FMGM 2015 – PM Dight (ed.)
© 2015 Australian Centre for Geomechanics, Perth, ISBN 978-0-9924810-2-5

Soil suction — what it is and how to successfully measure it

AM Ridley *Geotechnical Observations Ltd, UK*

Abstract

Soil suction (or negative porewater pressure) is important to the development of strength and changes of volume in soils that lie above the natural water table. The presence of soil suction is particularly important in the study of slopes where, should the porewater pressure increase, stability brought about by suction-induced increases of strength can be compromised. Over the last 20 years, methods for measuring soil suctions in laboratories and on sites have been developed. These have made it possible to make reliable measurements and have been be used to further our understanding of the role that suctions play in slope stability. This paper presents the background to the presence of soil suctions in ground, advances made in instrumentation for measuring soil suctions and field measurements made by the author.

1 Introduction

In recent years, soil suction has assumed a greater role in geotechnical engineering. There has been a number of reasons for this but the main ones are probably the emergence of new tools for measuring soil suction in the laboratory and in the field, together with a better understanding of the importance of soil suction and how to use it in geotechnical analysis. Measurements of soil suction can be used to estimate in situ stress (p’), an important parameter in the design of underground structures, and from such measurements, it can also be used to assess disturbance in clay samples after they have been removed from the ground. Soil suction is also of critical importance to the behaviour of clay embankments, excavations and slopes. It is the study of the latter that this paper will focus on.

Infrastructure embankments and cuttings are used to afford the passage of roads, railways, rivers and canals with a minimal need for changes in vertical alignment. In the cases of canals and railways in particular, many of these earth structures were constructed before the development of modern soil mechanics. The change in condition of the materials used to construct them and their progressive deformation has a critical effect on their long-term serviceability and stability. Finite element analyses indicate that seasonal cyclic stress changes cause a gradual outward movement in embankments formed of plastic clays, which induces strain softening and this can eventually lead to collapse through a mechanism of progressive failure (Kovacevic et al. 2001). These analyses suggest that the horizontal mid-slope movements and the number of cycles required to cause failure are linked to the amplitude of the porewater pressure variations. Finite element analyses also suggest that the long-term stability of cuttings formed of plastic clays is influenced by the gradual and slow increase of the porewater pressures that are initially decreased to negative values during excavation to form the slopes (Potts et al. 1997). These analyses also show that retaining a small suction at the surface boundary at the end of winter can significantly prolong the time to failure in embankments and cuttings that are formed of plastic clays. If analyses such as these are to be used, in a proactive way, to assess the serviceability and or stability of slopes it is therefore essential that they be fed with good data on porewater pressures and deformations, obtained from reliable field measurements.

2 What is soil suction and where can I get some?

Historically, soil mechanics theory has concerned itself mainly with the behaviour of what are termed saturated soils. This is not surprising, given that geotechnical engineering developed in temperate regions of the world where water tables are generally close to the surface and the foundations of most major structures are located below the prevailing water table. At such depths, the void space within the soil is considered full of water and the pressure in the water phase is a function of depth, the specific weight of the water (γ_w) and the hydraulic boundary conditions, e.g. the drainage conditions. This porewater pressure is generally positive and relatively easy to measure. The following paragraphs and figures demonstrate how complicated porewater pressure profiles can be, especially in the ground that lies above the water table (known as the vadose zone).

If the water contained in the voids of a soil was subjected to no other force than that due to gravity, the soil above the water table would be completely dry. However, powerful forces cause the water to be drawn into the otherwise empty void space in a similar way to how water is drawn upwards into a small bore tube by capillary attraction. These forces include molecular, physical-chemical forces acting at the boundary between the soil particles and the water, evaporation and transpiration acting at and close to the surface. The combination of these forces gives soil lying above the water table an attraction (or potential) for water that is termed 'soil suction' and is usually represented as negative porewater pressure (although there is no proof that the pressure in the water is actually negative relative to atmospheric pressure). Graphically it is customary to use the water table as a reference, e.g. zero, and to represent the porewater pressures in ground lying above the water table as negative values and an extrapolation of the positive porewater pressures that exist below the water table.

