Field measurement of pore water pressures

Prepared for Quality Services, Civil Engineering Division, Highways Agency

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Executive Summary

Wherever possible it is desirable to maintain the vertical alignment of transport infrastructure at the same level. This is frequently achieved through the use of embankments and cuttings, jointly referred to as earthworks. The design procedures adopted for embankment and cutting slopes are traditionally based on a static force equilibrium approach, the validity of which is well established. However, increasing emphasis is being given to the long-term maintenance of earth structures and this might require a different approach. The long-term stability of an earthwork is influenced by changes in the external loads, geometry and groundwater conditions at a site, and failures often occur many years after the end of construction. Analysis of these changes might require the application of advanced numerical techniques.

To predict the likelihood of failure, information is required on the site conditions and of any likely changes in these. Of particular importance are changes in the groundwater conditions. Past investigations have highlighted the need for accurate pore water pressure data gathered at the time of failure so that the mechanism of failure can be identified and the conditions at failure determined to an acceptable level of precision. However, most of the pore pressure sensors that are readily available are either unreliable or inadequate for the purpose of collecting a continuous set of data, particularly where negative pore water pressures are encountered on site.

Recent research in the soil mechanics section of the Department of Civil and Environmental Engineering at Imperial College has brought about the development of a new suite of piezometric equipment that can provide a continuous assessment of groundwater conditions. Importantly, the new instrumentation can be easily withdrawn for calibration checks and this is particularly useful for long term observations.

The report presents the theoretical background to the development of *in situ* pore pressure conditions commonly encountered in the UK. A review of the development of piezometric equipment is provided in the report, and problems that can be encountered using the more traditional equipment are identified and discussed. Finally, the development and operation of the new equipment is described and its use to monitor the pore pressures in a highway embankment is also described.

1 Introduction

For efficiency and safety it is desirable to maintain the vertical alignment of a transport route at a reasonably even level. For economy and practicality, this is often achieved through the use of embankments and cuttings. The design procedure for such earthworks is usually based on a static force equilibrium approach, the validity of which is well established. However, it is becoming increasingly important to assess the stability of existing earthwork slopes. The long-term stability of such slopes is determined by external loads, geometry, the properties of the soils and the groundwater conditions. The last on this list can vary cyclically, and the analysis of such changes might require the use of advanced numerical techniques. Thus the analysis of long-term performance, such as the onset of failure, requires information on the changes that are occurring on site.

Recent research in the soil mechanics section of the Department of Civil and Environmental Engineering at Imperial College (IC) has led to the development of a new suite of piezometric equipment that can provide a continuous record of groundwater conditions. The purpose of this report is to (a) review the development of piezometric equipment, (b) describe the new equipment and (c) demonstrate its application. In addition, the uncertainties in the measurement of pore water pressure are described in Appendix A.

1.1 Pore water pressure profiles

Below the permanent water table, the void space within a soil is saturated or nearly saturated and the pressure in the water phase is a function of the density of the water and the hydraulic boundary conditions. This pressure is positive and relatively straightforward to measure.

Were the water contained in the voids of a soil subjected to no other force than that due to gravity, the soil above the water table would be completely dry. However, molecular and physio-chemical forces acting at the boundary between the soil particles and the water cause the water to be drawn into the otherwise empty void space. The elevation to which this water rises above the water table is governed by the size of the void in the same way that the diameter of a small-bore glass tube governs the height to which water will rise inside it when it is placed in water. The potential energy of the water increases as the water is drawn up the tube.

In contrast to glass tubes, the continuous voids in a soil have a variable size and communicate with each other in all directions. For a void to remain full of water the downwards force (derived from its potential energy) must not exceed the upwards capillary force. At small elevations above the water table, where the potential energy is low, the soil remains saturated and in this *capillary fringe* the pore water, by virtue of its own weight and its position relative to the water table, is in a state of tension. Above the fully saturated layer is a zone of soil in which the larger voids can no longer hold on to the water - this therefore either returns to the fully saturated zone or is drawn further upwards by smaller voids lying closer to the surface. In this zone, only the smallest voids will be completely filled with water whilst, depending on their size, the remainder of the voids will be either empty or partly filled with water. Towards the surface, the effects of evaporation and transpiration can remove the pore water from even the smallest void, although rarely will all of the pore water be removed.

The tensile stress that is exerted on the pore water lying above the water table is called the *soil suction* and its magnitude is influenced by the void size, elevation and the presence of salt in the soil. In a salt-free soil, this stress (or more correctly potential) is termed the *matrix suction* and, where the soil is in equilibrium with the atmospheric air pressure, it is the equilibrium negative pore water pressure ($-u_w$) measured through a porous tip in intimate contact with the pore water.

1.1.1 Boundary conditions

It is important to recognise that, ultimately, a pore water pressure profile is dictated by the net flow condition at the boundary. Pore water that lies below the water table is normally referred to as being in *hydrostatic equilibrium* - a term that implies there is no vertical flow. In the absence of osmotic effects the potential for flow is derived from the relative position (gravitational head) and pressure potential (positive or negative), the sum of which is termed *total potential*. Flow occurs from locations with a high total potential to those with a low total potential. As illustrated in Figure 1, with a hydrostatic pore water pressure profile there is no *gradient* of *total potential* and therefore no flow. Upward flow (i.e. towards the surface) has a pore water pressure profile that lies to the left of the hydrostatic profile, whereas downward flow has a profile that lies to the right. In terms of *pressure* potential (Figure 1), upward flow has a pore water pressure profile with a shallower gradient than the hydrostatic profile, whereas downward flow has a steeper gradient.

The pore water pressure profile above the water table can be complex. As an example, Figure 2 illustrates the development of a pore water pressure profile (in terms of pressure potential) following net evaporation from an horizontal surface. The initial profile is assumed to correspond to net surface infiltration with flow down to the water table. When evaporation exceeds infiltration from the surface, a *zero flow plane (ZFP)* is established which lies parallel to the hydrostatic line. Towards the surface there will be net upward flow whilst towards the base there will be residual drainage to the water table. The zero flow plane will gradually move towards the hydrostatic condition. Eventually it will transcend the hydrostatic condition above the water table and merge with the upper surface of the capillary fringe. Persistent evaporation will subsequently cause the water table to move down the profile.

Following the establishment of a ZFP, should infiltration at the surface then exceed evaporation, a second ZFP will develop and gradually move downwards towards the water table; see Figure 3. However in this case flow to the second plane is both downwards from the surface and upwards

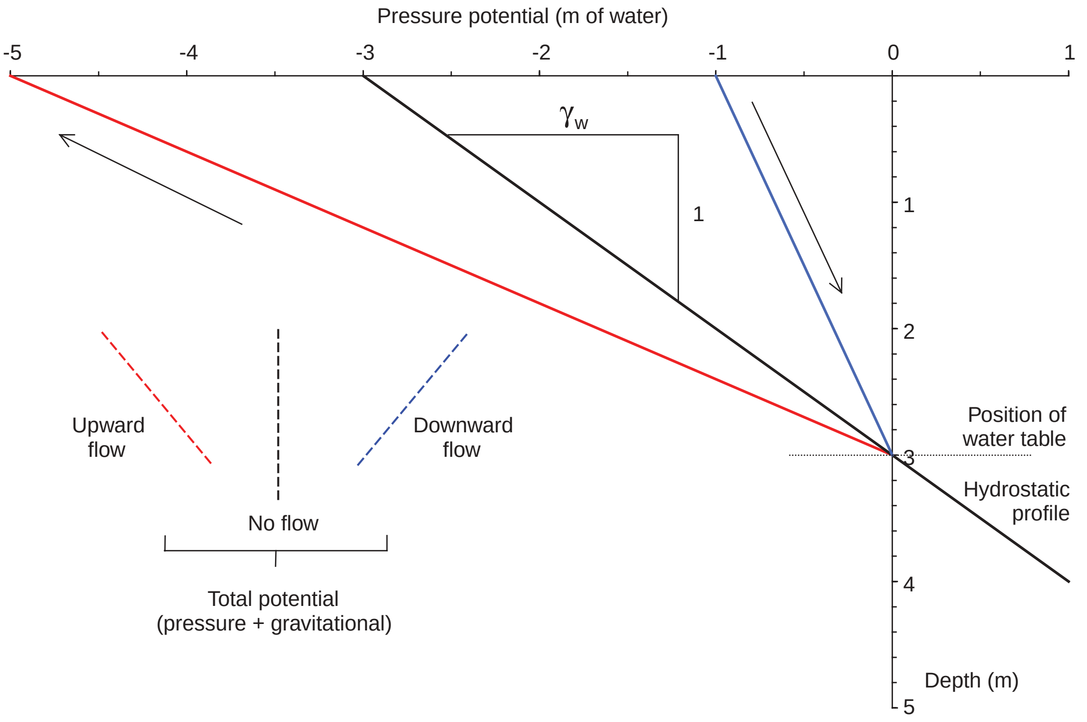

Figure 1 Pore water pressure profiles in terms of pressure and total potential

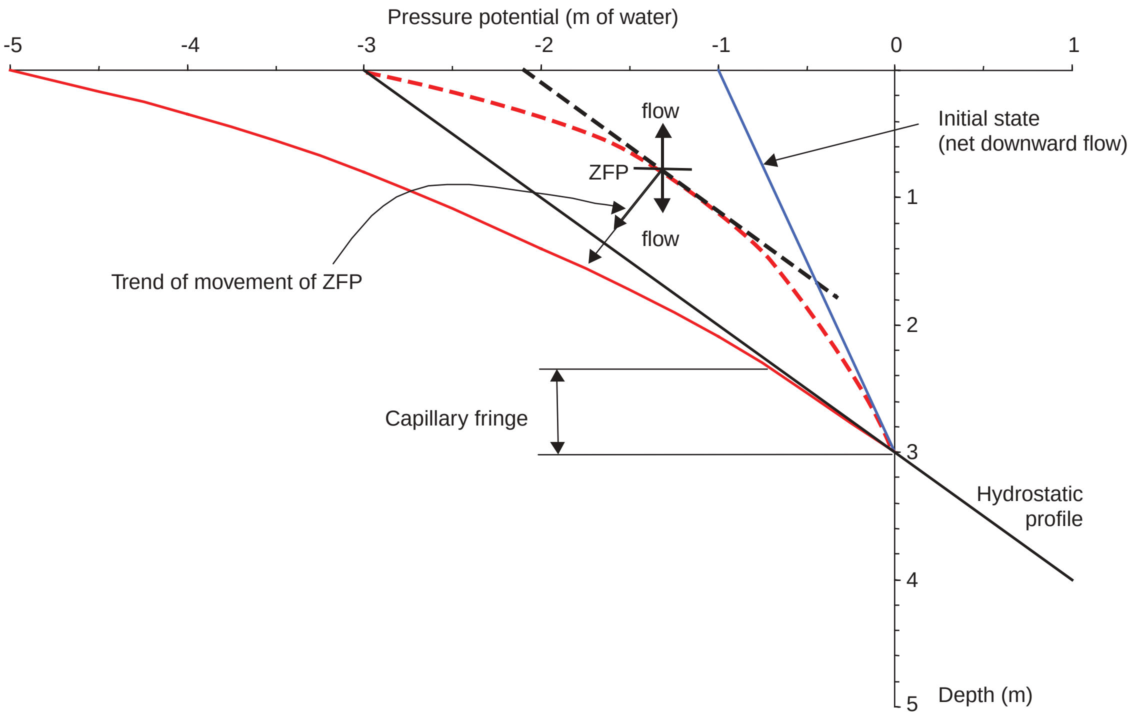

Figure 2 Pore water pressure profile generated by evaporation from a horizontal surface

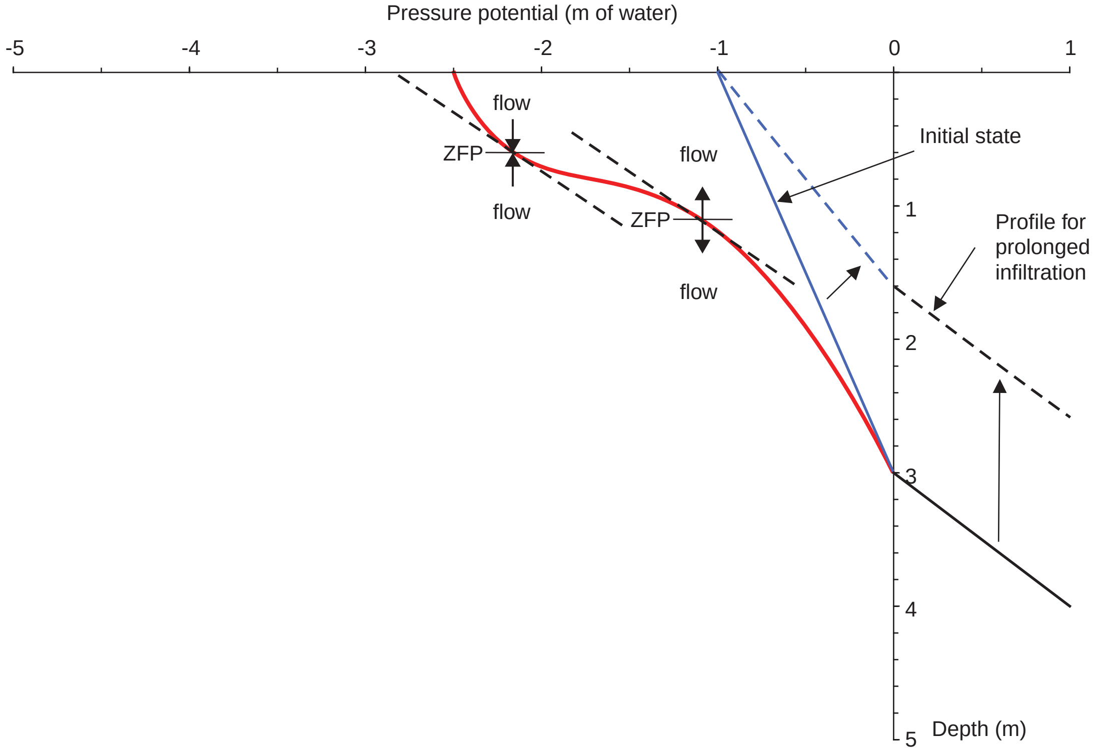

Figure 3 Pore water pressure profile generated by infiltration into a horizontal surface

from beneath it. When the two ZFP meet, the initial conditions of infiltration at the surface and percolation to the water table are re-established. Prolonged infiltration may eventually result in a rise in the water table.

1.1.2 The influence of soil type

Soil type is an important factor in the development of a pore water pressure profile: in particular through its influence on the relation between water content and soil suction (the relation is known as the *soil-water characteristic curve*, *SWCC*). In presenting such a relation it is usual to express water content in terms of either volumetric water content (θ) or degree of saturation (S_r),

$$\theta = \frac{S_r . e}{1 + e}$$

where e is the void ratio.

Figure 4 shows the influence of soil type on the SWCC: note the shift in the position of the curve as the particle size reduces and also the hysteresis that occurs through drying and wetting.

The degree of saturation influences the hydraulic conductivity (or permeability) of a soil. With a fully saturated soil, water can flow through all the voids; according to Darcy’s law the rate of flow is governed by the porosity of the soil. When a soil desaturates it does so progressively, with the water initially draining from the larger voids. Water that is subsequently added to the soil profile can (a) pass through the soil by moving through voids that are full of water or (b) enter, and gradually fill, partially filled voids. In all probability a combination of (a) and (b) will prevail. When the intensity of the rainfall

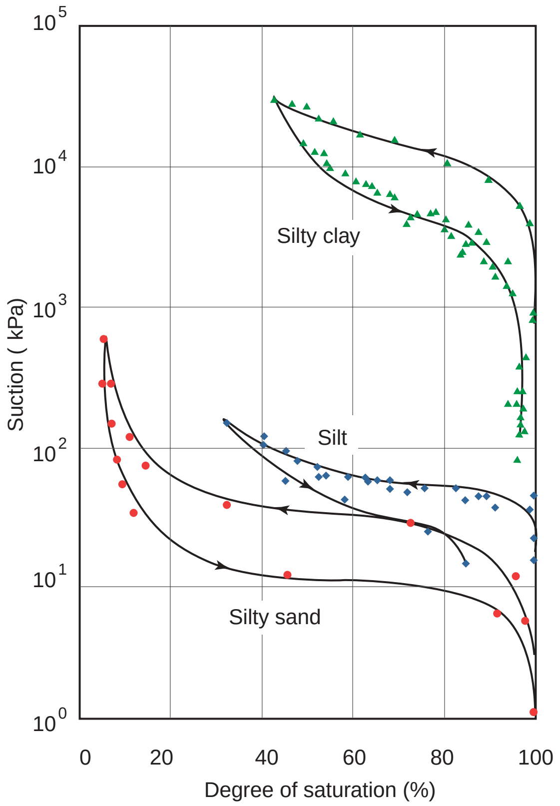

Figure 4 Typical soil–water characteristic curves

exceeds the ability of the soil to absorb water at the surface (referred to as the *infiltration capacity*) the water that does not infiltrate will either pond on the surface, and eventually evaporate, or it will run off.

The hydraulic conductivity of a saturated granular soil is high, but the degree of saturation quickly reduces with decreasing moisture content and the accompanying change in hydraulic conductivity can be many orders of magnitude. Once such a soil has desaturated, the hydraulic conductivity of the surface layer can be low and the movement of moisture to the surface from deeper in the profile will be predominantly through vapour transfer and therefore the rate of transfer will be quite slow. This means that in a granular soil the zone of *moisture deficit* (see Section 1.1.3) created by drying will often be quite shallow. Although following drying the hydraulic conductivity of a granular soil might be quite low, its storage capacity is high and upon wetting its hydraulic conductivity will increase rapidly. Therefore most granular soils readily absorb moisture and can cope with intense rainfall by a combination of absorbtion and drainage.

In contrast, clayey soils have a low hydraulic conductivity (even when saturated), they do not desaturate until a high soil suction is reached, and the reduction in degree of saturation through drying is gradual. Thus clayey soils do not readily absorb surface water, they require prolonged periods of rainfall to wet up, and the zone of moisture deficit can extend to great depth. However, clayey soils have a tendency to crack as the soil suction increases and this can lead to a substantial increase in their infiltration capacity.

Where the infiltration capacity of a soil is satisfied, a zone with a high degree of saturation will be generated close to the surface. As shown in Figure 5, a temporary *perched water table* might then be established above the permanent water table. In this case there will be a net downward flow from the perched to the permanent water table. This situation can occur in fissured clayey soils as persistent infiltration fills the fissures with water.

The quantity of water in the soil when the infiltration capacity is satisfied, and there is no vertical movement of moisture, is known as the *field capacity*[1]. In theory the pore water pressure profile corresponding to the field capacity should be hydrostatic with a zero pressure at the surface, but seldom in the UK is there sufficient rainfall to meet this condition and a small suction is normally retained at the surface.

