed to initiate any flow at all in a clay soil.

(6) Record the reading of the volume-change gauge on the back pressure line when it is steady.

(7) Open valve d (Fig. 20.8) or valve f (Fig. 20.9 (b)), or valve a_1 (Fig. 20.9 (a)) to admit the pressure to the base of the sample. When a steady condition is achieved the average effective stress in the sample is approximately equal to $\sigma_3 - \frac{1}{2}(p_1 + p_2)$. If a larger differential pressure is desired, p_2 can be reduced (but not enough to allow air bubbles to form) and p_1 increased by the same amount to maintain the same average effective stress. Some time may be needed for equilibrium to be established.

(8) When the rate of flow appears to be steady, read the volume-change gauge and start the timer. Record the reading of the volume-change gauge at half-minute intervals, or at regular intervals appropriate to the rate of flow.

(9) If the volume-change gauge reading nears the end of its travel so that the direction of flow in the burettes must be reversed, this should be done by quickly operating the reversing valve or valves at the same instant as the burette reading is observed and recorded. This reading provides the new datum for subsequent readings, to which the cumulative flow up to the time of reversal must be added.

If the flow is interrupted by closing either or both of the inlet and outlet valves b, d, a, or f, some re-distribution of pore pressure within the sample may take place and the steady state condition may not be resumed until some time after re-starting the flow.

CALCULATIONS

(10) Calculate the cumulative flow Q ml up to the time of each reading, and plot a graph of Q against time t minutes, as the test proceeds. Continue the test until it can be seen that a steady rate of flow is reached, i.e. the graph is linear.

(11) From the linear part of the graph measure the slope to calculate the rate of flow q ml/minute; i.e. $q = \delta Q/\delta t$ ml/minute.

A typical graph and flow rate calculation are shown in Fig. 20.10.

(12) If the rate of flow is relatively small, the effect of head losses in the pipelines and connections can be neglected and the pressure difference across a sample is equal to ($p_1 - p_2$). But if the head loss calibration (described in Chapter 17, Section 17.4.6) indicates that pipeline losses are a significant portion of the pressure difference, these losses must be deducted from the measured pressure difference. The total pipeline loss p_c observed during the test is read off from the calibration (of the type shown in Fig. 17.21 (b)), and Δp is equal to $(p_1 - p_2) - p_c$.

(13) The permeability k (m/s) of the sample is calculated by using the equation in Section 10.3.2 of Volume 2:

$$k = \frac{q}{60Ai} \quad \text{m/s} \tag{10.5}$$

where A is the area of cross section of sample (mm^2), i is the hydraulic gradient across the sample and q is the rate of flow (ml/minute).

A pressure difference of 1 kPa is equivalent to a head of water of 1/9.81 metres, i.e. 101.97 mm.

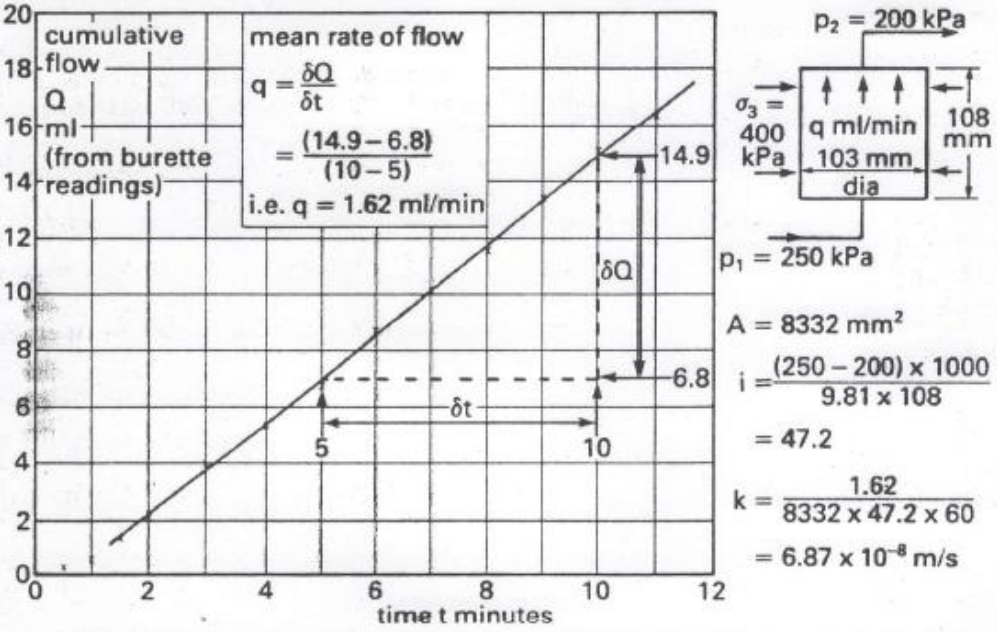


Fig. 20.10 *Graphical data from triaxial permeability test, with calculations of rate of flow, hydraulic gradient and permeability*