It is important to recognise that the pore pressure profile is ultimately determined by the net flow conditions at the boundaries. Water that lies below the water table is normally referred to as being at hydrostatic equilibrium, a term that implies there is no vertical flow occurring. In the absence of osmotic effects and significant velocities, the potential for flow is derived from the relative position (gravitational head) and pressure potential (positive or negative), the combination of which are termed the total potential (Figure 1). Flow will occur from locations with a high total potential to those with a low total potential. If the relative position is referenced to the surface, a hydrostatic pore pressure profile results in no gradient of total potential and therefore no vertical flow. Furthermore, upward flow towards the surface will result in a pore pressure profile that lies to the left of the hydrostatic profile, whereas downward flow will result in a pore pressure profile that lies to the right of the hydrostatic profile.

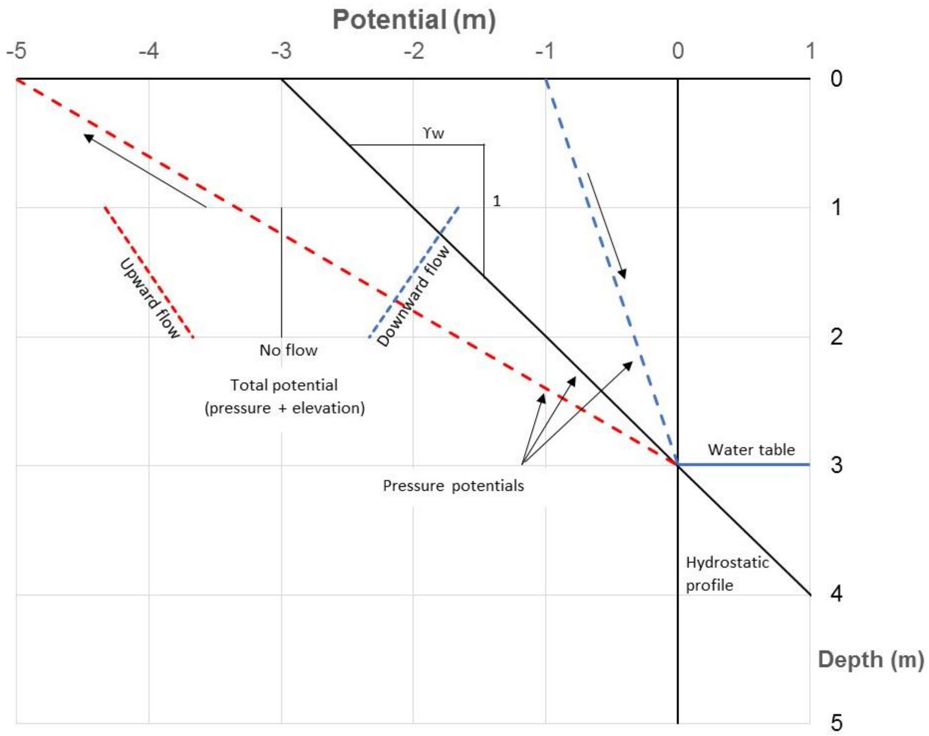


Figure 1 Flow conditions caused by different porewater pressure profiles

The development of a porewater pressure profile following net evaporation from a flat horizontal surface is shown in Figure 2 (adapted from Wellings & Bell 1982). The profile is assumed to be initially in equilibrium with net surface infiltration and flow through to the water table, resulting in a pore pressure profile that lies to the right of the hydrostatic condition. This is typical of the porewater pressure profile at the end of a wet winter in the UK. When evaporation exceeds infiltration from the surface a zero flow plane (ZFP) will be established where the pore pressure profile becomes parallel to the hydrostatic condition. Above this plane there will be net upward flow and below the plane there will be residual drainage through to the water table. If the evaporation continues with the same surface porewater pressure, the ZFP will gradually penetrate the profile towards the natural water table and the hydrostatic profile will be re-established. If, however, the surface porewater pressure continues to reduce, the pore pressure profile will transcend the hydrostatic condition above the water table and the ZFP will merge with the zone of no vertical flow at the upper surface of the capillary fringe. Persistent evaporation will subsequently cause the water table to move down in the profile.