1.1.3 The influence of vegetation

Plants extract moisture from soils through osmosis. Whereas the pore water in the soil is relatively salt free, the water in the stem of a plant is salt rich. By growing a semi-permeable membrane (contained in the root) between the soil water and the stem water, a plant is able to remove moisture from a soil. This water is then drawn through the stem of the plant by the gradient of total potential. Typical values of total water potential (ψ) for a deciduous tree are given below (after Moore *et al*., 1995):

[1] *Note field capacity is not necessarily equal to the saturated water content.*

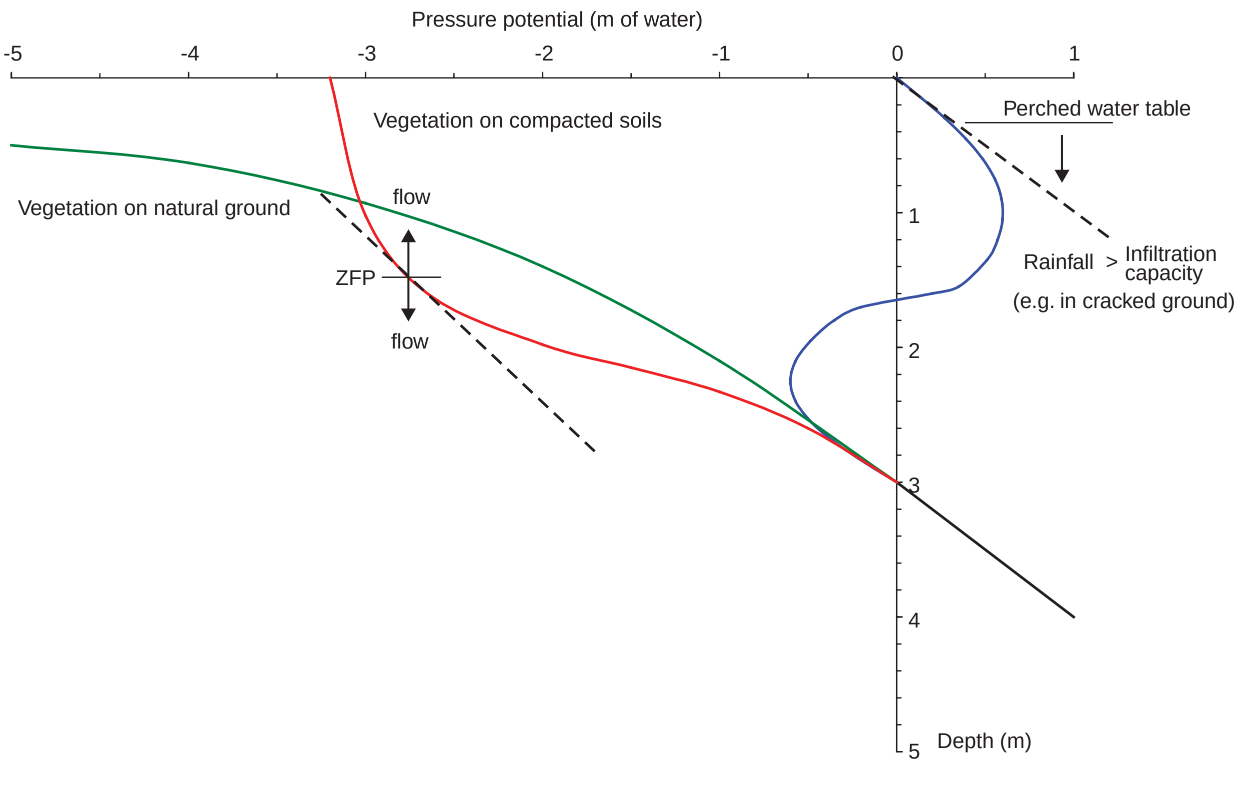

Figure 5 Pore water pressure profiles generated by vegetation and surface cracking

$\psi_{atmosphere}$ = -100,000 kPa (at 50 per cent relative humidity and 22ºC)

ψ_{leaf} = -1,500 kPa

ψ_{stem} = -500 kPa

ψ_{root} = -200 kPa

It follows that the presence of roots whilst not guaranteeing the existence of a suction at least suggests that the soil was, at some time, subjected to one.

Roots can only take up water when the suction they create is greater than the suction in the soil. The suction sustained by a soil increases as it dries; if it became greater than the maximum the root could apply (through for example evaporation), water could move from the root into the soil (Watt, 1999). Thus the above data suggest that roots can operate more easily at equivalent soil suctions of up to about 200 kPa. Roots have difficulty penetrating soils with any of the following: (a) a high clay content (b) strengths greater than 2.0 to 2.5 MPa and (c) bulk densities above 1.4 Mg/m^3 for clay soils and 1.7 Mg/m^3 for sandy soils (CIRIA, 1990). Hence the growth of a root system is dependent on soil type.

The availability of moisture ultimately dictates the suction a root is required to apply to a soil. Not all the water present in a soil is available for abstraction by vegetation. Observations suggest that the amount of water available to vegetation is between 20 and 40 per cent less than the field capacity (Meteorological Office, 1995). The soil suction at which vegetation can no longer remove water from the soil is known as the *permanent wilting point*. It is commonly held that the permanent wilting point is reached at a soil suction of about 1500 kPa. Although there are no direct measurements to support this value, it is interesting to note that the tallest trees are about 150 m high, i.e. equivalent to 1500 kPa. Measurements of water content in slopes, with and without trees, suggest that the estimate of 1500 kPa is realistic (Marsland *et al.*, 1998).

For understanding and prediction it is important to establish the extent of the existing root system. Until fairly recently it was thought that the root system of a tree reflected the pattern of the branches, but it is now understood that in most cases the roots extend laterally more than they penetrate vertically, rather in the form of a wine glass. On level ground the general direction of a root system will be radial but for a particular soil type and site the system can vary from this. For example, on a slope the thickest roots will run obliquely uphill, and therefore function as anchors. Roots do not plan the direction of growth, rather they simply follow a tortuous path of least resistance and so where there is a good source of water a root system is likely to proliferate in that locality.

Vegetation has to balance the effort required to remove moisture from a soil with that required for the roots to penetrate the soil to a depth where it is easier to remove moisture. In compacted soils it might be more efficient for the roots to develop a small but fairly constant suction at a shallow depth in which case the pore water pressure increases rapidly just below the root zone (see Figure 5). This has the advantage of drawing moisture from the surface and the water table simultaneously. Where the strength of the soil is too high for the roots to penetrate, vegetation will have to generate a relatively high suction to take in sufficient moisture. Thus a tree with a high water demand may generate a high suction close to the surface, whilst the soil just below the root zone remains relatively moist.

As the suction applied by the roots increases, a stress condition might be reached which generates cracking in a soil. This has a number of benefits for the vegetation.

i The roots can penetrate along the cracks and obtain water at a lower suction.

ii Once a crack has formed the mass permeability of the soil increases considerably - this allows the ingress of water, thereby improving the availability of water and reducing the need for deeper root penetration.

iii The roots acquire an easier access to oxygen along cracks – this will be particularly important in soils with a high degree of saturation such as plastic clays.

Where evaporation and/or evapotranspiration exceed rainfall, the amount of water within a soil will fall below its field capacity. The cumulative reduction in the quantity of soil water below the field capacity is known as the *soil moisture deficit (SMD)* and, as shown in Figure 6, is calculated over the whole profile. The soil moisture deficit is dependent on rainfall, the amount of runoff and evaporation, wind speed, soil type, the type of vegetation, and the presence of drains.

When attempting to model a pore pressure profile it is necessary to account for the interaction between the atmosphere and the soil. This can be done by linking climatic data, such as the SMD, to soil properties such as the SWCC. However there is little information available on the relationship between *in situ* water content and suction, and currently there are no analytical tools that can successfully account for the hysteresis in soil behaviour. Therefore an accurate prediction is difficult to achieve.

1.2 Examples of pore water pressure measurements

There are few well documented cases in the UK where the pore water pressure profile in an highway earthwork has been determined in detail. Notable exceptions include embankments on the M4 near Swindon (as reported by Anderson and Kneale, 1980) and on the A45 (now A14) near Cambridge (Crabb and Hiller, 1993). For both sites;

i a shallow failure occurred during the monitoring works;

ii there was no significant vegetation or drainage; and

iii the piezometers were fitted with *high air entry filters*[2] and the *scanivalve* system was used (as described in Section 2).

1.2.1 M4, Wootton Bassett near Swindon, Wiltshire

This investigation was undertaken on a Section of the M4 motorway to the west of Junction 16 near Swindon. The embankment, constructed from an overconsolidated clay,

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[2] *These are described in Section 4 and in Appendix A.*

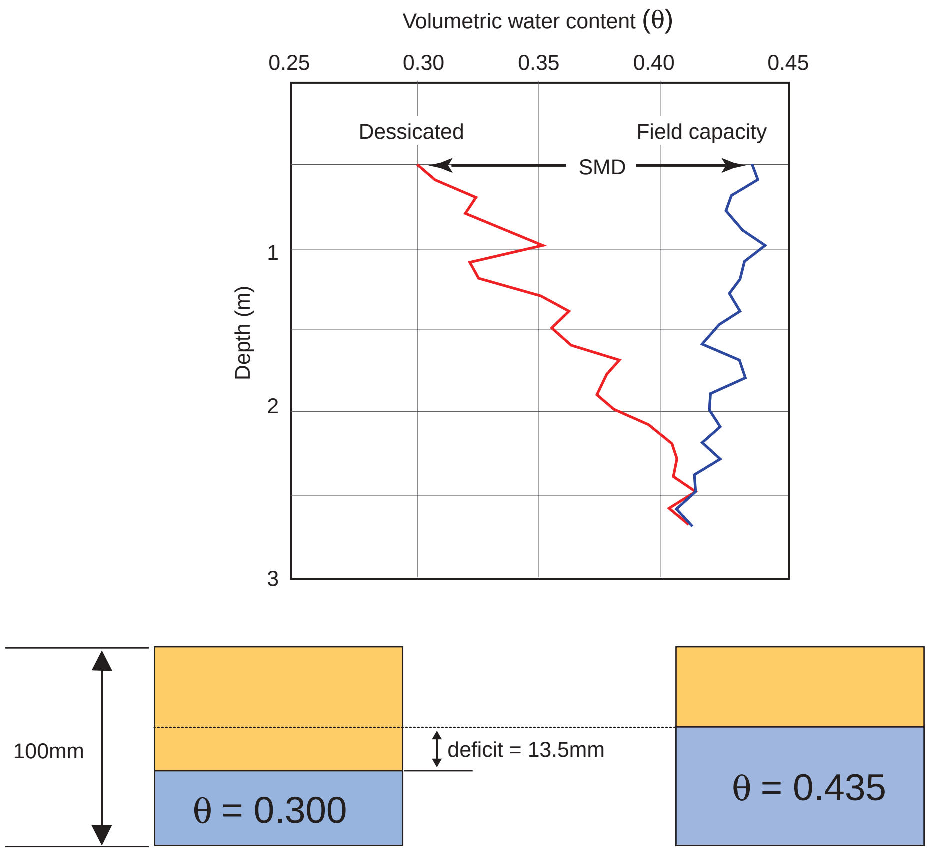

Figure 6 Soil moisture deficit

was about 6 m high having a downslope length of 20 m and a slope angle of about 26º. Piezometers were installed at depths of 0.25, 0.6 and 1.0 m, at four alignments and three cross-sections on the slope.

The site data showed significant variation of pore water pressure through the upper layer of the slope. The distribution of pore water pressure was particularly variable during the 'dry' season and was not necessarily replicated from year to year. Moreover, as shown in Figure 7, it is not clear that the changes in pore water pressure were in direct response to the variation in rainfall. The conclusion was drawn that '.... stability analyses in such material require accurate pore water pressure data at the exact time of failure if they are to reflect the mechanics and conditions of failure to an acceptable level of precision.'

1.2.2 Cambridge Northern Bypass

The instrumented section was part of the A45 (now A14) lying to the north of Cambridge where there is a history of slope failures in the earthworks formed of overconsolidated Gault Clay; a description of the site is been given by Johnson (1985). At this location the embankment was about 8 m high and had a slope angle of about 26º. The instruments were placed at depths of between 0.5 and 8 m at four alignments down the slope, and were monitored between January 1984 and January 1988.

As shown in Figure 8, beneath the carriageway at the top of the slope, with the exception of the uppermost measurement point, the pore water pressures seemed to have reached equilibrium with the groundwater in the underlying soil. Fluctuations in pore water pressure were recorded at shallow depths: here the pressure during the 'wet' season increased to a near-zero value but in the 'dry' season it was in line with the remainder of the profile.

Around the mid-slope the pore water pressures near the surface increased progressively and the profile reached a roughly hydrostatic condition during the 'dry' season. However large fluctuations were detected in the top 3 m of the upper mid-slope where the pressures in the 'wet' season increased to near-zero values.

It was concluded from this study that instability of the slope was due to the drained failure of the soil following infiltration during 'wet' periods; this led to a softening of the near-surface material.

2 Devices for measuring positive pore water pressure

2.1 Hydraulic piezometers

2.1.1 The open standpipe piezometer

An open standpipe piezometer is perhaps the most common instrument used to measure ground water pressure. First used during the construction of Logan Airport (Casagrande, 1949) it consists of a perforated lower section (the filter) attached to a pipe which rises to the surface; a typical arrangement is shown in Figure 9. The filter will normally include a fine porous plastic tube

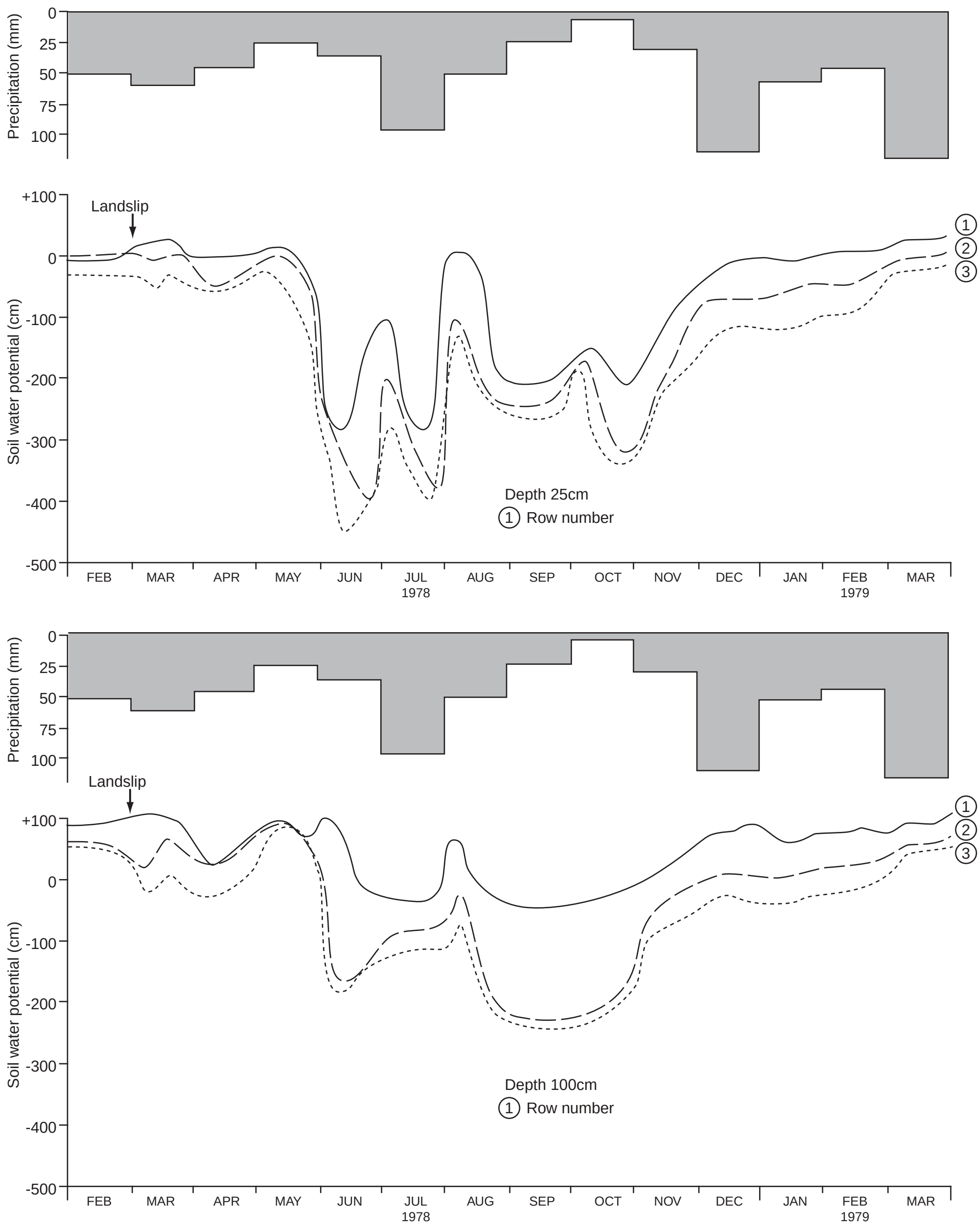

Figure 7 Relation between pore water pressures and precipitation for a site on the M4 near Swindon (after Anderson and Kneale, 1980)

to restrict the flow of fines into the piezometer, which would otherwise lead to a blockage. The pipe can be centred in the borehole using a simple disc. The annulus between the filter and the borehole is filled with wet sand immediately adjacent to the porous filter. The remainder of the borehole is filled with a layer of bentonite pellets above the sand, which are washed into place and topped with cement grout to the surface. In this way the instrument responds only to groundwater pressure around the filter element and not to pressures at higher elevations. It is essential to prevent rainwater or other external sources of water from entering open standpipes, and a suitable cover should always be provided.

PVC[3] or ABS[4] pipe with either cemented or threaded couplings is normally used for standpipes. With the former, one end of each length of pipe is machined as a male, the other as a female and the coupling connected using a PVC cement. Flush pipes can also be used with double-ended female couplings or a thread. All joint surfaces should be prepared by first roughening and then cleaning with spirit prior to the application of the cement. When threaded couplings are used, either a self-sealing type or an o-ring seal should be incorporated. In some circumstances it is acceptable to use beer hose to form a standpipe without junctions.