The mean hydraulic gradient is the difference in head per unit length, i.e.

$$i = \frac{102}{L} \times \Delta p$$

where L is the length of the sample (mm). Substituting in Equation (10.5),

$$k = \frac{qL}{60A \times 102\,\Delta p} \tag{20.25}$$

If the length L of the sample is about 100 mm, for any diameter, $i = \Delta p$ approximately, i.e. the mean hydraulic gradient is numerically about equal to the pressure difference in kPa. Equation (10.5) then becomes

$$k = \frac{q}{60A\,\Delta p} \tag{20.26}$$

For a sample 100 mm long and 100 mm diameter,

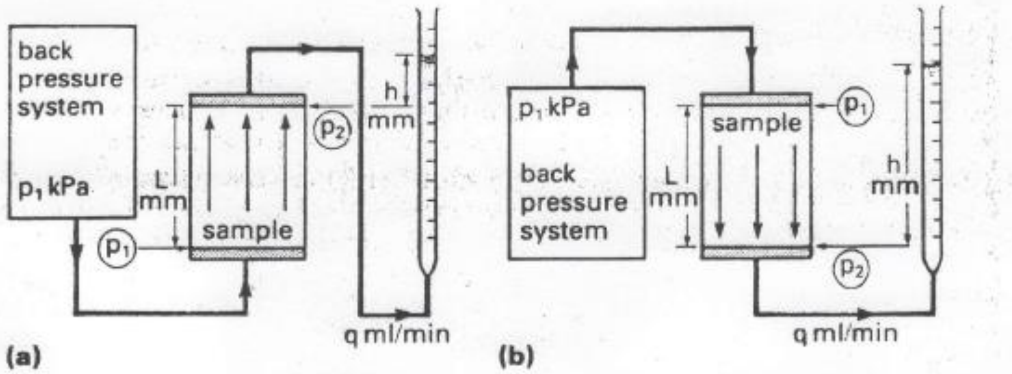
$$k = \frac{q}{60 \times 7854 \times \Delta p} = \frac{2.08q}{\Delta p} \times 10^{-6}\ \text{m/s} \tag{20.27}$$

The derived permeability relates to the mean effective stress in the sample at which the test was carried out. This should be reported with the results, together with the hydraulic gradient applied.

20.4.2 Triaxial Permeability Test with One Back Pressure System

APPARATUS

Permeability can be measured with only one constant pressure system connected to the sample (in addition to the system providing cell pressure) if the outlet from the sample is connected to



In (a) and (b), $p_2 = \frac{9.81\,h}{1000}$ kPa and $i = \frac{102\,p_1 - h}{L}$

Fig. 20.11 Arrangement for triaxial permeability test using one back pressure system: (a) upward flow, (b) downward flow

an open burette as shown in Fig. 20.11. If the permeability is high enough to permit displacement of air from the voids in the sample by upward movement of water, the back pressure system should be connected to the base, allowing drainage from the top (Fig. 20.11 (a)). If saturation is first achieved by application of back pressure increments, the direction of flow is immaterial and the burette can be connected either to valve f in Fig. 20.9 (b); or to valve a_1 in Fig. 20.9 (a) after disconnecting the pore pressure panel or null indicator. Flow is then downwards as indicated in Fig. 20.11 (b). The outlet pressure can be raised slightly above atmospheric by elevating the burette so that the water level is higher than the exit point from the sample. For every metre increase in height the pressure is increased by 9.81 kPa.

When hydraulic gradients exceeding unity are to be applied, upward flow can lead to instability and piping especially in non-cohesive soils. Downward flow gives stable conditions and is generally to be preferred.

Bubbles of air or gas are likely to emerge from the sample at these low pressures. If the bubbles are allowed to emerge through the burette the water level readings would be affected. Air can be removed by fitting an air trap, filled with water initially, as indicated in Fig. 19.8. Tubing leading to it should slope upwards so as not to form another air trap. The burette readings then measure the total volume (air + water) emerging from the sample, and this should be equal to the volume of water entering.