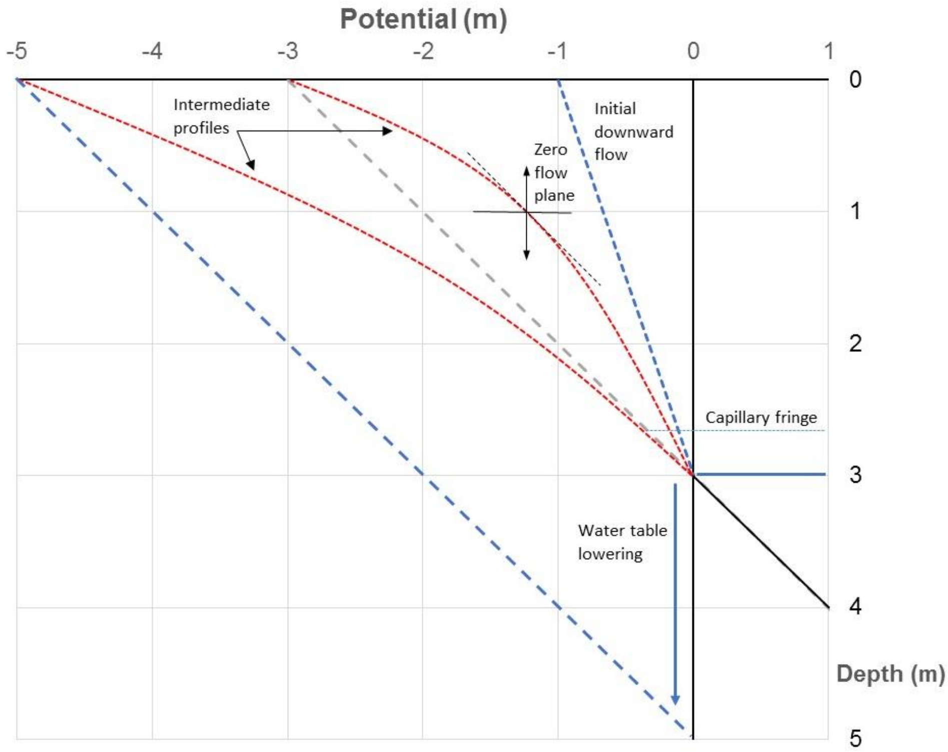


Figure 2 Development of a porewater pressure profile in the vadose zone due to evaporation

If infiltration at the surface again starts to exceed evaporation a second zero flow plane will develop that will also gradually penetrate towards the water table from the surface (Figure 3). However, in the case of this plane, the flow is downwards from above the plane and upwards from below the plane. When the two zero flow planes meet, the initial conditions of infiltration at the surface and percolation through to the water table are re-established. Prolonged infiltration may eventually result in the water table rising.

The progress of infiltration from the surface to the water table is affected by, amongst other things, the saturation and permeability of the ground in the vadose zone. When a soil is fully saturated, water can flow through all of the voids and the rate at which the water can flow is governed by the soil's porosity, tortuosity and change in total potential in accordance with Darcy's law (for simplicity, here modelled as one-dimensional, in accordance with the framework presented in Figures 1 to 3).