When properly sealed, the standpipe piezometer is a reliable means of measuring ground water pressure. The data from other types of piezometer are often evaluated on the basis of how well the results compare with those of adjacent standpipe piezometers. However the volume of

[3] *PVC polyvinyl chloride*
[4] *ABS acrylonitrile butadiene styrene*

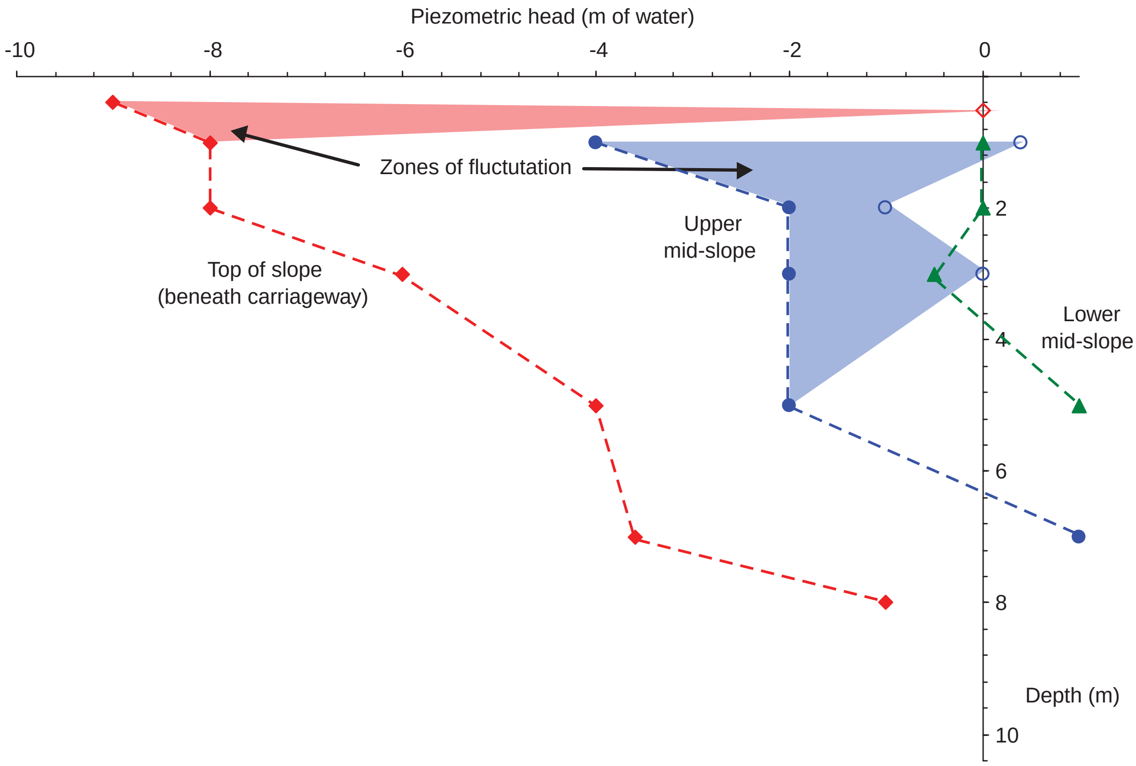

Figure 8 Pore water pressures measured at Cambridge Northern Bypass

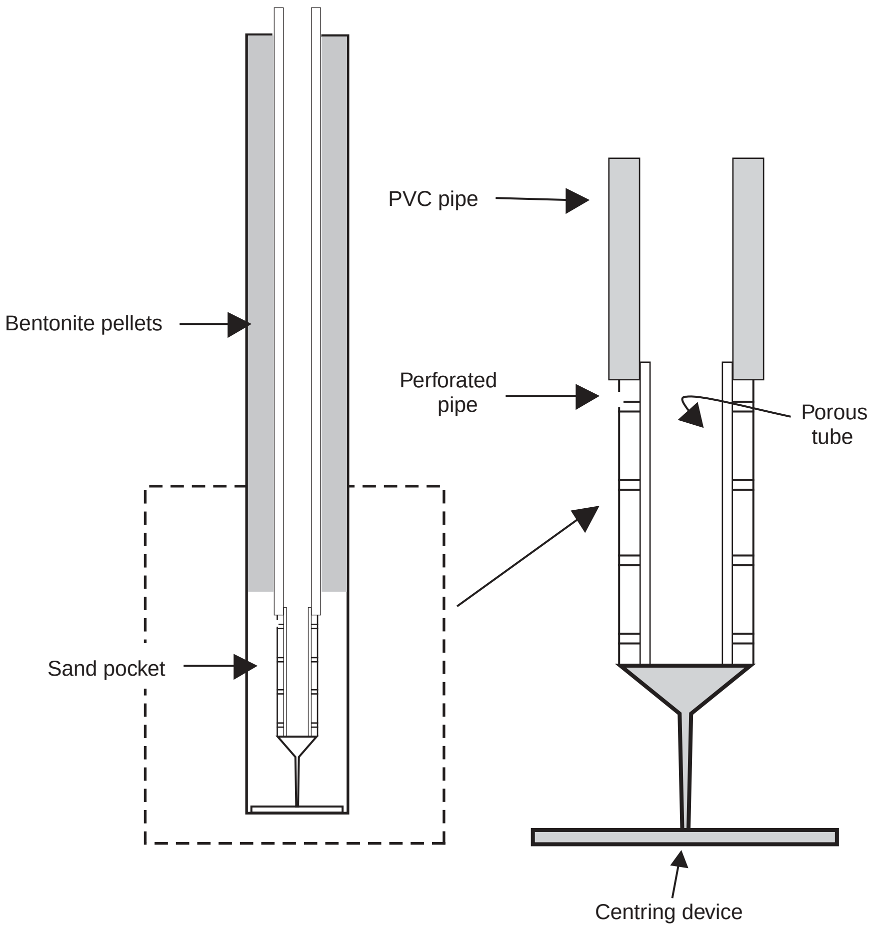

Figure 9 Open standpipe piezometer

water in a standpipe is relatively large and, particularly in fine grained soils, a long period may be required for the water level to respond to a change in pressure.

An open standpipe is of little use when a suction exists in the soil adjacent to the porous filter, because under these circumstances the water will be drawn from the standpipe into the soil.

Instruments for recording the water level in standpipe piezometers

Although the design and installation of the standpipe piezometer are more or less standardised there is a variety of instruments available for measuring the position of the water level. Many of these are, however, overly complex and undermine the simplicity of the standpipe system.

The most commonly used instrument for measuring the depth to the water level is the dipmeter. This consists of a stainless steel weight fixed to the end of a measuring tape. The weight is constructed in two sections that are insulated from each other but connected via a battery to an audible alarm. The weight is lowered down the standpipe and when it makes contact with the surface of the water, the circuit is completed and the alarm activated. The weight is raised and lowered several times until the operator is satisfied that it is just making contact with the water. The distance from the top of the standpipe to the water level can then be read off from the tape.

A cheap alternative to the dipmeter is the Halcrow bucket (as described by Brand *et al.*, 1983). A series of plastic containers, fixed along a weighted nylon string at selected intervals, can be used for recording peak water levels in the standpipe. When the buckets are withdrawn, an indication of the maximum height to which the water reached is given by the highest water-filled bucket.

Neither the dipmeter or the Halcrow buckets are able to provide information on how quickly the water level rises inside the pipe or when the maximum water level occurred.

The water level in the standpipe can also be determined using a pressure sensor located at a known depth inside the standpipe. The output from the sensor can be calibrated in metres head of water. Any suitable sensor such as a pneumatic, vibrating wire or electrical resistance strain gauge device can be used. This system has the advantage that where the sensor is left in the standpipe, data can be automatically collected from a remote location.

2.1.2 The twin-tube hydraulic piezometer

As shown schematically in Figure 10, a twin-tube hydraulic piezometer consists of a porous filter element connected via polythene or nylon-66 tubes to a pressure sensor located at the surface. A twin-tube system is used so that any air trapped within the filter element or tubing can be flushed out. It is essential that the tubing is impermeable to both air and water. Therefore because nylon tubing is slightly permeable to water, it should be shrouded in a polythene sheath. In early installations of twin tube piezometers by the United States Bureau of Reclaimation (USBR) copper tubing was used. Saran tubing, which is plastic and impermeable to both air and water, has also been used, mainly in the USA. It is important that the tubing is ductile and that in-service it can accommodate the strains generated in the surrounding soil. Buried joints are best avoided: plastic tubing readily pulls out of compression fittings if the joint is tensioned. Joints can be anchored by forming several coils in the tubing at the point of the joint.

The pressure sensor can be a Bourdon-type pressure gauge or a mercury filled manometer (but both of these are rather outdated) or an electrical pressure transducer. In large investigations a substantial and conspicuous enclosure is required to house the pressure sensors and the equipment required for flushing de-aired water through the piezometers. When freezing weather is likely to be encountered, the facility must be heated to avoid bursting the water-filled tubes. It has become common practice to connect each filter element to a single electrical transducer through a rotating valve system - the scanivalve as shown schematically in Figure 11. However, the use of a single transducer with this system means that any errors in calibration or malfunctions affect all the measurements. Moreover if leakage is to be prevented it is essential that the rotating valve lines up correctly.

As shown in Figure 12, the pore water pressure at the sensor is determined by adding the pressure reading to the elevation of the sensor relative to the porous filter. To measure the ‘true’ or uncorrected pressure, the sensor has

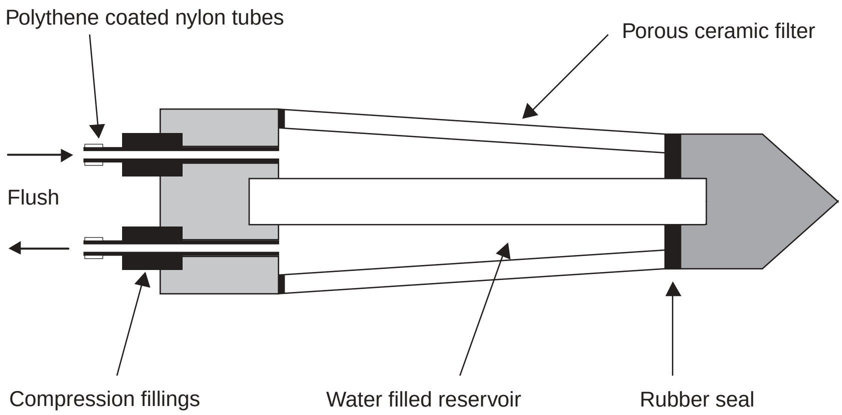

Figure 10 Twin-tub piezometer

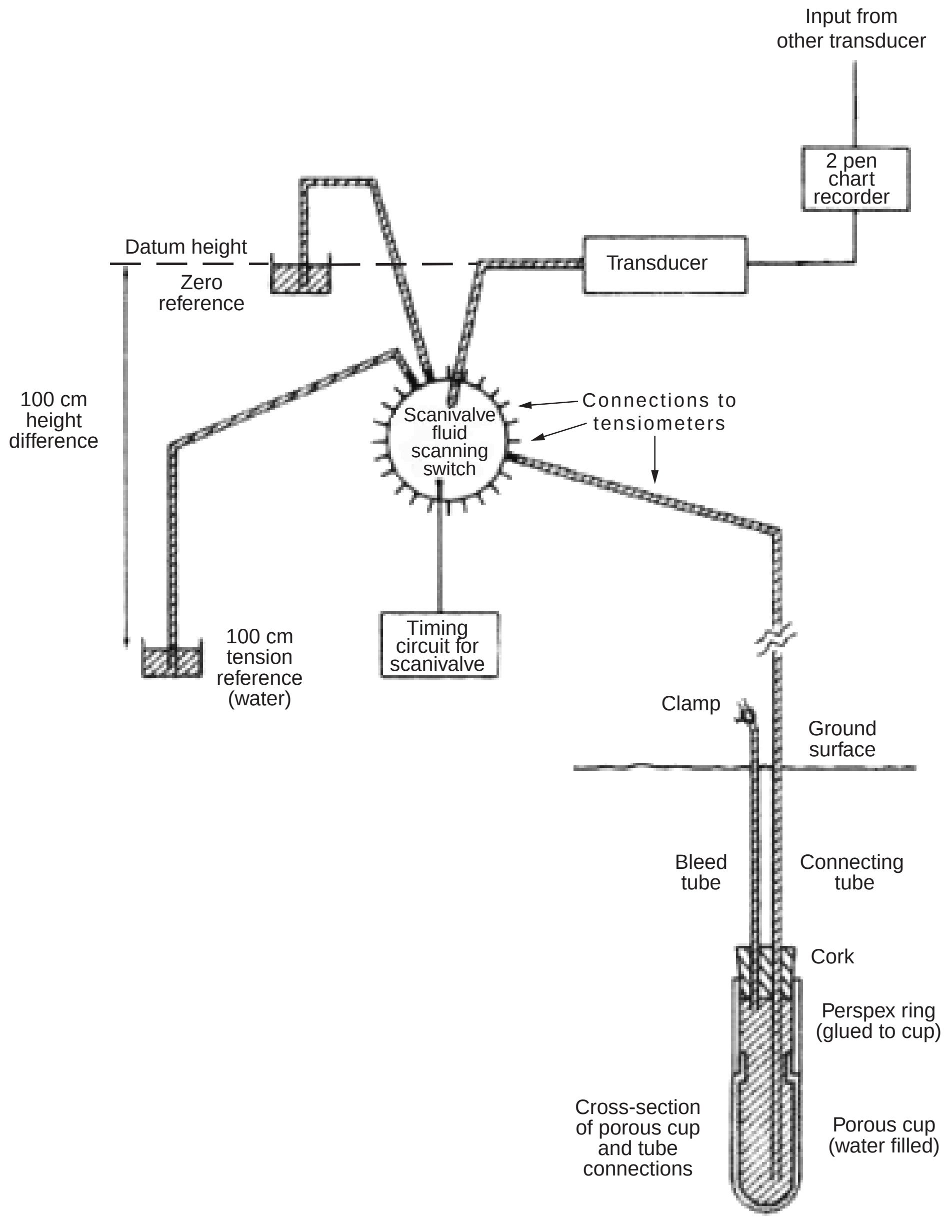

Figure 11 Scanivalve system for reading an array of hydraulic piezometers (after Anderson and Burt, 1977)

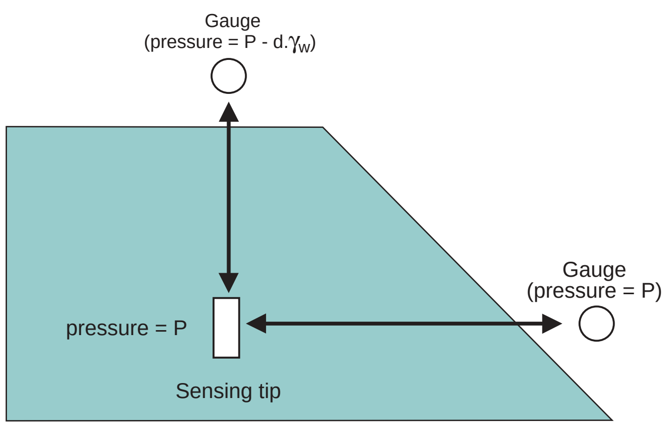

Figure 12 Limitation on measurement range due to difference in elevation

to be at the same elevation as the filter. It is preferable that the tubing does not lay above the elevation of the sensor. It should be appreciated that the level of the sensor can change through ground movements.

Because it is effectively sealed, a twin tube piezometer can be used for measuring a limited range of suction. For this it is necessary for the porous filter to be of a sufficiently small pore size that air cannot easily pass from the soil to the piezometer (see Section 3). In addition, it is necessary for the hydraulic seals to withstand the suction without leakage. Provided air is not present in the system the ability of water to sustain tension means that when the pore water pressure is sub-atmospheric the sensor will register a negative value when the sensor and the filter are located at the same horizon. The level of the sensor relative to the filter determines, by and large, the range of tensions that can be measured. For every metre that the sensor lies above the filter the maximum recordable tension reduces by 10 kPa. Since the maximum pore water tension that can be measured with this type of instrument is about 80 kPa, a few metres difference in elevation severely restricts their operational range.

Advantages:

- *In situ* constant or rising/falling head seepage tests can be performed to measure the permeability of a soil, but measurements can only be made where the soil is less permeable than the piezometer filter.
- Their operation is simple and involves no inaccessible moving parts: this makes them particularly well suited to long-term monitoring works.
- The pressure sensing equipment is either located at the surface or is retrievable - this makes calibration checks easy.
- Under certain conditions they can be used to measure sub-atmospheric pore water pressures.

Disadvantages

- It is necessary to fill the piezometer lines with clean de-aired water.
- There is the problem of the relative elevation of the sensor and tip - as described above.
- Hydraulic systems are susceptible to freezing. Anti-freeze chemicals cannot be used because they may generate osmotic pore water effects.
- The relatively large volume of water within a hydraulic piezometer and the requirement to circulate water to remove air can change (temporarily) the ambient pore water pressure in the ground (see Appendix A).
- The hydraulic connecting leads to the porous tip can be broken if the ground movements are too large.

2.2 Pneumatic piezometers

Pneumatic piezometers consist of two gas filled tubes connected to a sealed piezometer cavity. The cavity comprises a porous ceramic filter and a flexible diaphragm that covers the tubes and prevents the water in the reservoir escaping; the arrangement is shown in Figure 13. The instrument is operated by applying a gas pressure to one tube until the pressure exceeds that in the cavity. At this point the gas flows around the system and can be detected as it emanates from the second tube. The gas supply is then shut off and the pressure in the supply tube monitored as it decays. The pore water pressure is taken to be the final steady pressure developed when the diaphragm closes.

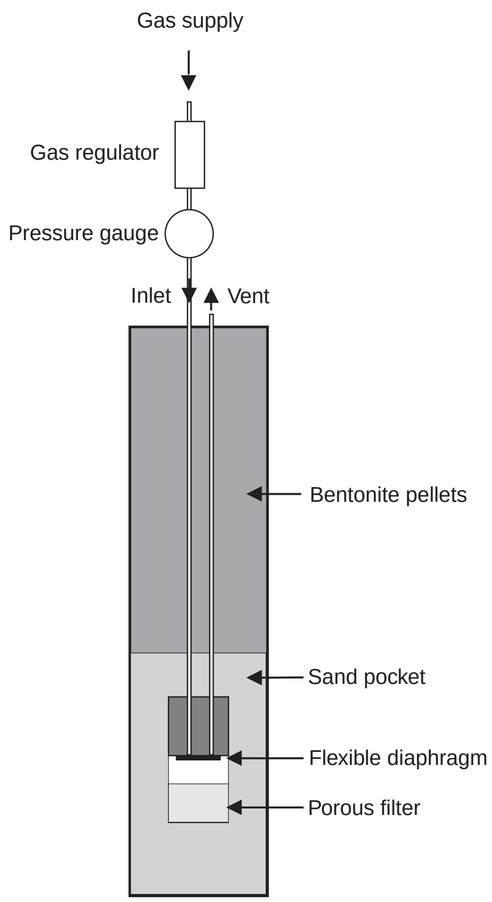

Figure 13 Arrangement of a pneumatic piezometer

Advantages

- The piezometers are relatively cheap - but the provision of readout units and gas supply add to the cost of a complete system.
- The use of gas rather than water means there are no problems of elevation and freezing.

Disadvantages

- The operation requires a controlled increase in gas pressure and the recording of the stable end pressure. With particularly long connection leads, operation can be time consuming.
- The presence of moisture in the connecting leads will affect the readings, and so it is usual to use dry nitrogen as the operating gas. It is essential that the tubes are impermeable to water.

- The system must be kept scrupulously clean; if an instrument is not operated regularly, dirt particles lodged under the diaphragm can prevent it from sealing. Moreover, a diaphragm may 'stick' in one position.
- The connecting leads to the instruments can be broken through large ground movements.
- The device cannot be used to measure suctions.
- Unless subjected to regular use, pneumatic piezometers frequently have a relatively short life.

2.3 Vibrating wire piezometers

The vibrating wire piezometer consists of a flexible diaphragm separated from a porous filter by a water filled reservoir; the arrangement is shown in Figure 14 (a). A tensioned wire is attached to the midpoint of the diaphragm on the opposite side to the reservoir, such that deflection of the diaphragm leads to a change in the length of the wire, and hence the tension. When the wire is vibrated through excitement by a magnetic field, the voltage across the ends of the wire varies with the length of the wire. The voltage can be measured and thus calibrated against the pressure of the water in the reservoir.

The cavity containing the vibrating wire can be either vented to atmosphere via the electrical cable, or sealed. With the former absolute pressure is measured, whereas gauge pressure is measured with the latter.

Advantages

- The relatively small volume of water in the cavity means that response time is fast, and the presence of the instrument has little or no effect on the ambient pore water pressure.
- Because of the depth of installation of the sensor, in most cases there will be no problem of water freezing in the reservoir.
- The device can be used to measure small sub-atmospheric pore water pressures.
- The output signal is independent of the length of the electrical cable because the signal is frequency based.
- Electrical devices such as this do not require any correction for differences in elevation.

Disadvantages

- There is no independent means of recording the position of the sensor and therefore if large settlements are likely care must be taken in the interpretation of results.
- The most common vibrating wire piezometers have a closed reservoir. In such devices it is impossible to flush out air that enters the reservoir and if this occurs the measurement will be incorrect: this is particularly likely to occur when the initial pore water pressure is negative.
- Because the measuring device is buried, calibration checks and replacement of the transducer are impossible.
- The connection leads can be broken by large ground movements.

2.4 Electrical resistance piezometers

Electrical resistance piezometers consist of a deflecting diaphragm separated from a porous ceramic filter by a water filled reservoir; the arrangement is shown in Figure 14 (b). Attached to the dry side of the diaphragm is a strain gauge, which can be bonded or unbonded: normally the former is a semi-conductor device. Small bonded resistance strain gauges are available, but they are difficult to attach to a metallic surface, positioning them to achieve the maximum output is difficult, the failure rate is high, and their long term stability is uncertain.