PROCEDURE

(1) *Small rate of flow*

If the rate of flow is small, the test is carried out in a manner similar to that described in Section 20.4.1, except that flow measurements are obtained by reading the burette. A volume-change gauge could be used on the inlet pressure line for comparison, if desired. The condition of constant head is applicable if the burette is progressively lowered so that the water it contains is maintained constant at the initial level. The length of connecting tube should be long enough to allow for this movement.

Notation is the same as that used in Section 20.4.1. The hydraulic gradient i across the sample (without allowing for pipeline losses) is given by the equation

$$i = \frac{102p_1 - h}{L} \tag{20.28}$$

If the pressure head due to the height of water in the burette is small (say less than 5% of p_1), Equation (20.28) approximates to

$$i = \frac{102p_1}{L}$$

The rate of flow q ml/minute is obtained from a graph of burette readings over a period of time, as described in Section 20.4.1. The coefficient of permeability k m/s is calculated from Equation (20.25) if the above approximate is valid.,

i.e.

$$k = \frac{qL}{60A \times 102p_1} = \frac{qL}{6120Ap_1} \qquad (20.29)$$

(2) *Large rate of flow*

If the rate of flow is relatively large, such that during the test period the total flow exceeds the capacity of the burette, an overflow arrangement similar to that shown in Volume 2, Fig. 10.23, should be provided. The outlet water level then remains constant, and the flow is measured by collecting the water in a measuring cylinder. Cumulative flow should be recorded so that the graphical method for determining rate of flow under steady conditions (Fig. 20.10) can be applied. A correction for pipeline losses may be necessary.

(3) *Falling head test*

If the inlet pressure is not much greater than the outlet pressure under the head of water in the burette, and a constant level overflow is not used, the variation in outlet pressure as the water level in the burette rises might be significant (Fig. 20.12 (a)). The conditions are then those of a falling head test (Volume 2, Section 10.7), and the calculation of permeability is based on Equation (10.15) of Section 10.3.6, modified as follows.

$$k = 3.84\left[\frac{aL}{At}\log_{10}\left(\frac{102p_1 - h_0}{102p_1 - h_f}\right)\right] \times 10^{-5}\,\text{m/s} \qquad (20.30)$$

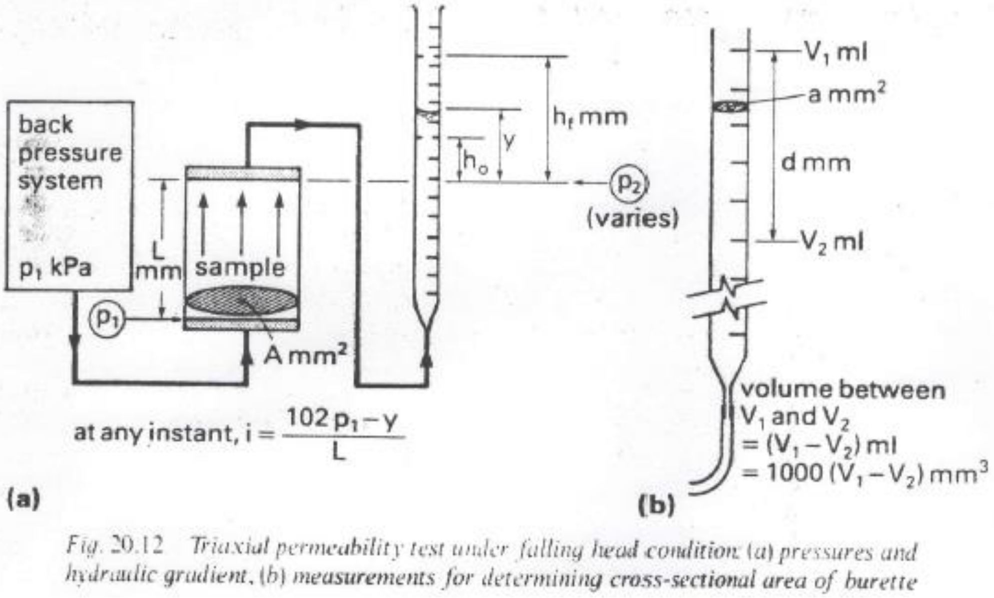


Fig. 20.12 Triaxial permeability test under falling head condition: (a) pressures and hydraulic gradient, (b) measurements for determining cross-sectional area of burette