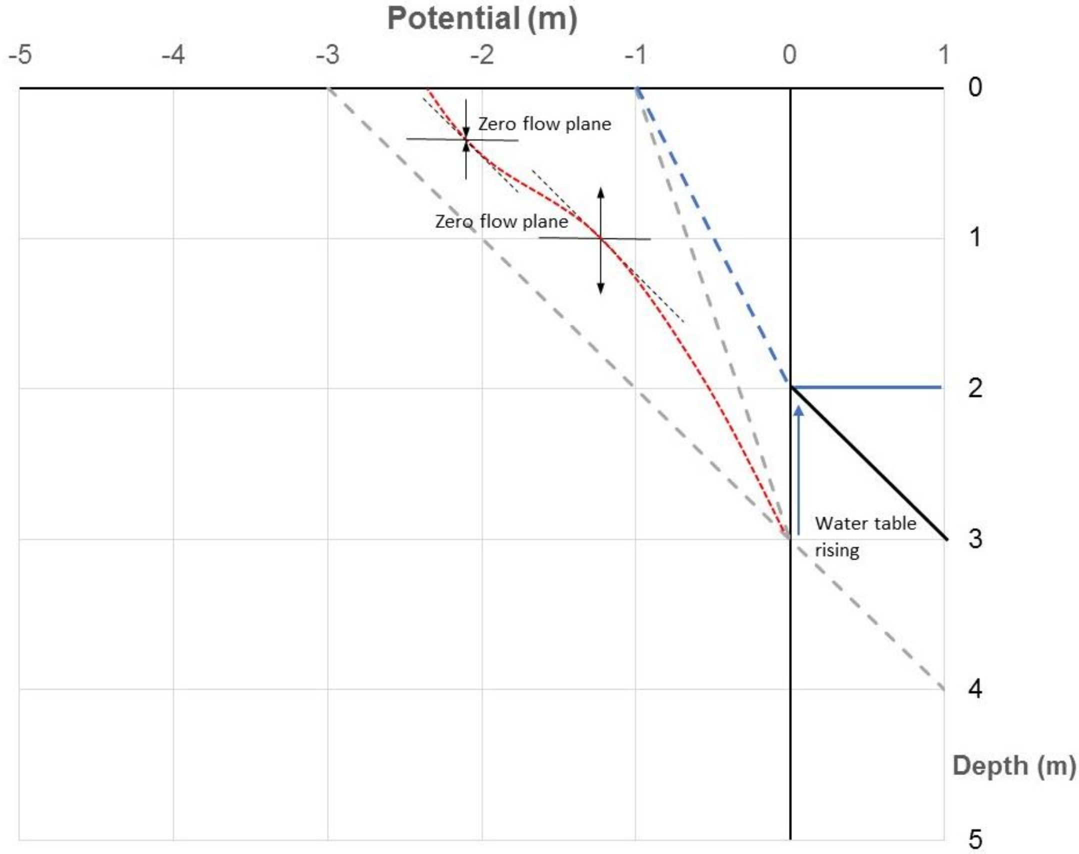


Figure 3 Development of a porewater pressure profile in the vadose zone due to infiltration

When a soil desaturates, it does so in a progressive manner with the water initially draining from the larger voids. Water that is subsequently added to the soil profile can (i) pass through the profile by moving through those voids that are full of water or (ii) enter the partially full voids and gradually fill them. In all probability, a combination of (i) and (ii) will prevail. If the intensity of the rainfall exceeds the ability of the soil to absorb water at the surface (referred to as the infiltration capacity) the water that does not infiltrate the profile will either pond and then evaporate or will run off. If the infiltration capacity of the soil is satisfied a zone will be generated close to the surface that has a high degree of saturation. A temporary hydrostatic condition may then be established in the profile, lying above the permanent water table (Figure 4). In these circumstances there will be a net downward flow from the upper zone to the permanent water table and negative porewater pressures can exist that are sandwiched between two zones of positive porewater pressures. This situation can also occur in clayey soils when cracks exist at the surface and persistent rainfall causes the cracks to fill with water.