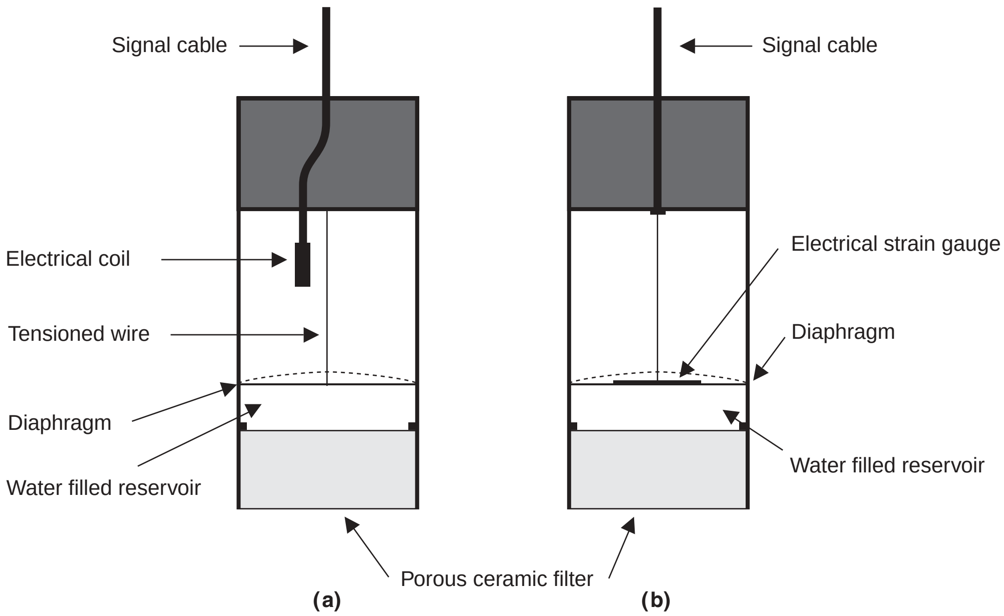

Figure 14 Vibrating wire and electrical resistance piezometers

Advantages and disadvantages
These devices share most of the advantages and disadvantages of vibrating wire piezometers. However the principal disadvantage of being unable to undertake calibration checks has been overcome in a few instruments, the most notable of which is probably the BAT piezometer, as described by Torstensson (1984). As shown in Figure 15, in this device above the porous filter is a small volume nozzle which is sealed with a rubber disk at the top. The filter section is mounted at the front end of a series of extendable tubes which are pushed into the ground. A measurement of pore water pressure is made by lowering a transducer unit into the pipe. A hypodermic needle at the base of the transducer unit pierces the rubber disk to create a hydraulic connection. When the needle is withdrawn the rubber disk self-seals. Torstensson (1984) claims that the rubber disk can be penetrated by the hypodermic needle several hundred times without loss of its self-sealing property. Öberg (1995) describes the use of the BAT piezometer to measure seasonal changes of pore water pressure (including small pore water suctions) in a clay slope.

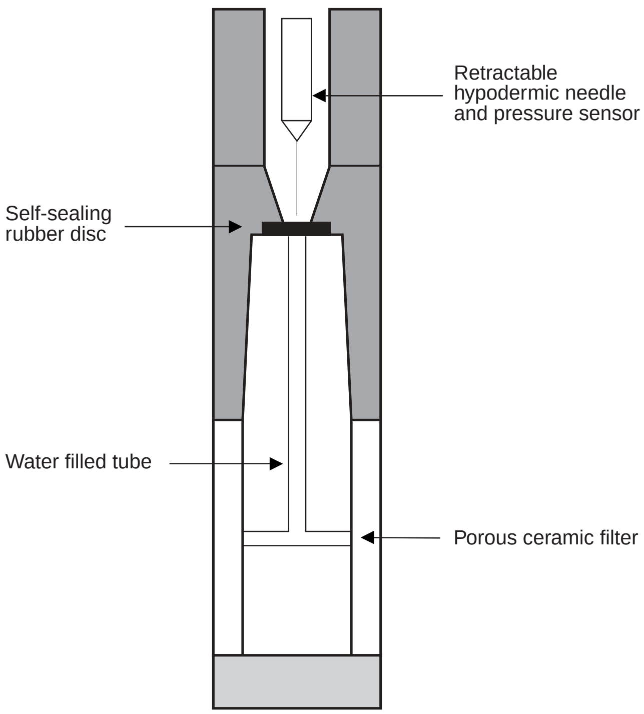

Figure 15 Essential features of the BAT piezometer (after Torstensson, 1984)

3 Devices for measuring negative pore water pressure

In essence, a tensiometer consists of a porous filter and a means of measuring stress separated from each other by a fluid (usually water) filled reservoir. In practice, water is extracted from the reservoir, through the porous filter, and into the soil until the stress holding the water in the tensiometer is equal to the stress holding the water in the soil (i.e. the soil suction). At this point no further flow of water occurs between the soil and tensiometer. The sub-atmospheric pressure in the soil water manifests itself as a tensile stress in the water in the reservoir, and this can be recorded by the stress measuring device. Provided there is no air in the reservoir, the measured tension will accurately reproduce the stress in the soil water.

The main difference between the various commerically available tensiometers, designed for use in the field, lies with the pressure measuring device: one of three types of device is commonly used - (a) a mercury manometer, (b) a vacuum gauge, and (c) an electronic pressure transducer.

3.1 Manometer tensiometers

The manometer type of tensiometer comprises a porous filter cup connected by a water-filled tube to a mercury reservoir: the general arrangement is shown in Figure 16. The suction imparted at the cup causes a differential pressure in the mercury manometer, which manifests itself as a difference in the level of mercury in the two limbs of the manometer. The suction can be related to the difference in the mercury levels (Δh) and the depth of the porous cup as follows:

$$suction = \left(\rho_{H_g} - \rho_{H_2o}\right).\Delta h - \rho_{H_2o}.(h+d)$$

where ρ_{H_g} and ρ_{H_2o} are respectively the densities of mercury and water.

Whilst researching the movement of moisture beneath covered areas, Black *et al.* (1958) used a tensiometer that had a glass tube with a 0.7 mm bore, a sintered glass filter with an average pore size of 1 micron and a mercury

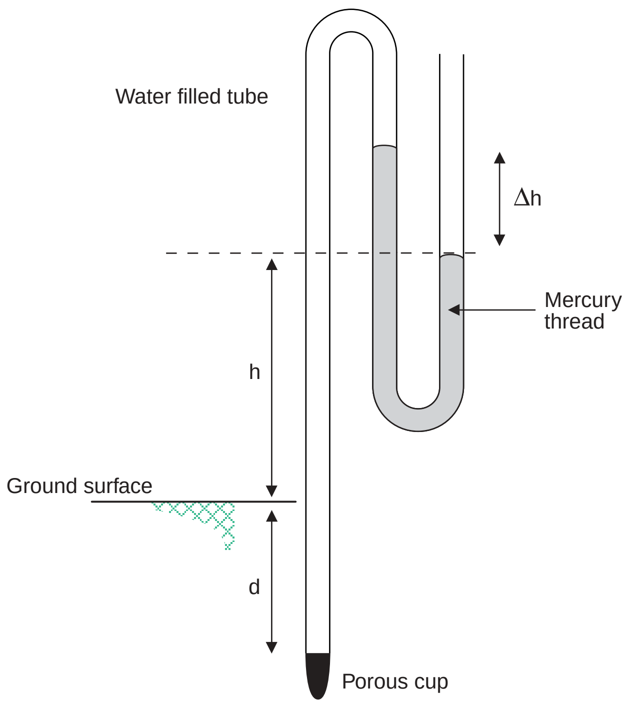

Figure 16 Arrangement of a manometer tensiometer

manometer located remote from the filter. Using the arrangement shown in Figure 17 they were able to make observations of suction of up to about 94 kPa: the range was extended by up to a further 100 kPa using filters with a smaller pore size.

3.2 Vacuum gauge tensiometers

In recent years the design of commercially available tensiometers has changed to make use of modern and cheaper materials. Nowadays, the most common construction of a vacuum gauge tensiometer uses a transparent stiff nylon tube (with a 10 mm bore), a ceramic filter (with a pore diameter of about 2 microns), and a vacuum gauge located remote from the filter. In addition, this type of tensiometer often incorporates a reserve supply of water mounted in a storage container at the top of the tensiometer: this is used to replace (with water) any air that may form within the measuring system. The arrangement is shown in Figure 18. This type of tensiometer has been used widely and can, with careful preparation, make measurements of suction of up to about 80 kPa. However they can, in some circumstances, give quite misleading measurements: this is discussed below.

3.3 Electric tensiometers

Tensiometers that use an electrical pressure transducer are similar in form to the electrical devices discussed in Section 2. For the most part they have many of the same

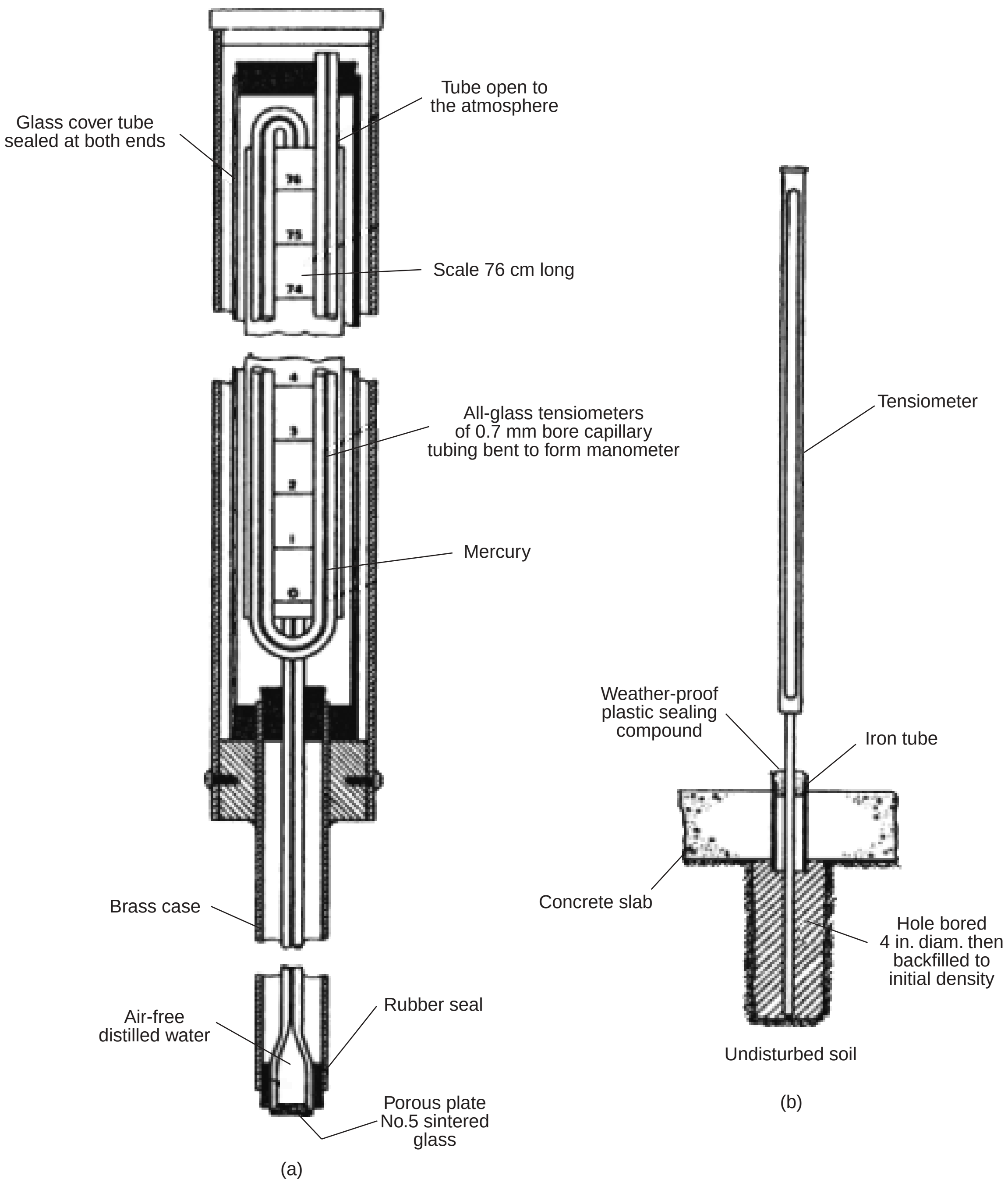

Figure 17 Arrangement of a mercury manometer tensiometer (after Black *et al*., 1958)

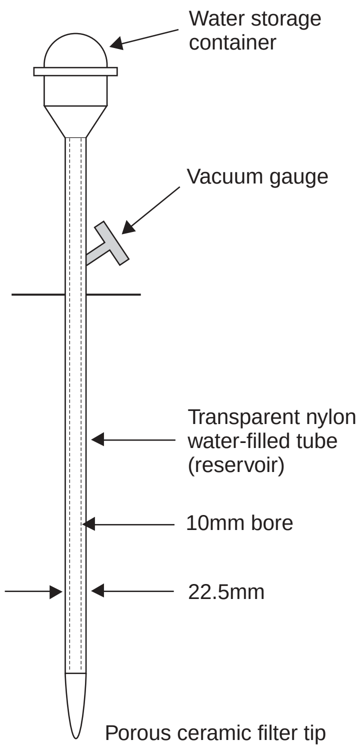

Figure 18 Arrangement of a gauge tensiometer with 'jet-fill' reservoir

advantages and disadvantages, but they have a further distinct advantage of being able to measure negative as well as positive pressures. Until recently their range of operation was restricted to pressures greater than about -100 kPa, but they could only achieve this with the pressure sensor located close to the porous filter. In 1993, Ridley introduced a new electrical device with a much reduced reservoir volume (of about 15 mm^3), a pressed kaolin ceramic filter with a pore diameter of about 0.2 microns and a high range pressure sensor located close to the filter. Ridley and Burland (1995) further improved the design by reducing the volume of the reservoir to about 3 mm^3; the arrangement is shown in Figure 19. The range of this miniature tensiometer is from high positive values to about -1500 kPa. Although this device will not sustain a high suction indefinitely, long-term measurements have been made to values as low as –1000 kPa.

3.4 Measuring range

The factors that limit the minimum pressure that can be measured by a tensiometer are;

i the procedure used to remove air from the reservoir;

ii the volume of the fluid reservoir;

iii the material used to manufacture the reservoir; and

iv the pore size of the filter.

The range of operation of all tensiometers is limited by the formation of vapour cavitites within the fluid reservoir. In the field of soil mechanics, the phenomenon of cavitation has been used to explain the formation of air in pore pressure measuring systems subject to a pore water tension. Cavitation is the formation of vapour cavities within the liquid itself or at its boundaries with another material. The theory for the tensile strength of pure liquids predicts that a vapour cavity will only form when the liquid is placed under extremly high tension (i.e. about 500 MPa), or when the liquid is superheated. Since neither of these conditions exist within the tensiometer when air forms within the reservoir, its presence cannot be due to a rupture of the molecular bond between adjacent water molecules. However imperfections that exist in the surface of objects, even after the finest machining or polishing, provide an ideal trap for tiny amounts of air that can remain after thorough de-airing using vacuum equipment: this is shown schematically in Figure 20 (a). When the water in the reservoir of a tensiometer is placed in a state of tension the air trapped in the imperfections can easily be drawn out of them to form a bubble in the reservoir as shown in Figure 20 (b).

Harvey *et al.* (1944) found that if the water inside a vessel had been previously compressed it was possible to record a tension in the water higher than 1 atmosphere. Pressurising the water in the reservoir and filter forces the air trapped in an imperfection to be dissolved into solution. When the high

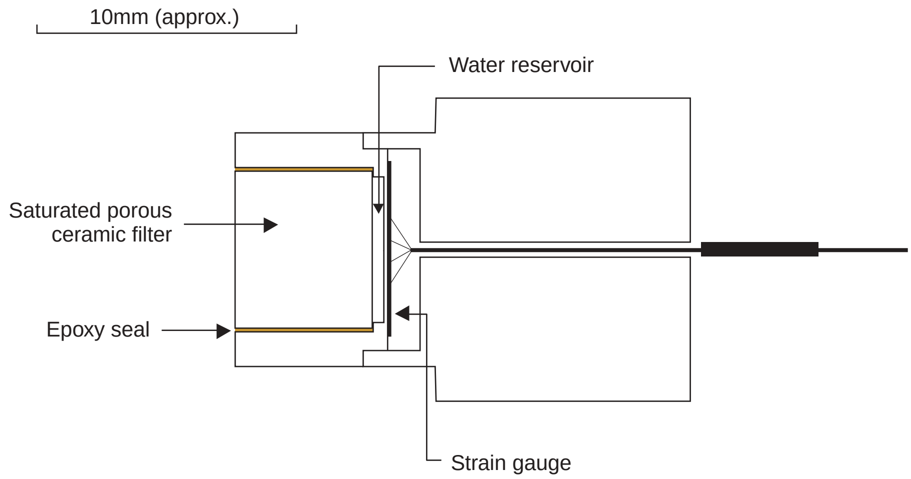

Figure 19 The Imperial College miniature tensiometer (the 'suction probe')

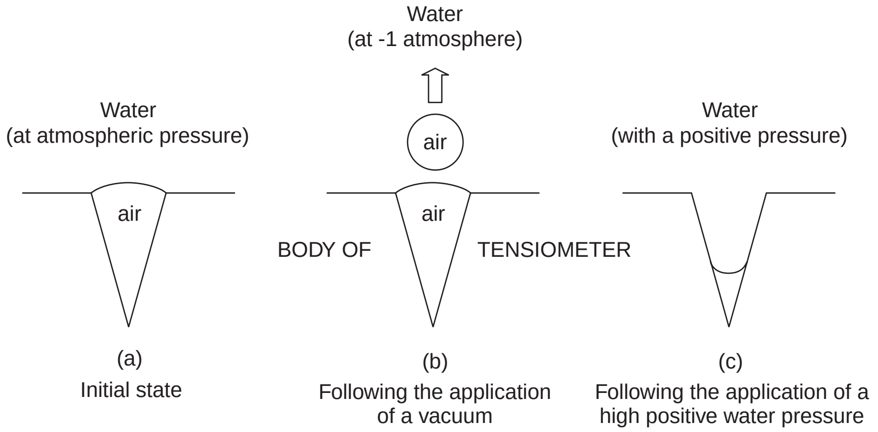

Figure 20 The crevice model for explaining 'cavitation'

pressure is subsequently reduced back to atmospheric level the dissolved air comes out of solution where the water meets the atmosphere. As a result the amount of air within each imperfection is reduced as shown in Figure 20 (c), and the water in the reservoir is then capable of resisting a high (i.e. > 100 kPa) tensile stress.

The number and size of imperfections within the body of a tensiometer is determined by the size of the reservoir, the material used to manufacture the tensiometer and the presence of impurities within the water in the reservoir. Nylon is more likely to contain such imperfections than glass or stainless steel and therefore nylon tensiometers require a thorough de-airing to achieve a reasonable operating range. Furthermore the procedure of introducing water into the reservoir through the porous filter will reduce the likelihood of impurities being present in the water. In the case of the mercury manometer tensiometer, Black *et al.* (1958) filled the glass tube by drawing de-aired water through the filter under vacuum until the manometer was full and then introduced the mercury through the open end of the manometer, thereby pushing the water back through the filter until equilibrium was reached at the prevailing atmospheric pressure.

Vacuum gauge tensiometers are filled by first immersing the ceramic filter in de-aired water under vacuum, then filling the reservoir with de-aired water, taking care not to trap air within the reservoir. This is difficult to achieve and is frequently unsuccessful. Therefore it is normal practice to apply a vacuum to the top of the tensiometer to remove any large air bubbles from the reservoir and gauge prior to fixing the storage container to the top of the device.

The miniature tensiometer is assembled dry, and water is introduced into the filter and the reservoir by (a) placing the tensiometer in an evacuated chamber, (b) allowing the chamber to fill with de-aired water such that the filter is immersed and (c) allowing the chamber to return to atmospheric pressure whilst keeping the tensiometer immersed. After this the tensiometer is removed from the chamber and placed in a manifold that allows a hydraulic pressure of 4 MPa to be applied, usually, for a period of about 24 hours. Further details are given by Ridley and Burland (1999).

3.5 Installation

Black *et al*. (1958) installed their mercury manometer tensiometer inside a 4 inch (100 mm) diameter borehole with the porous filter placed firmly in contact with the soil at the bottom of the hole. The remaining space inside the borehole was backfilled with soil cuttings to the same density (as near as could be achieved) as the *in situ* soil.

Vacuum gauge tensiometers are commonly installed in a 7/8 inch (20 mm) diameter (tight fitting) hole with the vacuum gauge sited just above the ground surface. Contact between the ceramic filter and the soil can be enhanced by pouring a slurry of cuttings removed from the hole into the base of the hole to form a seat for the filter. The remainder of the hole is backfilled using a compacted fill or a cement grout.