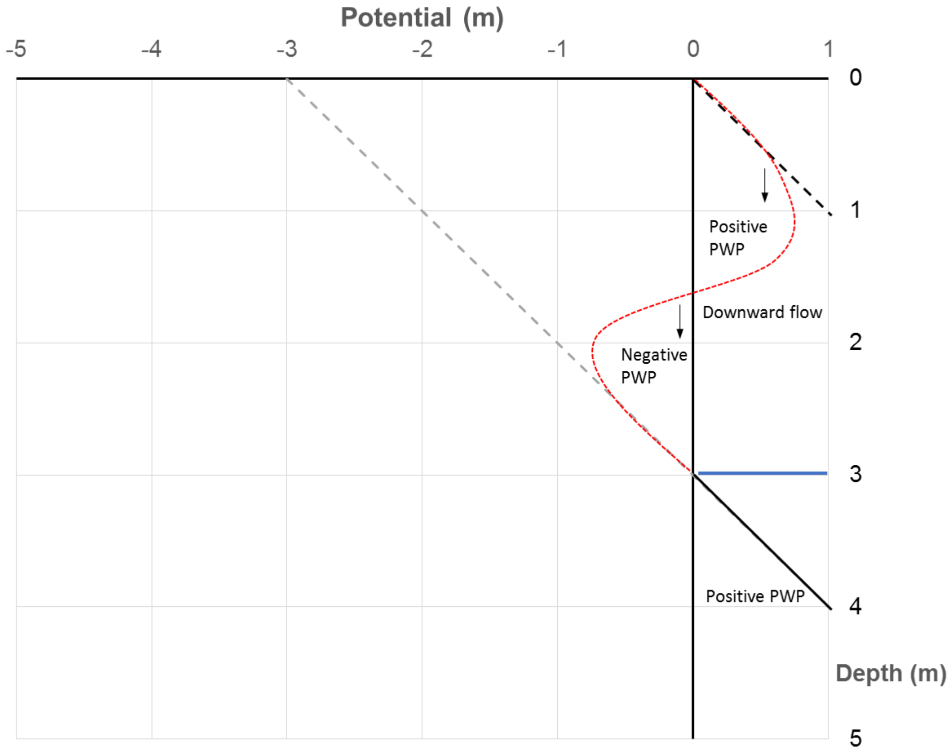


Figure 4 Typical porewater pressure profile in a soil profile with variable permeability

The topography of slopes is generally above the zero pressure horizon for porewater pressure and the foregoing discussion illustrates that if the porewater pressure profile and its influence on the stability of slopes is to be correctly interpreted and understood, it is essential to make measurements of porewater pressure at a range of depths (above and below the water table) in the profile. The foregoing discussion also illustrates that devices for measuring porewater pressures in the vadose zone should ideally be capable of measuring both positive and negative porewater pressures. This is a theme that will be developed later in this paper.

3 How to successfully measure soil suction

The study of soil moisture is considerably older than the study of soil mechanics with Buckingham (1907) being amongst the first to investigate this subject. It was agriculturalists rather than engineers who recognised the significance of the subject, except, that is, for Terzaghi, who made several references to the importance of soil suction in his works.

In 1935, Schofield, working at the Agricultural Research Station in Rothamsted, Hertfordshire, UK, published a paper on 'The pF of soil water', which detailed the definition of and methods of measuring soil water potential (or soil suction) at that time (Schofield 1935).

There are a wide range of devices for measuring soil suction, many of which make what are known as indirect measurements, which means that rather than measuring the soil suction directly they measure a related property (e.g. humidity) that is related to the soil suction and convert the measurement to a soil suction using an appropriate calibration. These indirect methods of measurement are comprehensively covered by Ridley and Wray (1996). This paper and the measurements presented in it will concentrate on direct measurements of negative porewater pressure.

All piezometers with diaphragms (vibrating wire, electrical and fibre-optic) have potential to measure negative porewater pressures. It is only the measurement range that is limited. The key thing to keep in mind is that it is the attraction that a soil has for water (i.e. soil suction) that is being measured and that to successfully transmit that to the device that is making the measurement, i.e. the diaphragm, the piezometer has to remain saturated and the water in the device must be in contact with the water in the soil. If there is air inside the piezometer the volume of air will increase or decrease depending on which direction the water is flowing. Pure water has a very high tensile strength and if there is no air present inside a piezometer it is possible to transmit the high attractive force that some soils have for water, directly to the diaphragm and measure it using whatever measuring device is chosen, e.g. vibrating wire, electrical strain gauge or fibre optic. This is why it is misleading to refer to negative porewater pressures in terms of 'atmospheres'. Providing there is no air in a piezometer, there is no partial vacuum and the water can exist at positive pressures or in tension until the bonds between the water molecules or at the surface between the water molecules and anything else are ruptured.

The generic term for instruments that directly measure negative porewater pressures is 'tensiometers'. A tensiometer consists of a porous filter and a means of measuring stress, which are separated by a fluid (usually water) filled reservoir. Tensiometers are therefore similar in their constituent parts to piezometers. They work by allowing the water to be extracted from the tensiometer, 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. When this condition is present, no further exchange of water will occur between the soil and the tensiometer. The soil suction will then manifest itself in the reservoir as a tensile stress in the water and can be measured by the stress measuring instrument, e.g. a manometer, a vacuum gauge or an electric pressure sensor. In this way tensiometers measure porewater tensions or negative porewater pressures.

In specifying the design of a tensiometer, it is possible to vary (a) the location of and type of pressure sensor, (b) the porous filter, (c) the volume of the fluid in the tensiometer, and (d) the material from which the tensiometer is constructed. Whilst researching the movement of moisture beneath covered areas, Black et al. (1958) used a tensiometer that had a glass tube with a 1 mm bore, a sintered glass filter with an average pore size of 1 micron and a mercury manometer located remotely from the filter. Using this arrangement they were able to make suction observations up to about 94 kPa and state that this was extended by up to a further 100 kPa using filters with a smaller average pore size.

More recently, the design of commercially available tensiometers changed to make use of modern and cheaper materials. The most common construction uses a transparent stiff nylon tube with a 9.7 mm bore, a pressed kaolin ceramic filter with a pore diameter of about 2 microns and a differential vacuum gauge located remote from the filter (Figure 5). In addition to the normal attributes, 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 any air that may form within the measuring system with water. This type of tensiometer has received widespread use but can, in some circumstances, give quite misleading measurements. Ridley et al. (1998) reported their use for measuring soil suctions in clay embankments. A number of vacuum gauge tensiometers were installed in a 70-year-old vegetated embankment that consisted of clay fill overlain by a variable thickness (up to 3 m) of granular fill. The ceramic filters were located approximately 50 cm into the clay fill. Figure 6 shows observations made over an eight month period on a tensiometer buried at a total depth of 1.21 m and with the vacuum gauge deliberately left protruding 50 cm above the ground surface.

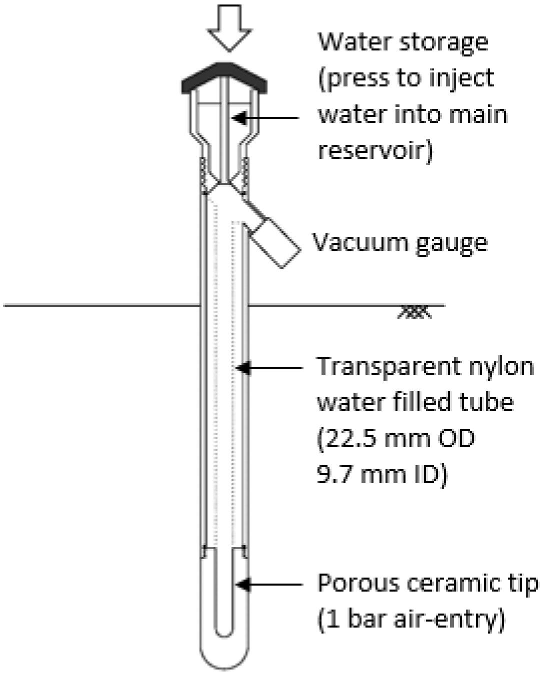


Figure 5 Schematic of a vacuum gauge tensiometer

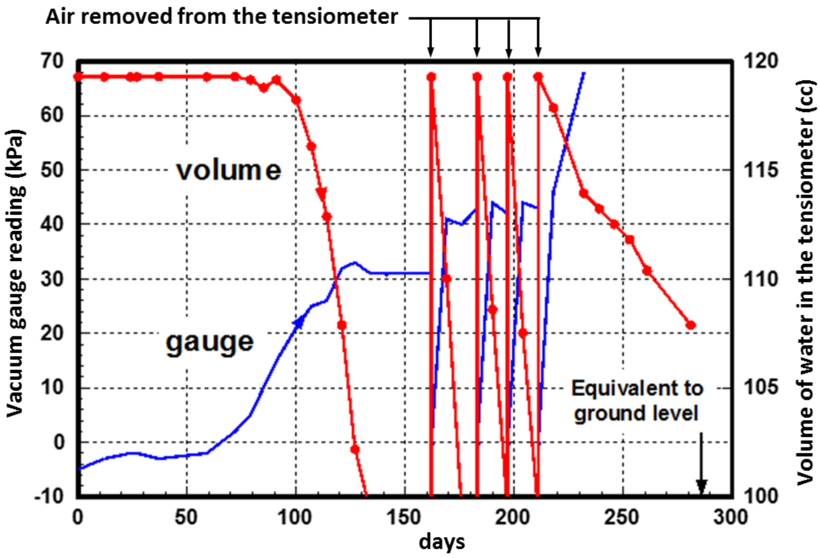


Figure 6 Field tests with a vacuum gauge tensiometer (after Ridley et al. 1998)

Although the suctions measured by the tensiometer are entirely believable, the presence of air within the tensiometer gave some cause for concern. Note that the volume of water in the tensiometer starts to reduce as soon as tension starts to be recorded by the vacuum gauge. Eventually the level of the water would disappear below ground level and the reading on the vacuum gauge became steady at about 30 kPa. When the air was removed from the tensiometer by introducing water from the storage container, more air would quickly form and the measured tension would increase again slightly. This means that the no-flow condition required for an accurate suction measurement was not being achieved. Furthermore, in some instances, if a tensiometer was left without flushing air from the reservoir, the quantity of air would continue increasing until eventually the tensiometer would record a zero suction, a measurement that was obviously incorrect. The concern with these observations was that it is normal practice to bury a tensiometer of this type so that the vacuum gauge is located just above ground level. Under such circumstances the presence and amount of air in the reservoir could be uncertain and the measurements could be misleading.