Ridley and Burland (1996) installed their miniature tensiometer inside a 2 inch (50 mm) diameter borehole lined with PVC tubing. This was done to facilitate (a) the easy removal of the tensiometer and (b) the collection of small moisture content samples.

3.6 Suction measurements

The operation and interpretation of measurements made using two different designs of tensiometer are considered below. Because no glass mercury manometer tensiometers were readily available, the observations are restricted to those made with a vacuum gauge tensiometer and a miniature electric tensiometer.

3.6.1 Field measurements using vacuum gauge tensiometers

On behalf of the London Underground Limited (LUL), a number of vacuum gauge tensiometers were installed in a 70-year old vegetated railway embankment, consisting of clay fill overlain by a variable thickness (up to 3 m) of granular fill, in North London. The ceramic filters were located about 0.5 m into the clay fill. Figure 21 presents the data obtained over an eight-month period from a tensiometer with its tip buried at a depth of 1.2 m and with the vacuum gauge protuding 0.5 m above ground level. The gauge measurements have been reduced by about 17 kPa

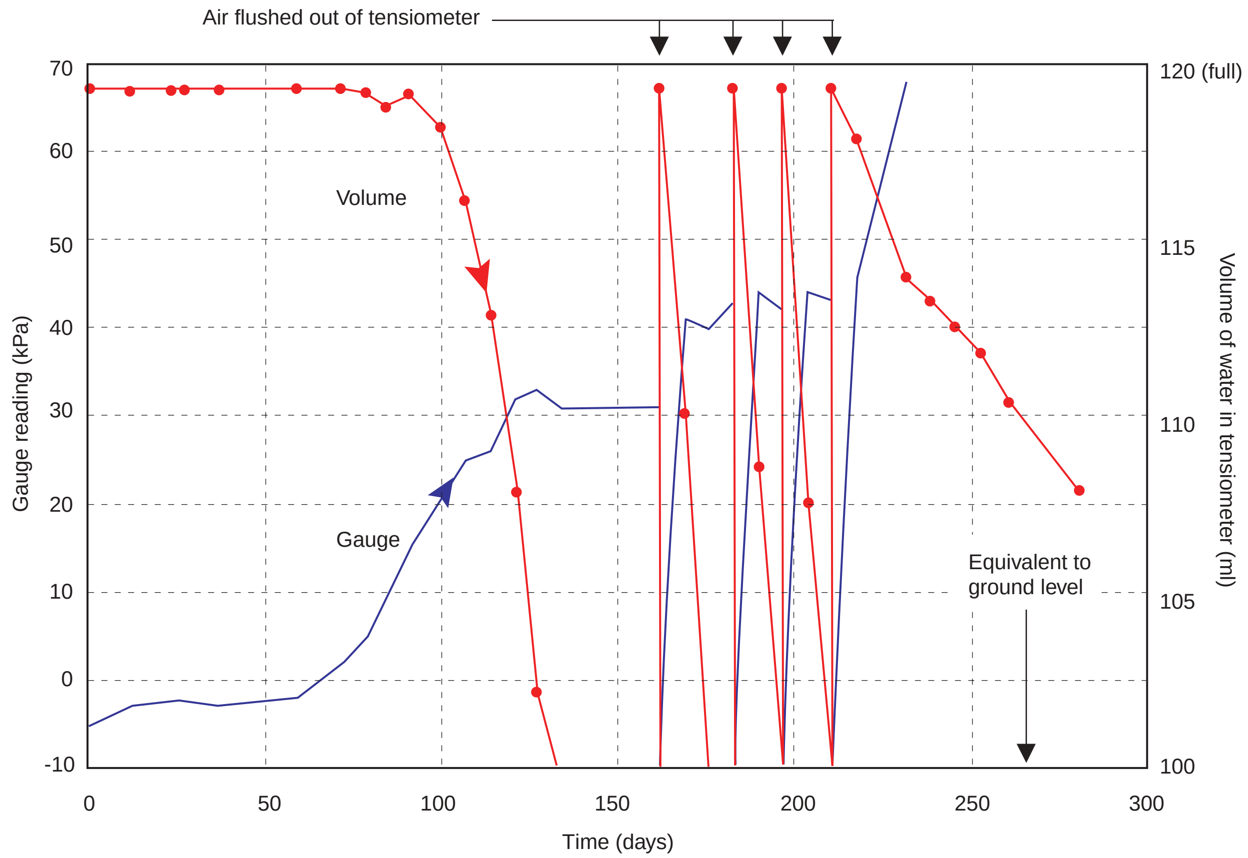

Figure 21 Field measurements using a vacuum gauge tensiometer

(equivalent to 1.7 m of water) and so the measurements presented in the figure are relative to the ceramic filter. Note that because a vacuum gauge was used a positive gauge measurement corresponds to a suction.

Although the suctions measured by the tensiometer are entirely believable the presence of air within the device (indicated by the reduction in the volume of water) gave cause for concern. In particular when the volume of air in the tensiometer reached about 20 ml (so that the volume of water was about 100 ml), the gauge reading levelled out at a suction of about 30 kPa. But as the volume of water in the tensiometer continued to reduce, eventually the gauge reading reduced to zero - a value normally associated with a saturated soil. When air was removed from the tensiometer by flushing using the storage container, the gauge reading increased, albeit temporarily, to a value greater than the previous maximum. However more air would quickly form again and the gauge reading would reduce to zero. The de-airing procedure was repeated several times and on each occasion the gauge reading increased, temporarily, but water would rapidly drain from the tensiometer: thus the no-flow condition required for an accurate measurement was not achieved.

It is normal practice to install a tensiometer of this type so that the vacuum gauge is located just above ground level. But under such circumstances the presence and amount of air in the reservoir could be uncertain and the measurements could be misleading.

3.6.2 Comparison of data from vacuum gauge and miniature tensiometer

Following the field observations described above, a series of controlled laboratory tests were undertaken with a vacuum tensiometer (fitted with an electric sensor) and with a miniature tensiometer like the one described in Section 3.3.

In the first, the filter of a vacuum tensiometer and a miniature tensiometer were buried in a clayey silt within a chamber provided with bottom drainage; the arrangement is shown in Figure 22. To reduce evaporation the exposed surface of the soil was covered with a perspex disc and a layer of lead shot. Tension was applied to the water in the drainage system by reducing, in a stepwise manner, the pressure in the air above the free water surface using a vacuum pump. As shown in Figure 23, good agreement was obtained between the two devices. No air was observed in the reservoir of the vacuum gauge tensiometer at suctions of up to 25 kPa, but at that suction an air gap formed at the top of the reservoir. Following further increments of suction the size of the air gap eventually stabilised at 50 kPa (suggesting that equilibrium was reached) and good agreement was still maintained between the two readings. This suggests that for suctions less than 50 kPa the vacuum gauge tensiometer provided accurate measurements. As shown in Figure 24, after several hours at a stable value of –50 kPa the pressure recorded by the sensor started to reduce again. At the same time the volume of air in the vacuum gauge tensiometer started to increase, the pressure in the drainage line started to

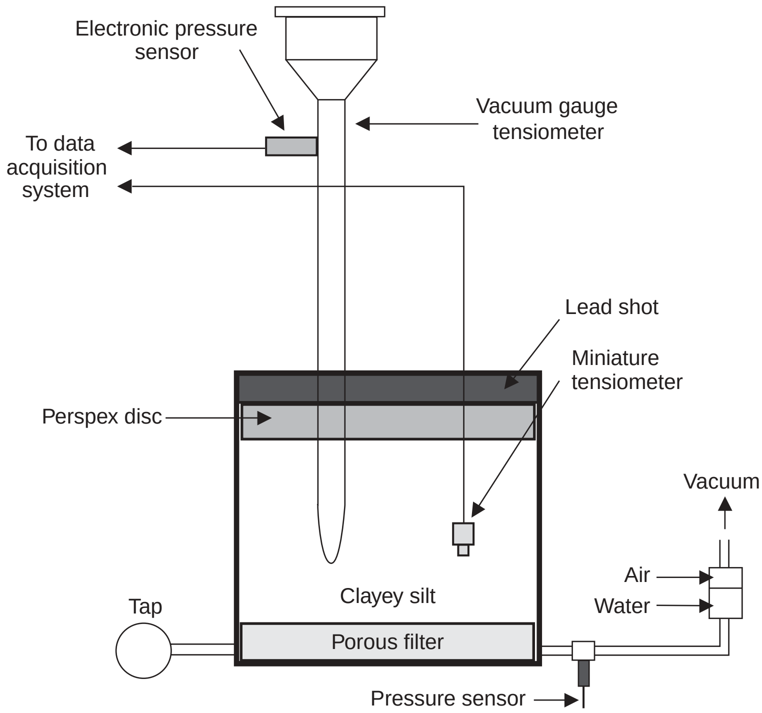

Figure 22 Arrangement for comparing the readings from a vacuum gauge tensiometer and a miniature tensiometer

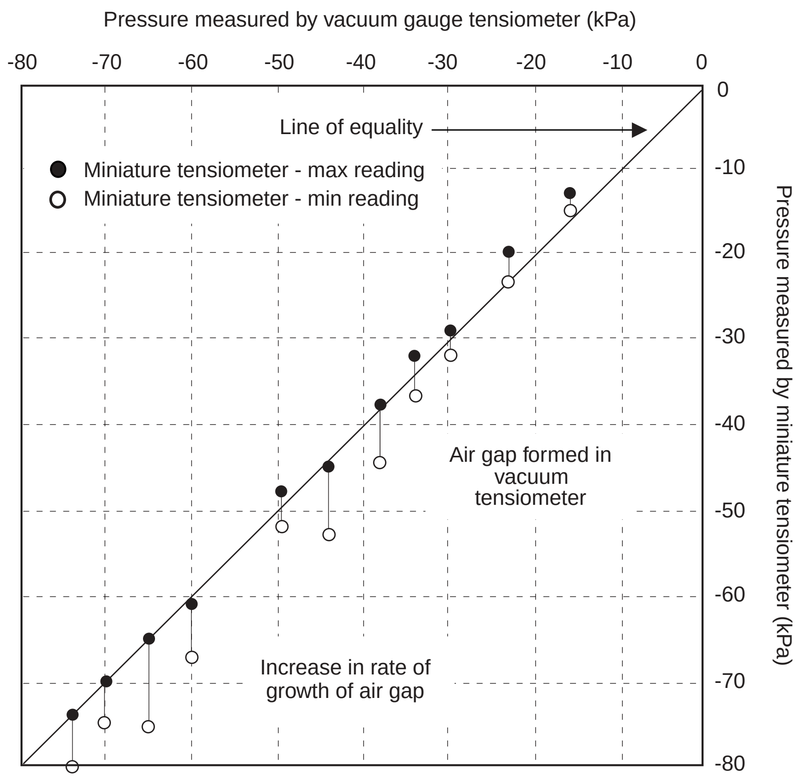

Figure 23 Data from vacuum gauge tensiometer and miniature tensiometer

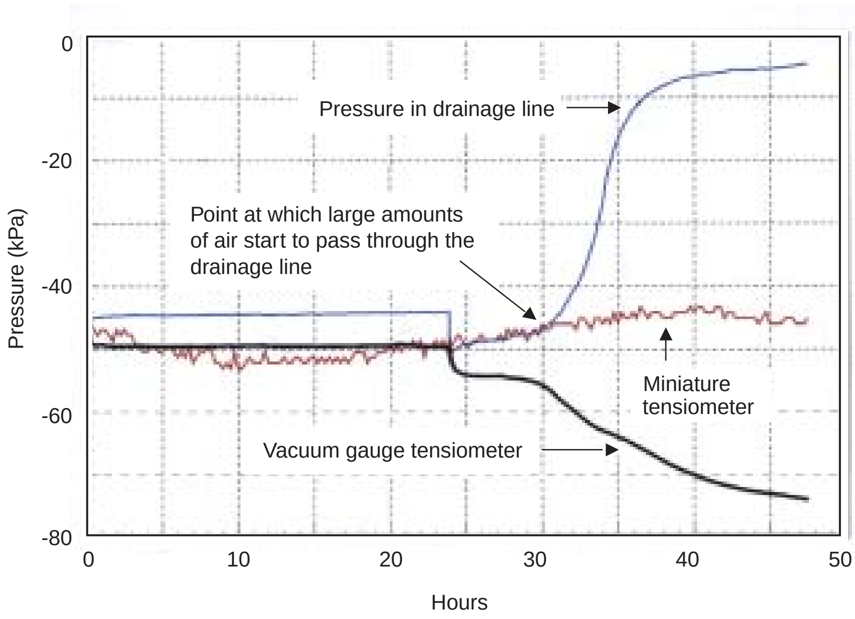

Figure 24 Comparison of pressures measured by a vacuum gauge tensiometer and miniature tensiometer

decrease and large amounts of air flowed through the line. During this stage of the test, the suction measurement on the miniature tensiometer decreased, but only slightly. This was probably due to the flow of water out of the vacuum gauge tensiometer. Either the air entry value of the soil has been reached or shrinkage cracks had formed in the soil allowing air to pass through it: laboratory tests on the soil indicated that its air entry value was in excess of 150 kPa. To prevent the formation of cracks a vertical stress was applied to the top of the sample and a wax seal poured over the top cap. Following this, and as shown in Figure 23, agreement between the two tensiometers was good up to a suction of 75 kPa. Throughout this series, the response time of both tensiometers was rapid, but the response of the miniature tensiometer was sensitive to the ambient temperature.

In a second exercise, the same devices were buried in a compacted clay known to have a suction in excess of 500 kPa. As shown in Figure 25, the response of the vacuum gauge tensiometer was almost immediate. However an air gap formed at the top of the reservoir and the size of the gap increased as the tensiometer continued to record a suction a little greater than 60 kPa. When the water level in the tensiometer dropped below the level of the vacuum gauge, the reservoir was vented to atmosphere through the storage container, but it was deliberately not filled with water. Upon closing the vent, the reading increased to eventually reach a value of 44 kPa. Throughout this time, the quantity of air in the reservoir continued to increase and eventually the water level in the tensiometer disappeared below the surface of the clay. After 29 days the reading on the vacuum gauge dropped rapidly to zero. The recovered tensiometer was dry; the suction in the soil had removed all the water from the device. On the other hand, and as shown in Figure 26, the suction measured by a miniature tensiometer installed adjacent to the vacuum gauge tensiometer was 570 kPa. It is a concern that the vacuum gauge tensiometer gave readings that over a period of about a month were believable but in fact were dramatically incorrect.

Details of the laboratory investigation are given by Ridley *et al.* (1998).

Even in a thoroughly de-aired tensiometer, air can still enter the fluid reservoir when the difference between the tensile stress in water within the reservoir and the atmospheric air pressure outside the tensiometer is equivalent to the air entry value of the porous filter. Ridley and Burland (1995) demonstrated this by inserting a range of different ceramic filters into the miniature tensiometer and allowing water to evaporate from the exposed surface of the filter. In each case the fluid tension in the reservoir increased to a threshold value, roughly equivalent to the air entry value of the porous filter, at which point it instantly returned to a value of 100 kPa. Therefore whilst identifying the maximum suction that can be measured with each type of ceramic filter, the rapid change in the measured value when air enters the miniature tensiometer provides a clear indication of an incorrect measurement of pore water pressure.

4 Development of a new piezometer system

4.1 Considerations

The advantages and disadvantages of the more commonly used devices for measuring positive and negative pore water pressures have been described earlier. However in many situations the sign of the pore water pressure changes frequently. Furthermore, where all the essential components of a piezometer are located permanently below the surface, it may be difficult to distinguish between natural variations in the pore water pressure

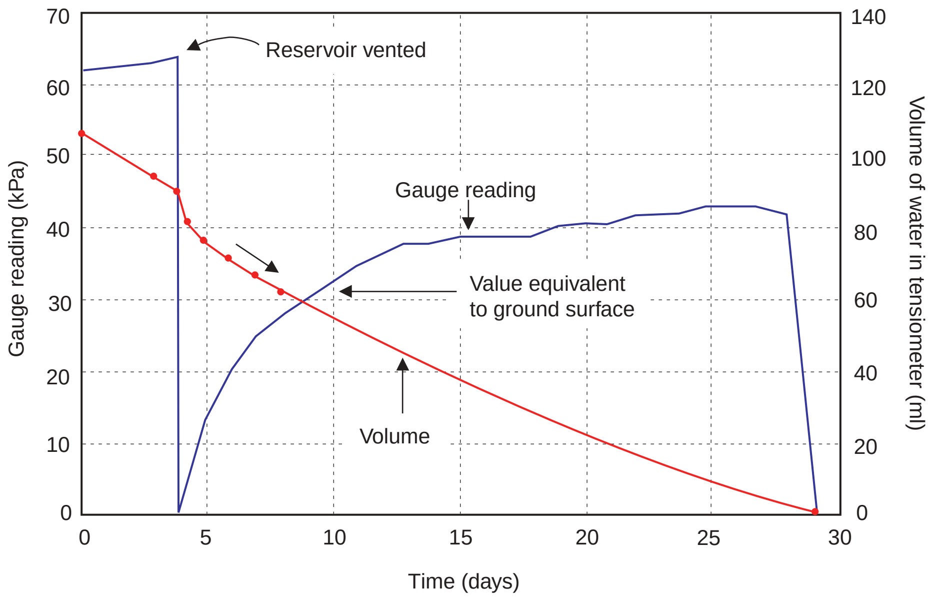

Figure 25 Response of a vacuum gauge tensiometer in a high suction environment

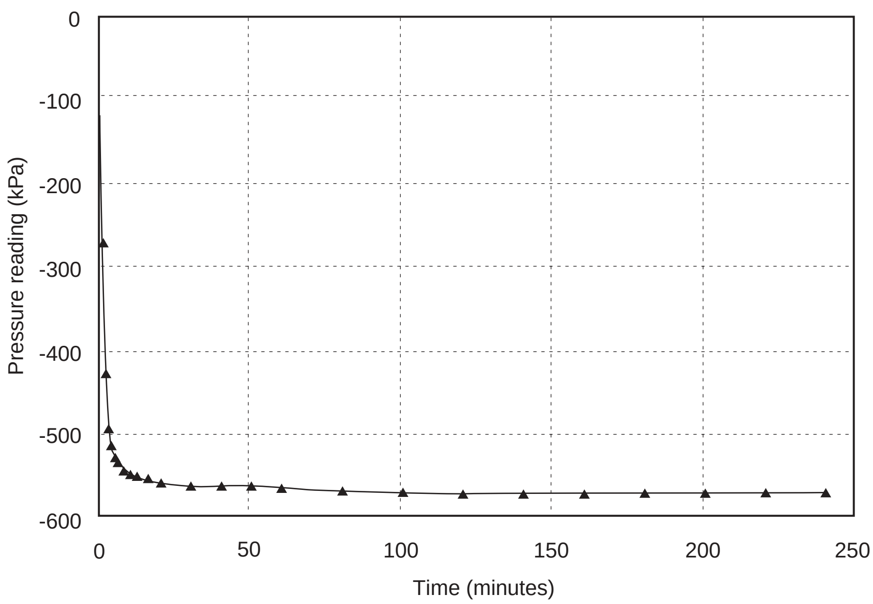

Figure 26 Response of a miniature tensiometer in a compacted clay fill

regime and malfunction of the equipment. In such situations it is desirable to be able to withdraw the piezometer and check its condition and calibration.

Another important, but uncertain, aspect affecting the performance of a piezometer is the contact between the filter and the surrounding soil. When positive pore water pressures are to be measured it is usual to place the filter within a high permeability medium, such as sand. Provided the sand is saturated (or reasonably so), the contact between the groundwater and the water in the piezometer should be continuous. However when the pore water is in tension there is a tendency for the soil to remove water from the piezometer, in which case the sand will desaturate and the essential contact between the groundwater and the water in the piezometer might not be maintained.