In 1990, the author of this paper first observed the ability of water to sustain tensile stresses in excess of 100 kPa, something that Black, Croney and Jacobs had mentioned in their 1958 paper (Black et al. 1958). This led the author of this paper to undertake detailed studies of the properties of water, in particular hydraulic tensions, and to design a new tensiometer (Ridley & Burland 1993) with a vastly reduced reservoir (~15 mm^3) made from stainless steel, a pressed kaolin ceramic filter with a pore diameter of about 0.2 microns (equivalent to an air entry value of about 1,500 kPa), and a high range electric pressure sensor located close to the filter. Ridley and Burland (1995) improved the design of their suction probe by reducing the volume of water in the device to about 3 mm^3 (Figure 7). These devices have been repeatedly used to measure soil suctions in excess of 1,500 kPa in field and laboratory situations and the principles behind their success will now be described.

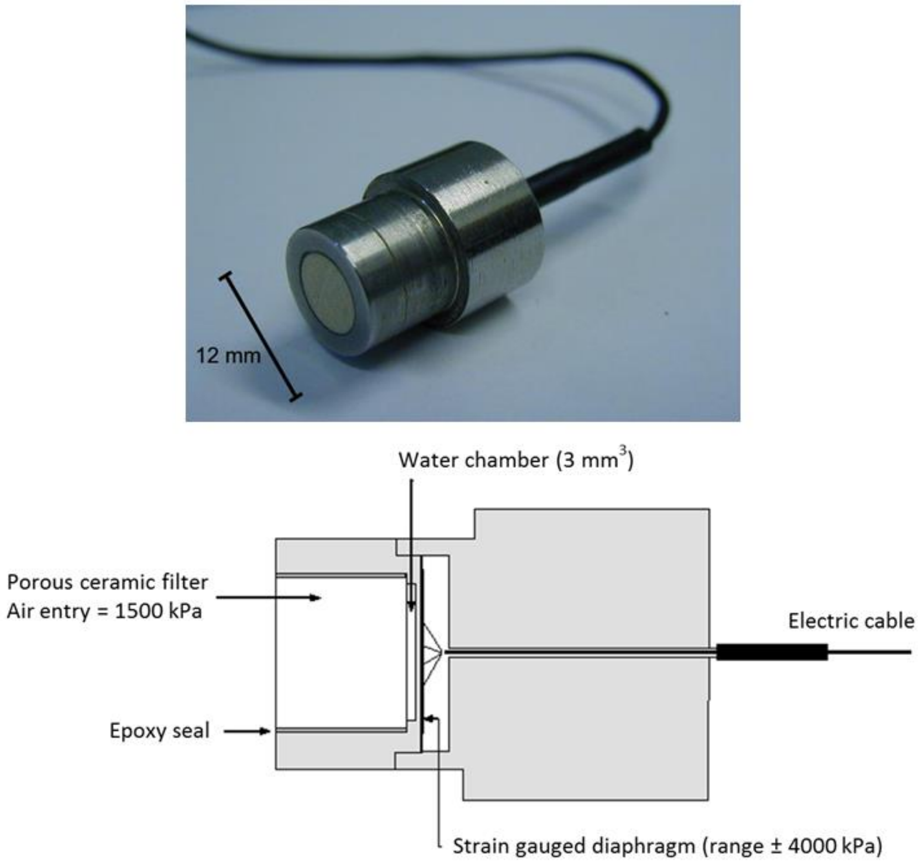


Figure 7 A suction probe (after Ridley & Burland 1995)