An important aspect in the measurement of pore water suction is the provision of a high air entry porous filter to the piezometer. (The maximum air-water pressure difference a filter can resist is known as the ‘air entry’ value.) The air entry value of a porous medium is related to its permeability. The permeability of a cement grout is sufficiently low (when set) to sustain a high suction whilst remaining saturated. Furthermore Vaughan (1969) demonstrated that the low permeability of cement grout also provides an effective seal for a piezometer inserted in a borehole. However care must be taken to ensure that the permeability of the grout is not so low that it substantially slows the response time of the piezometer.

Taking the above into account a new piezometer system for use in earth embankments, such as those used to support roads and railways, was developed by the Soil Mechanics Group at Imperial College in the mid 1990s.

4.2 Requirements

The requirements for the new system were as follows:

- Installation in an uncased borehole which can be formed using lightweight and man-transportable drilling equipment. This is necessary because, often, embankment slopes are steep, relatively inaccessible and heavily vegetated, making it difficult to erect drilling rigs.
- The ability to operate as a standpipe to provide long term observations of positive pore pressure, and for performing *in situ* response tests with continuous automatic recording.
- The ability to operate as a sealed piezometer, with continuous automatic recordings coupled with the ability (as a matter of course) to measure pore water suctions (up to say 80 kPa).
- Reliability and moderate cost.

Thus from the above, the equipment should include a relatively cheap permanent installation into which various recoverable instruments can be fitted. The purpose of recovery is for recalibration or for moving the measuring device to another installation. The required options are (a) a standpipe with a recording system for automatically measuring the height of water in the standpipe, and (b) a flushable sealed piezometer for measuring positive pore water pressures or pore water suctions (of up to about 80 kPa).

4.3 The piezometer stem

The piezometer stem is a 50 mm diameter PVC pipe, with a porous filter at the bottom. The porous filters come in three forms. Type I is a small bull-nosed ceramic tip (with an air entry value of approximately 100 kPa) and requires a hole with a minimum diameter of 70mm. Type II is a cylindrical Casagrande style filter made from a porous ceramic material (with an air entry value of approximately 100 kPa) and requires a hole with a minimum diameter of 70mm. Type III is a cylindrical Casagrande style filter made from porous plastic and requires a hole with a minimum diameter of 80mm. The three types of stem are shown in Figure 27.

All configurations can be easily installed in boreholes drilled with window sampling equipment, cable percussion rigs or rotary rigs. Each stem is inserted into the borehole and the annulus between the stem and the ground is filled with a cement grout (details of which are presented in Section 4.4) through a tremie hose.

Type I stems can be installed in direct contact with the soil at the bottom of the borehole. This is done by coring a small hole (having a diameter slightly smaller than the tip) at the bottom of the borehole and pushing the piezometer tip into the hole. The annulus between the borehole and the stem is then filled with cement grout.

Type II and Type III stems can be installed 'floating' within a borehole. However, to ensure the proper operation of the Type III stem in the presence of a suction, it is essential that there is a complete annulus of grout between the plastic filter and the ground. This is less important for the Type II ceramic filter. The set grout then acts as a filter (with a high air entry value to restrict the formation of air within the cavity) and as a seal. The Type II and Type III ceramic tips must be presaturated by first evacuating the ceramic element, then immediately immersing it (under vacuum) in de-aired water, and finally bringing the pressure back to the prevailing atmospheric value. Each tip must remain immersed in de-aired water until it is required for installation.

Figure 27 Type I, Type II and Type III porous filters

4.4 The grout

The grout surround serves as the necessary seal to the borehole and as an additional filter which has a sufficiently fine pore size and air entry value such that the piezometer can measure small suctions without air forming in the sealed cavity. The latter is an essential requirement where the plastic filter is used because this would not, on its own, prevent the passage of air into the piezometer cavity when the soil sustains a pore water suction. The action of the grout as a filter is less important where a ceramic filter is used, but the grout does, however, maintain continuity of the flow path between the soil and the piezometer, and lengthens the path over which dissolved air has to travel.

The requirements for the grout to form a satisfactory seal were given by Vaughan (1969). The error (e_0) in the measured head is defined by the following expressions:

$$e_0 = \frac{1}{\sqrt{A+B}}$$

$$\text{where } A = \frac{f.k}{a.k_g} \text{ and } B = \frac{F.k}{a.k_g}$$

where a is the cross-sectional area of the grout plug;

F is the intake factor from Hvorslev (1951);

$f = 2\pi/\ln(r_0/r_g)$;

r_0 and r_g are respectively the radius of the zone of soil affected by flow (into or out of the filter) and the radius of the grout plug; and

k_g and k are respectively the permeability of the grout and the soil.

With a grout annulus of radius r_g and permeability k_g, the flow (q) per unit length of the filter under a head H through a soil with permeability (k) is given by:

$$q = \frac{2\pi.H.k}{1n(r_0/r_g) + (k/k_g).1n(r_g/r_p)}$$

Ignoring end effects, the intake factor (F) is equal to (qL/kH) where L is the length of the filter, and H is the differential piezometric head. (This in effect assumes that flow to and from the tip is radial between the inner boundary of the stem at r_p and an outer boundary at a distance r_0.) Thus:

$$F = \frac{2\pi.L}{1n(r_0/r_g) + (k/k_g).1n(r_g/r_p)}$$

Values of the intake factor F are given in Table 1 for the Type II and III standpipes, dimensional details for which are provided in Table 2. In all cases the radius of the zone of influence, r_0, has been fixed at 0.7 m. The data show that the response of the piezometer slows down considerably as the value of the ratio (k/k_g) increases above 10. This is not so important if the ground has a high permeability. They also show that a piezometer fitted with a plastic filter is more efficient than one with a ceramic filter, but the advantage of the latter in not requiring a complete annular grout coverage to measure suction is an important (and perhaps over-riding) consideration.

The corresponding values of e_0 for the above are given in Table 3.

Table 1 Values of the intake factor, F (m)

k/k_g	*0.01*	*0.1*	*1*	*10*	*100*	*1000*
Plastic, 80mm dia	0.85	0.84	0.74	0.32	0.05	0.005
Ceramic, 60mm dia	0.44	0.43	0.34	0.12	0.015	0.002
Ceramic, 80mm dia	0.48	0.46	0.34	0.10	0.011	0.001

Table 2 Dimensions of plastic and ceramic standpipe piezometers

	Plastic (m)	*Ceramic (m)*
r_p	0.025	0.013
L	0.390	0.220

Table 3 Values of the error in measured head, e_o (m)

k/k_g	*0.01*	*0.1*	*1*	*10*	*100*	*1000*
Plastic, 80mm dia	0.26	0.04	0.005	0.001	0.8×10^{-3}	0.6×10^{-3}
Ceramic, 60mm dia	0.24	0.043	0.007	0.002	0.001	0.7×10^{-3}
Ceramic, 80mm dia	0.33	0.060	0.011	0.004	0.002	0.001

In designing a grout mix to provide an adequate seal to the piezometer but which will not inhibit the response time of the instrument, the permeability of the grout should be close to that of the surrounding soil. Information on the permeability of grouts is given in Appendix A.

The air entry value of a cement grout is directly related to its effective pore size and, hence, permeability. Commercially manufactured ceramic discs having an air entry value of about 150 kPa are quoted as having a permeability of about 10^{-8} m/s. However, as shown in Figure 28, for an equivalent permeability, the air entry value of a cement grout can be much lower than that for a ceramic filter. To obtain an air entry value of about 150 kPa, a cement grout should have a permeability of between 10^{-9} and 10^{-10} m/s. Provided that the permeability of the ground is less than about 10^{-9} m/s, the use of a cement grout should ensure that requirements of the piezometer (to have an adequate seal, a low measurement error, and an high air entry filter) are met.

4.5 The standpipe and water level recorder

As shown in Figure 29, a standpipe can be inserted into the piezometer stem and sealed in position with an o-ring located just above the porous filter. The water level in the standpipe can be recorded manually using a dipmeter or automatically using a differential pressure transducer placed at the bottom of the standpipe and connected via an electric cable to a datalogger at the surface (see Figure 30).

With the ability to automatically record pore water pressures, falling and rising head tests can be completed routinely and interpretation of the data from such tests is relatively simple. In an incompressible material, the rate of change of water level with time in a falling or rising head test can be represented by an exponential expression of the form:

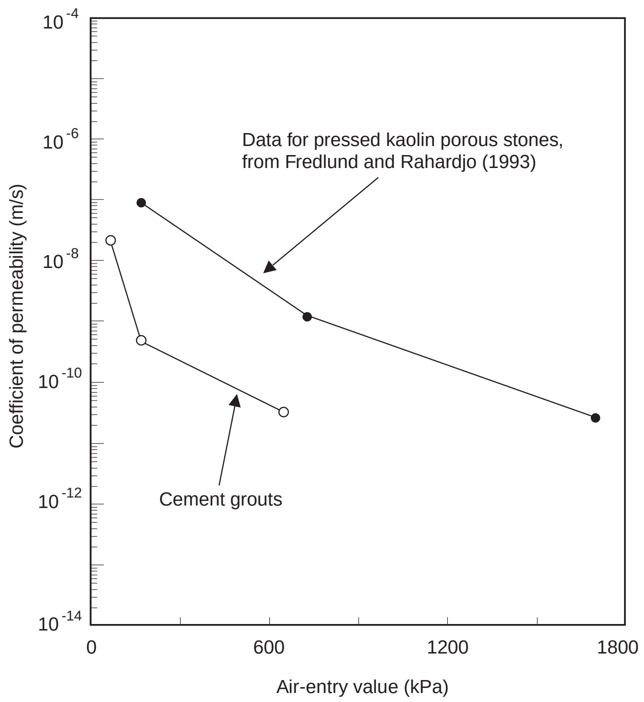

Figure 28 Data on the air entry values of ceramic filters and cement grouts

$$E = \frac{h_t - h_\infty}{h_0 - h_\infty} = exp[-\frac{Fkt}{V\gamma_w}]$$

where E is the equalisation ratio;

h_0, h_∞ and h_t are, respectively, the water levels at time zero, at equilibrium and at some time t between the two;

F is the intake factor - calculated as above;

k is the permeability of the ground;

V is the volumetric or compressibility factor of the piezometer system – defined as the flow into the piezometer for unit pressure change in the cavity; and

γ_w is the unit weight of water.

This relation can easily be programmed into a spreadsheet package with h_t as the prime variable: a best fit curve to the data can be drawn in by ‘eye’ and used to forecast the equilibrium pore water pressure. Alternatively, when the full data set is available it can be used to determine the *in situ* permeability.

4.6 The flushable piezometer

A standpipe cannot measure a pore water suction: at equilibrium it will be dry. To measure suction the standpipe can be replaced with a flushable electric piezometer unit (see Figure 31) that screws into the piezometer stem just above the porous filter and is sealed with an o-ring.

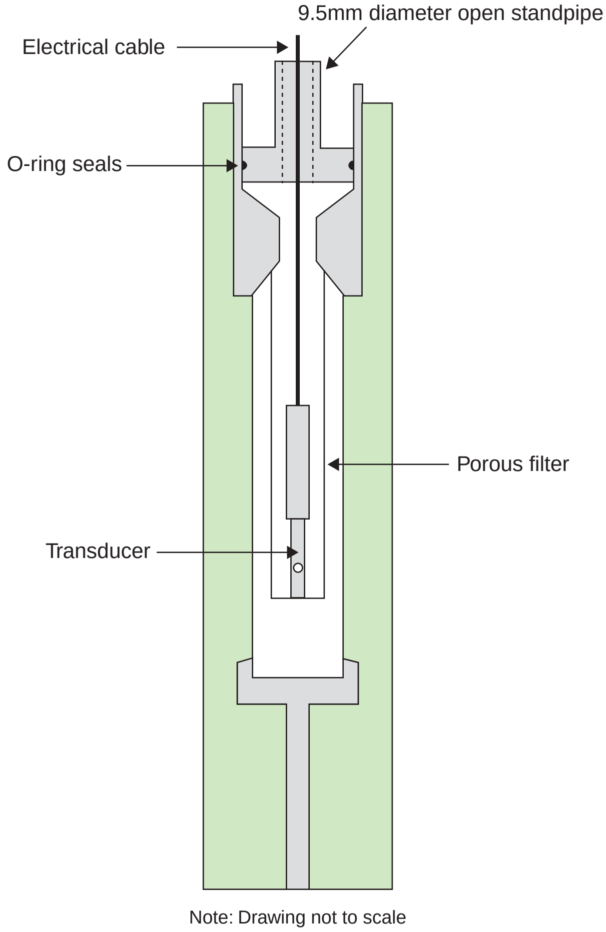

Figure 29 Piezometer stem with open standpipe and water level recorder

Figure 30 Water level recorder

Figure 31 Flushable electric piezometer

Each flushable piezometer unit includes an inlet and outlet port, which are connected to the surface with flexible tubing to allow water to be flushed through the piezometer removing any air that might be present in it. A hydraulic valve located in the head of the unit can be operated from the surface to open and close the flushing ports. A differential pressure transducer, also located in the head of the unit and connected to a data logger at the surface, records the water pressure (or tension) in the piezometer. The placement of the pressure sensor and the hydraulically operated valve at the head of the piezometer (i.e. at the same level as the measurement) removes the need to correct the recorded pressure and therefore increases the range of suction that can be measured by the device.

This system can be used to measure suctions of up to about 80 kPa. Where higher suctions are present it is necessary to use the miniature tensiometer as described in Section 3.3.

4.7 Examples of measurements using the new piezometer system

The new piezometer system has been used extensively in the UK on road, railway and river/canal embankments and cut slopes. The remainder of this report will present some examples of measurements that have been obtained using the new piezometer system.

Figure 32 shows two falling head tests undertaken with and Type II and Type III porous filters, each fitted with a 9.5mm diameter open standpipe. The porous filters were installed at the same depth in an excavated clay slope. The data were recorded using a water level recorder. The response of the piezometer with the plastic filter is much faster than that of the piezometer with the ceramic filter, although both piezometers appear to be tending to the same condition in the long term.

Figure 33 shows a falling head test undertaken with a Type II porous filter, fitted with a 9.5mm open standpipe and installed at a depth of 4m in a clay fill embankment. The water level quickly dropped to a level that was below the bottom of the piezometer stem. Therefore the 9.5mm diameter open standpipe was withdrawn from the stem and replaced with a flushable electric piezometer, which was capable of measuring the suction present in the embankment at this depth. Over the subsequent summer months the suction proceeded to increase to a maximum value of 40 kPa before decreasing again in the autumn. Throughout this time an open standpipe would have remained in the same 'dry' condition.

Figure 34 shows the response of Type II and Type III porous filters, each fitted with flushable electric piezometers and installed above the water table in different clay fill embankments. In the case of the piezometer with the plastic filter the measurement was confirmed using a suction probe (Ridley and Burland, 1996) installed in a borehole adjacent to the new piezometer stem. The piezometer with the ceramic filter had a suction that was relatively close to the 'air entry value' of the filter. It was therefore flushed, no air was present in the piezometer and when the hydraulic valve was closed the pressure quickly returned to the same value as before the flushing. This is a good indication that the measured suction was correct.

Figure 35 shows the response of a stem with a Type I porous filter and fitted with a flushable electric piezometer. The stem was installed at a depth of 1 m in a clay fill embankment and monitored for a period of four years. The suction can be seen to increase in the summer months to a value that is in excess of the air entry value of the ceramic tip. However in the autumn the readings were seen to reduce to a value within the range of the instrument after the piezometer had been flushed.

These results illustrate the suitability of the new piezometer system for situations where the pore pressure may be positive or negative and where the sign of the pore pressure is unknown before the piezometer is installed or may change during the period of observations.

Clearly there may be particular situations which best suit the different filter arrangements. For example the Type I filter is well suited to shallow installations that are above the water table and where the presence of an *in situ* suction is most certain. Type II filters work well in clay fills, at intermediate depths where there is likely to be a positive pore water pressure, but where the possibility exists of there being a pore water suction present at certain times of the year. Type III porous filters work best in natural clay slopes where the permeability of the clay is low, although they have been used extensively in clay fills, but usually at deeper depths.

Moreover the cylindrical filters are well suited to situations where the borehole must (for profiling reasons) be drilled to a deeper depth than the depth at which the measurement of pore pressure is required. In such

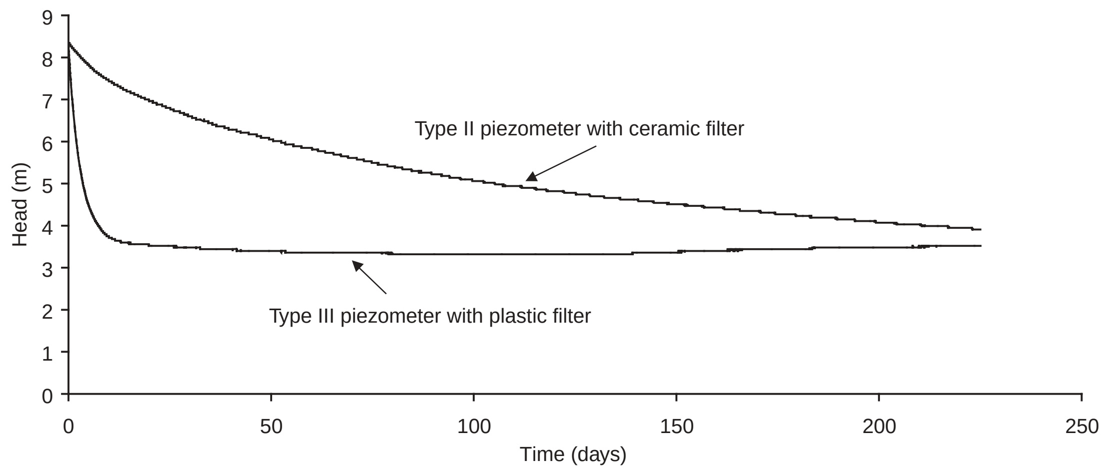

Figure 32 Falling head tests

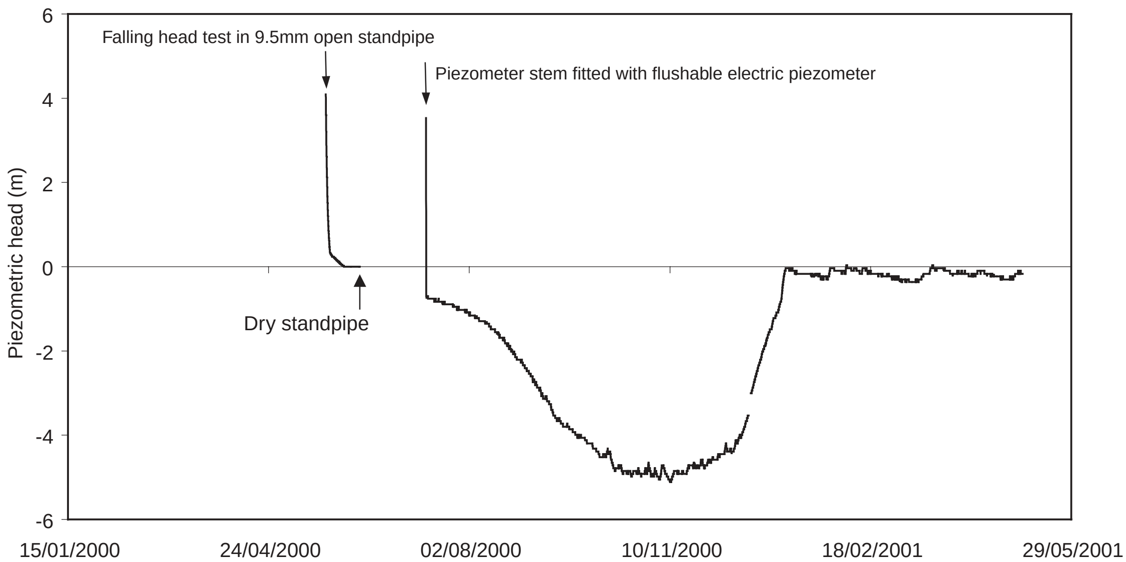

Figure 33 Monitoring using a Type II piezometer stem

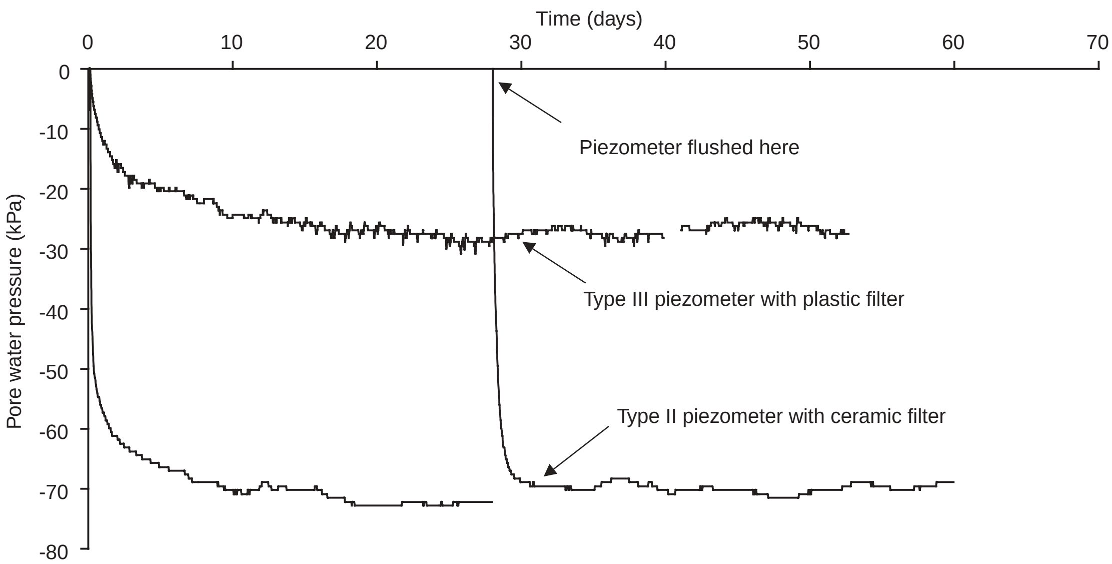

Figure 34 Suction measurement using flushable electric piezometers

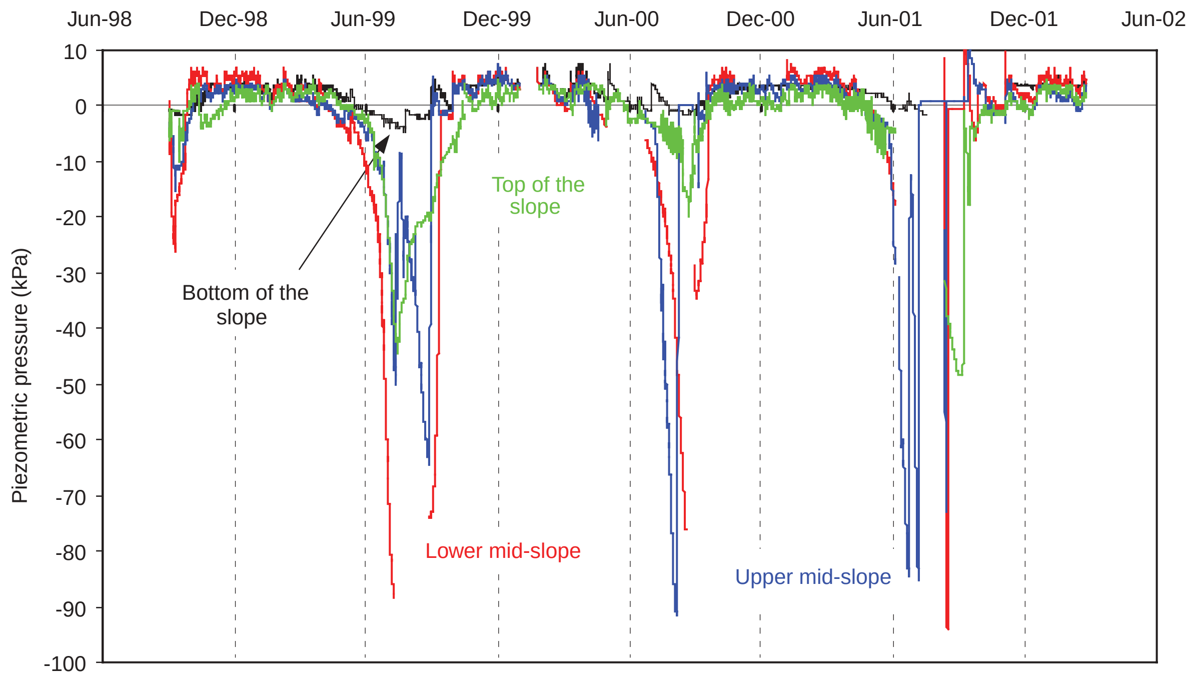

Figure 35 Suction measurements using a Type I piezometer stem

situations Type II and Type III filters can then be installed 'floating' in the borehole. It is also worth noting that the Type III filter can be inserted in a borehole with a sand pocket filter and used to record positive pore water pressures using either the standpipe or the flushable electric piezometer.

5 Conclusions

The development of the pore water pressure profile in a slope is a complex process which is dependent on, amongst other things, the geometry, the surface boundary condition established by the climate and vegetation, and the soil type. The assessment of the pore water pressure profile is equally complex. In particular above the groundwater table, where the pore water pressure is sub-atmospheric, a greater understanding of the principles involved in the operation of the measuring equipment (and also in the interpretation of the results) is required.

This report has reviewed the operating features of widely available piezometric equipment. In doing so it has highlighted the need for equipment that can be used for the long-term and continuous measurement of pore water pressures. Where equipment has to be used for long-term measurements, it should be designed to allow it to be withdrawn for routine maintenance and calibration checks. In addition, where the equipment has to be installed above the natural groundwater table it must be capable of measuring both positive and sub-atmospheric pore water pressures. Until recently there were no commercially available devices that met all these requirements. The report also describes a new piezometer system that can provide a continuous assessment of groundwater conditions for positive and/or sub-atmospheric values.

6 Acknowledgements

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Appendix A: Sources of uncertainty in piezometric measurements

A1 Introduction

It is important to appreciate the uncertainties inherent in piezometric measurements and how to recognise where a measurement is in gross error. Piezometric error can be defined as the difference between the measured and the true pressure - i.e. that remote from the influence of the installation.

Three sources of error are considered here:

i That due to leakage along the piezometer leads.

ii That due to the finite time taken for hydraulic equilibration, i.e. the hydraulic response time.

iii Uncertainties due to the presence of air in the piezometer.

A2 Error due to leakage

Leakage can occur along the connection leads of a piezometer, in particular where they pass through the seal to the filter tip and at joints. When a piezometer is placed in fill, leakage can be controlled, to some extent, by compacting relatively impermeable soil around the leads. But it might be difficult to properly compact heavy clay fills in narrow trenches dug to accommodate the leads, and compaction operations can affect the integrity of joints.

Where a piezometer is installed in a borehole, it is usual to install the filter tip in a sand pocket at the bottom of the hole and to fill the annulus around the standpipe with a cement/bentonite grout. Vaughan (1969) examined the operation of a piezometer installed in a sand pocket at the bottom of a borehole filled with grout of permeability k_g, in ground of permeability k. The piezometric error is small provided the permeability of the grout is not more than 20 times that of the ground, but even a larger ratio might not generate a significant error.

The permeability of a compacted clay fill is likely to vary widely. Its structure will consist of large clods of clay embedded in a matrix of coarser infill material. Where the fill is compressed through the weight of the overlying soil in an embankment, it is possible that its permeability will approach that of the intact clay (say 10^{-10} m/s). But where infill material predominates, it is likely that the permeability will be much higher (say 10^{-7} m/s). In this case a grout with a permeability as low as 10^{-9} m/s should provide an adequate seal and, in itself, will not lead to a substantial measurement error.

Figure A1 provides data on the permeability of cement grouts. A small quantity (up to 5 per cent) of bentonite powder is usually added as a stabilising agent to reduce the bleed of the mix. Permeability is a function of the initial water content (or void ratio) of the mix and the time after mixing.

A grout must have a reasonably high void ratio to be pumpable. Grouting should be done by pumping through a pipe to the base of the hole. A convenient way of doing this is to loosely tie a length of flexible hose (lay-flat, plastic tube is suitable) to the standpipe or piezometer leads during their installation. The hose can be pulled free after sufficient grout has been pumped down the borehole; this should ensure that air is not trapped in the hole.

Bentonite pellets, which swell on contact with water, are also a convenient means of sealing boreholes. Rocha-Filho (1975) showed that the seal produced by tipping these pellets into a wet borehole had a permeability of 10^{-10} m/s. However bentonite pellets should be tamped into place to ensure that they do not jam in the hole.

A3 Hydraulic response time

The hydraulic response time is defined as the time taken for the pore water pressure in the piezometer reservoir to

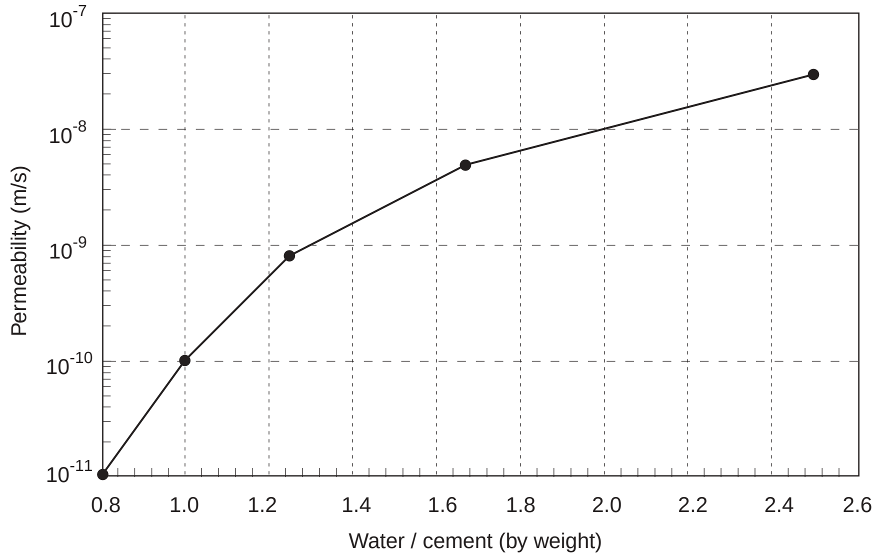

Figure A1 Permeability of cement grouts (data from Littlejohn, 1982) reach a defined degree of convergence with an initially out-of-balance uniform pore water pressure in the soil surrounding the tip.

The theory for the response of a piezometer was developed by Hvorslev (1951) for an incompressible soil, and by Gibson (1963) for a compressible elastic soil obeying Terzaghi's theory of consolidation. These theories can be used to estimate the permeability of the soil from the results of equalisation tests, or to estimate the time for equalisation to occur for a pore water pressure measurement of sufficient accuracy to be made.

The solutions to these theories are plotted in Figure A2, in terms of the dimensionless factor $Fkt/V\gamma_w$, for various values of μ;

$$\mu = \left(F^3.m\right)/\left(16\pi^2.V\right)$$

where F is the intake factor of the piezometer;

m is the coefficient of volume change of the soil (assumed to be equal in compression and expansion); and

V is the volumetric or compressibility factor of the piezometer system – defined as the volume flow into the piezometer for unit pressure change in the cavity.

For an incompressible soil, m = 0, thus μ = 0, and the solution is:

$$E = \frac{u_g - u_t}{u_g - u_0} = exp\left(\frac{-F.k.t}{V.\gamma_w}\right)$$

where, u_g = the pore water pressure in the ground;

u_0 and u_t are the pressures in the reservoir at times t_0 and t respectively;

k is the coefficient of permeability of the soil; and

γ_w is the unit weight of water.

Note that the abscissa can be expressed in other ways, such as by μT where $T = C_v t/a^2$, and C_v is the coefficient of consolidation. (Note also that different symbols are used in the literature.)

As shown in Figure A2, increasing compressibility of the soil accelerates equilibration in its early and middle stages, but it has little influence after about 90 per cent equilibration (i.e. equalisation ratio < 0.1).

Through its effect on the compressibility factor, the hydraulic response time of a piezometer can be substantially lengthened by the presence of air within the reservoir, the sand pocket (if used) and the pressure measuring system. Particular care should be taken to eliminate air from sand pockets; in general the sand should be pre-soaked to saturation before being placed in a water-filled borehole and, where possible, rodded into place.

A3.1 The response of piezometers in the field

In the following, consideration is given to the change in pore water pressure as measured by a piezometer to; a change in drainage; a change in total stress with undrained conditions; installation; and following the completion of an *in situ* test.

Change in drainage

When the pore water pressure in a soil changes through drainage, the rate of change is controlled by the coefficients of permeability and consolidation of the soil. The hydraulic response time of a piezometer is controlled by its permeability and compressibility. Thus where a soil has a low permeability and the pore water pressure changes slowly, the response time of a piezometer will generally be sufficient to provide a reasonably accurate measurement. But where a piezometer is close to a hydraulic boundary at which the pressure changes rapidly,

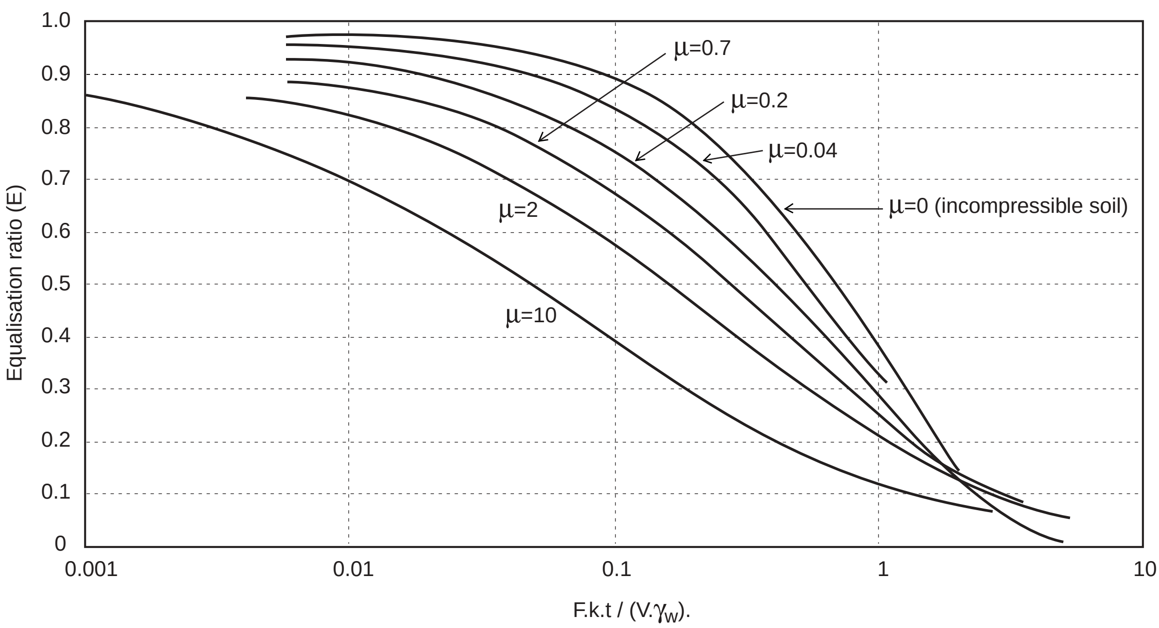

Figure A2 The hydraulic response of a piezometer (after Hvorslev, 1951 and Gibson, 1963) the response time of the piezometer might be too slow to follow the changes in pore water pressures accurately.

Change due to undrained loading

The rate of change in pore water pressure through undrained loading is controlled by the rate of loading and not by the permeability of the soil and so rapid changes in pore water pressure can occur. Normally a piezometer is much stiffer than the surrounding soil and this affects the change in the total stress adjacent to the instrument. Thus the change in pore water pressure close to the piezometer tip might bear no resemblance to that developed at points remote from it. The equalisation of the pressure at the tip to the ‘true’ value depends on the rate at which the pore water pressure in the soil adjacent to the tip equalises, as well as the hydraulic response time of the piezometer.

The time required for the pressure in the perturbed zone to equalise (the so called stress-response time) reduces with decreasing size of the piezometer tip. On the other hand, the hydraulic response time reduces as the size of the tip increases. Where the measurement of a rapidly changing pore water pressure is required, the piezometer tip should be as small as possible because, provided a standpipe is not used, the hydraulic response time will not normally govern. However, the readings from a rigid ‘push-in’ piezometer can be particularly prone to error because the stress change due to loading will be concentrated at the end of the probe where the pore water pressures are measured.

A stiff grout backfill to a borehole may act as a rigid inclusion but clay-cement grouts are usually sufficiently flexible to avoid severe problems of registration. Figure A3 provides data from one-dimensional compression tests undertaken on cement-bentonite grouts.

Equilibration following installation

Through its installation, a perturbed zone of soil is created around the piezometer tip. In this zone, large changes in the stress and pore water pressure regimes can be generated: generally the pore water pressure in the perturbed zone will be reduced from its true value. Thus where the piezometer can respond more rapidly than the pore water pressure in the perturbed zone can equalise, the piezometer may equalise at a lower pressure than the ‘true’ value.

This effect is illustrated in Figure A4, which shows the response of a pneumatic piezometer installed in a sand pocket within a borehole in brecciated Upper Lias clay of low permeability. The figure also shows the response of a standpipe piezometer installed in the same soil. The pneumatic instrument has a rapid hydraulic response time and so equilibrates to the pore water pressure around the borehole: with time the out-of-balance pressure increases to the ‘true’ value. On the other hand, the stress-response time of a standpipe piezometer is shorter than its hydraulic response time and so does not record the temporary out-of-balance pressure.

The time to achieve equilibrium after installation can be reduced, to some extent, by the adoption of an instrument with a faster response time. In impermeable clays, the response time may also be shortened by using small diameter boreholes or a quick setting grout. The permeability in such soils might be of the order of 10^{-12} m/s, in which case equilibrium following installation can be some months. Readings must therefore be taken for some time and at a sufficient frequency to show when equilibrium has been attained.

The use of dry bentonite ‘pellets’ as a borehole seal can also increase the equilibrium time. These pellets will develop large suctions and swell considerably, and therefore substantially affect the pore water pressure regime surrounding the piezometer tip.

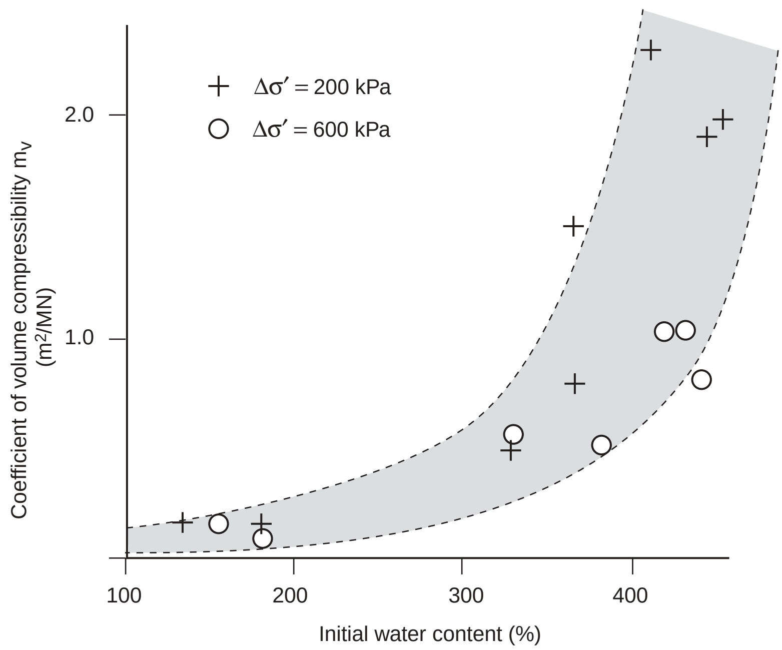

Figure A3 Stiffness of cement-bentonite grouts measured in one-dimensional compression

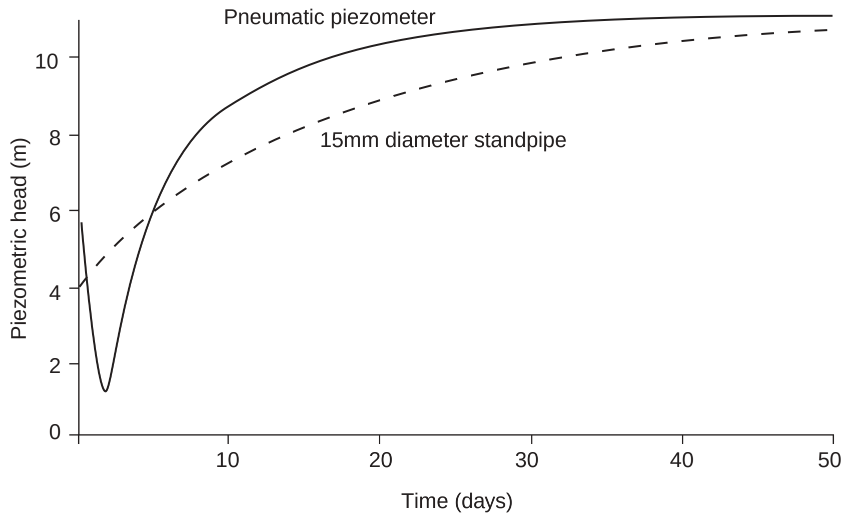

Figure A4 Equalisation of piezometers with different hydraulic response times (after Vaughan, 1973)

Equalisation following in situ tests or 'de-airing' of hydraulic piezometers

Hydraulic piezometers can be used to measure permeability through falling and/or constant head tests, and also to estimate the minor principal total stress from hydraulic fracture tests (see for example Vaughan, 1972). Such piezometers may also be 'de-aired' by circulating water through the connecting tubes under a differential pressure. These operations disturb the pore water pressure regime around the piezometer tip; the size of the disturbed zone depends on the time for which the disturbing pressure has been applied and on the volume of water forced into the soil. Equilibration of pore water pressure is governed by principles similar to those described for stress equilibration.

The equalisation of the pore water pressure measured by piezometers installed in a fill, with a saturated permeability of 2×10^{-7} m/s, following the application of a constant out-of-balance pressure is shown in Figure A5.

A4 The presence of air in the piezometric cavity

The manner of forming a compacted earth embankment leads to air being trapped within the structure of the soil. Therefore the soil is initially (at least) partly saturated, and at this time the pore air pressure will be close to the prevailing atmospheric value and the pore water pressure will be sub-atmospheric (due to the effects of capillarity). The difference between the measured air and water pressures is known as the soil suction. At depth within an embankment the initial pore water suction is likely to be the highest ever experienced; this is because the pore water pressure increases (i.e. the magnitude of the suction reduces) as the fill is placed whilst the pore air pressure equalises with the atmosphere. On the other hand close to the surface, through transpiration, the pore water suction might increase after construction.

Trapped air may be distributed in two ways: a continuous phase (when the permability of the soil to air will be quite high) and as occluded bubbles (when the permeability to air is low because flow can only occur by diffusion). When air is continuous it can equilibrate relatively rapidly to the prevailing atmospheric pressure (even in fine-grained soils). Because the pore water pressure will always be lower than the pore air pressure, a positive pore water pressure in a partly saturated soil usually implies that the air is trapped, i.e. occluded: under

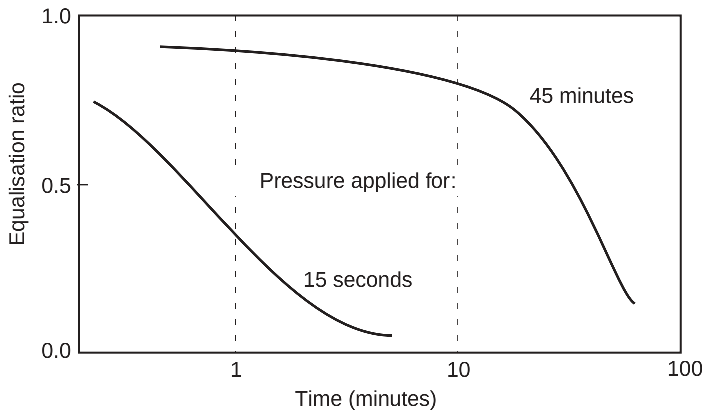

Figure A5 Equalisation of a piezometer (with the intake factor, F, = 13cm) following application of a constant out-of-balance pressure (after Vaughan, 1973) such circumstances it might be necessary to evaluate both the pore air and water pressures.

It is essential to know whether a particular device is measuring the pore water pressure or pore air pressure. Usually measurements of pore water pressure are much more useful because this variable controls the effective stress in the soil and affects drainage. When the pore water pressure is above atmospheric and the pore air is occluded, the effective stress can be computed to sufficient engineering accuracy from the pore water pressure.

The first requirement for a correct measurement of pore water pressure, in the presence of air, is that the pores of the piezometer filter are sufficiently fine for it to be able to withstand an air/water pressure difference (i.e. suction) at its boundary greater than the air/water pressure difference in the soil. The maximum air/water pressure difference a filter can resist is known as its air-entry value, or blow-through pressure.

The accuracy of a measurement of pore water pressure is uncertain when air is present in the cavity of the piezometer. Where the measured cavity pressure is positive it is likely to be close to the actual pore water pressure; in which case the pore air pressure will be positive and the pore air will be occluded. However, where the pore water pressure is negative the measured pressure in the cavity will not necessarily be equal to either the pore water pressure or the pore air pressure. In this case the measured pressure will then depend on:

i the magnitude of the pore water tension;

ii the air entry value of the piezometer filter; and

iii whether the quantity of air in the cavity is constant.

Where the pore water tension is high (say in excess of 80 kPa) the cavity pressure will be quite low. The cavity will only remain full of water if the water in the cavity (and the body of the device) can support the tension. A thoroughly de-aired system will sustain quite high tensions but, in most circumstances, small amounts of air remain in the system and these will form bubbles as the tension approaches an atmosphere. This is usually because piezometers are routinely de-aired using a vacuum, i.e. -1 atmosphere. Since a high air-entry filter will prevent the passage of air bubbles from the exterior to the interior of the piezometer, a partial vacuum will form in the cavity when the tensile capacity of the system is exceeded.

Where the pore water suction in the soil removes all the water from the piezometer cavity and sufficient water has also been removed from the filter to enable air to pass into the cavity, the measured pressure will rise to the prevailing pore air pressure, which most probably will be equal to the atmospheric value. The data, shown in Figure A6, was obtained from a small flushable piezometer with an air-entry value of 100 kPa installed in a very dry clay fill. The data seem entirely believable: but the gradual decrease in suction, consistent with wetting, is due to the presence of air in the cavity. Eventually the pressure increases rapidly to zero as the filter desaturates.

Where the pore water tension is relatively low (say less than 50 kPa) the cavity pressure will equilibrate with the pore water pressure at a rate determined by the hydraulic response time. It is possible that air will not form in the cavity in which case the measured pressure will remain equal to the pore water pressure. It is also possible that air bubbles will form but, if the air entry value of the piezometer filter is sufficiently high, the volume of air may stabilise. At equilibrium, a mixture of air and water will be present in the cavity and the measured pressure will be equivalent to the pore water pressure. When the air is removed from the cavity (by flushing) the measured pressure should rapidly return to the actual pore water pressure.

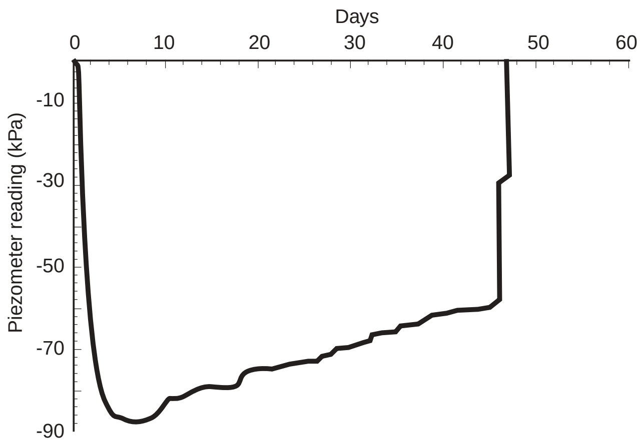

Figure A6 The response of a piezometer to a pore water suction in exces of the air-entry value of the piezometer filter

It is possible that at a relatively low pore water tension the volume of air in the piezometer will continue to increase due to long term diffusion. Figure A7 (a) represents the situation where some air is present in the cavity and, because of its large volume, is at the same pressure as the water in the cavity. In this case the water in the cavity is continuous with the soil water and is at the same pressure. The air in the soil is therefore at a higher pressure than that in the cavity. Thus diffusion of air occurs from the soil to the cavity, relieving the partial vacuum there and leading to an increase in the measured pressure. Throughout this period, the measured pressure lies between the soil pore water and soil pore air pressure, and changes not in response to a change in the soil pore water pressure but to the effects of diffusion. Eventually the cavity is filled with air, as shown in Figure A7 (b), at which point pore air pressure is measured. However, provided the filter does not desaturate, the air can be removed from the cavity and the piezometer once again used to measure pore water pressure.

Figure A8 shows data obtained by a hydraulic piezometer, with a high air-entry filter, installed in a rather dry Mudstone fill at Balderhead Dam (Bishop *et al*., 1964). As shown in the figure, initially a negative pore water pressure was measured, but the pressure increased with time - consistent with a response to wetting-up of the fill. Following de-airing the measured pressure returned to a value close to the initial reading but, again, soon afterwards the readings became unreliable.

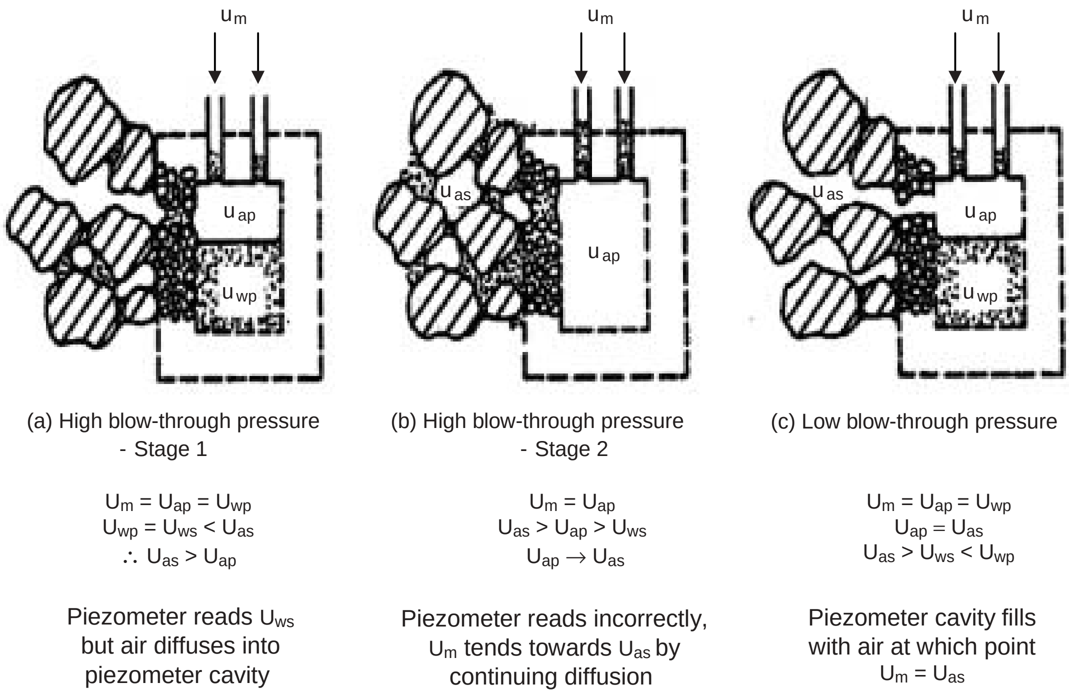

Figure A7 Entry of air into a piezometer cavity

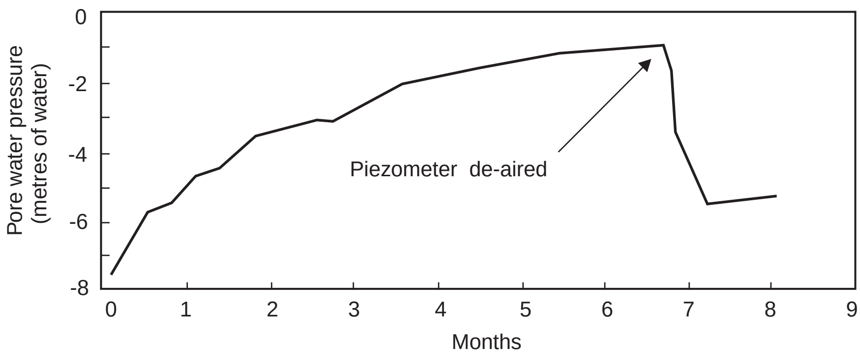

Figure A8 Pore pressure measured in a mudstone fill by a hydraulic piezometer with a high air-entry filter (after Bishop *et al.*, 1964)

As shown in Figure A7 (c), where the air-entry value of the piezometer filter is low or the filter is insufficiently saturated, the measured pressure will increase as the cavity fills with air. This is because the water in the cavity is continuous with the water in the soil, thus at the filter boundary there is air at the soil pore air pressure and water at the soil pore water pressure. Air can enter the filter, displacing the water there into the soil. Once inside the cavity, which is relatively large, the air will be at the same pressure as the water, and flow continues until the cavity is drained of water and full of air. As soon as there is a substantial volume of air in the cavity, the measured pressure will be the pore air pressure. Therefore a method of measuring the pore air pressure is to use a filter with a low air entry value.

Figure A9 shows the pressures measured by twin-tube hydraulic piezometers in a sandy clay fill, which lay between the drainage layers on the downstream side of Selset Dam embankment (Bishop *et al.*, 1964). Pressures were measured by piezometers fitted with low air-entry filters and also with high air-entry filters. At the end of construction (in 1959), similar pressures were measured by both types of piezometer. Those with high air-entry filters showed a systematic decay to zero pore pressure, as expected, between the closely spaced drainage layers. But those with low air-entry filters consistently recorded pressures of about 5 m head of water. When the latter instruments were de-aired they, temporarily, showed pressures close to zero, but pressures then increased quite rapidly following the de-airing. There is little doubt that these instruments were measuring pore air pressure. The high air entry pressure instruments were also de-aired (three times), and the amount of air in them measured. The inflow of air averaged 5 ml/year. Given the size of the piezometer cavity, it would have taken at least 5 years for the cavity to empty and hence for the measurement of pore water pressure to increase to the pore air pressure.

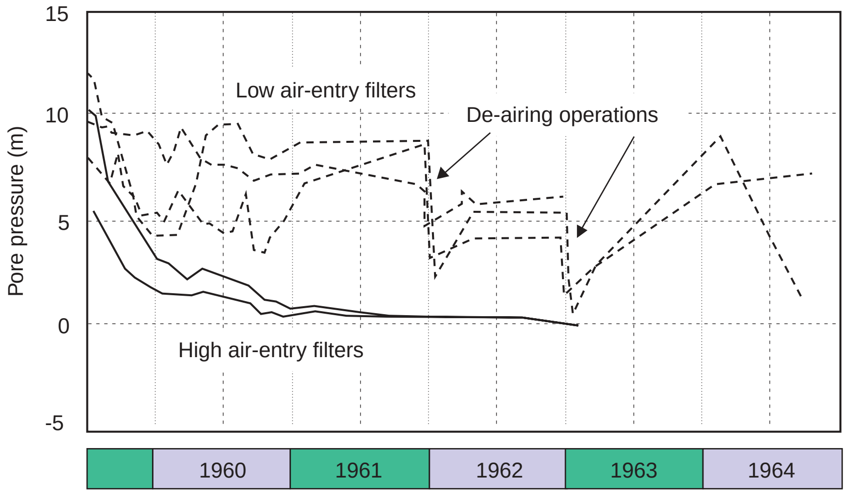

Figure A9 Pore pressures measured by hydraulic piezometers at Selset Dam (after Bishop *et al*., 1964)

Figure A10 provides measurements of pore pressure taken during the construction of Chelmarsh Dam. The data are from (a) an hydraulic piezometer fitted with a high air-entry filter, and (b) an electrical piezometer with a small sealed cavity and a low air-entry filter (Penman, 1978). The electrical piezometer, which might be expected to measure pore air pressure, consistently measured a higher pressure than the hydraulic piezometer, which might be expected to measure pore water pressure.

The following additional points should be noted:

i Diffusion is due to mass transfer and will only occur where there is air present in both the piezometer cavity and the soil. Therefore the removal of air from the piezometer cavity is a prerequisite for the prevention of diffusion.

ii The rate of diffusion of air into the cavity of a piezometer is proportional to the length of the diffusion path and to the absolute pressure difference. Therefore lengthening the diffusion path should increase the time which elapses before the pore water pressure measurement breaks down.

iii Where air is continuous, the length of the diffusion path is constant. Where air is occluded, the length of the diffusion path increases as the bubbles nearest to the piezometer filter diffuse into the cavity; this slows down the rate at which the cavity drains.

iv From the above, it may be expected that a piezometer reading will break down relatively quickly when the pore water pressure is low, $u_a - u_w$ is large, and the air is continuous. Conversely it is unlikely to break down when the pore water pressure is above atmospheric, $u_a - u_w$ is small, and the pore air is occluded.

iv To measure pore water pressure accurately it is not sufficient for the piezometer to have a high air-entry filter: the seals between the filter and the piezometer body must meet the same criteria, as must the connections and any tubing used with hydraulic instruments.

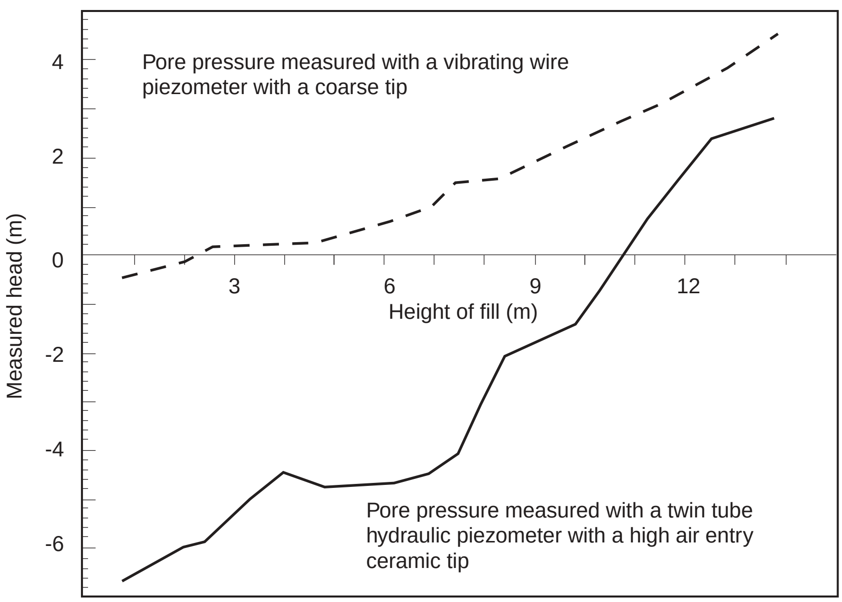

Figure A10 Measurements of pore pressures during the placement of compacted fill (after Penman, 1978)

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Abstract

Embankments and cuttings are used to provide a reasonably uniform vertical alignment to highways. Increasingly, emphasis is being given to the long-term maintenance of these earthworks. Their long-term stability is influenced by a number of factors but of particular importance is the pore water pressure regime. There is a need for accurate pore water pressure data to define in-service conditions and to identify potential and actual failure mechanisms. However, in the main, the pore pressure sensors that have been commonly used are either unreliable or cannot provide a continuous data set.

This report reviews the theoretical background and the development of piezometers. It discusses the problems that might be encountered when using such devices, and describes the development, operation and use of a new suite of piezometric equipment designed to continuously monitor the variation in pore water pressure. Data obtained with the new piezometric equipment from a highway embankment are also presented and discussed.

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