The four factors that restrict the measurement range of tensiometers are (i) the procedure used to remove air from the tensiometer, (ii) the volume of water in the tensiometer, (iii) the material used to manufacture the body of the tensiometer, and (iv) the pore size of the porous filter. The range of operation of all tensiometers is limited by the formation of vapour cavities within the tensiometer as discussed previously for the vacuum gauge devices. In the field of soil mechanics the phenomenon of cavitation has been used to explain the formation of air in pore-pressure measuring systems that are subjected to a hydraulic 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 extremely high tension, i.e. about 50 MPa, or when the liquid is superheated, e.g. boiled. Since neither of these conditions exist within a tensiometer when air forms within it, its presence cannot be due to a rupture of the molecular bond between adjacent water molecules. Nevertheless, 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 (Figure 8(a)). When the water inside a tensiometer is placed in a state of tension by, for example, an applied vacuum or when the tensiometer is placed in contact with a soil that has an attraction for moisture, i.e. a soil suction, the air trapped in the imperfections can easily be drawn out of them to form a bubble (Figure 8(b)).

Harvey et al. (1944) found that if the water inside a container had been previously compressed it could withstand tension. Therefore, by pressurising the water in the container, the air trapped in an imperfection is dissolved further into solution. When the high pressure is subsequently reduced back to the ambient atmospheric value, 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 (Figure 8(c)) and the water in the container is then capable of resisting a high, i.e. >100 kPa, tensile stress.

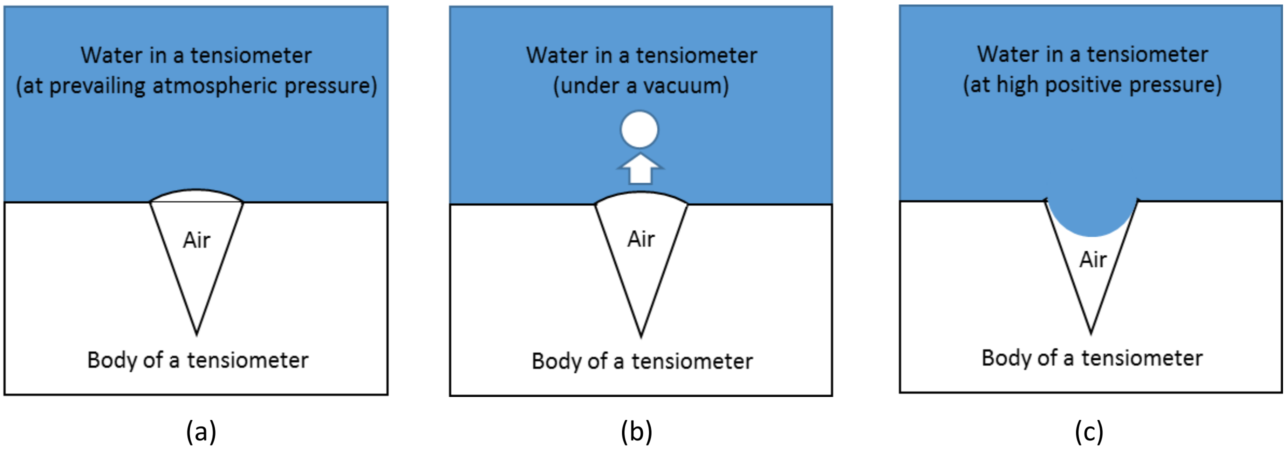


Figure 8 Mechanisms for trapping air inside a tensiometer

The number and size of imperfections within a tensiometer will be determined by the size of the water chamber, the material used to manufacture the tensiometer and the presence of impurities within the water inside the tensiometer. Nylon is more likely to contain such imperfections than glass or stainless steel and; therefore, nylon tensiometers require very thorough de-airing to achieve a reasonable operating range. Furthermore, the procedure of introducing water into the tensiometer through the porous filter (used by Black et al. 1958) 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 they 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. A vacuum pump is then applied to the top of the tensiometer and used to remove any large air bubbles from the device prior to fixing the storage container to the top of the tensiometer.

A suction probe is assembled dry and water is introduced into the filter and the reservoir by (i) placing the device in an evacuated chamber (Figure 9(a)) with water at a level below that of the suction probe, (ii) adjusting the orientation of the chamber so that the suction probe is immersed in the de-aired water (Figure 9(b)), and (iii) allowing the chamber to return to the prevailing atmospheric pressure whilst keeping the suction probe immersed. The suction probe is then removed from the chamber and placed in a manifold that allows a hydraulic pressure of 4,000 kPa to be applied (Figure 10) for a period of at least 24 hours.

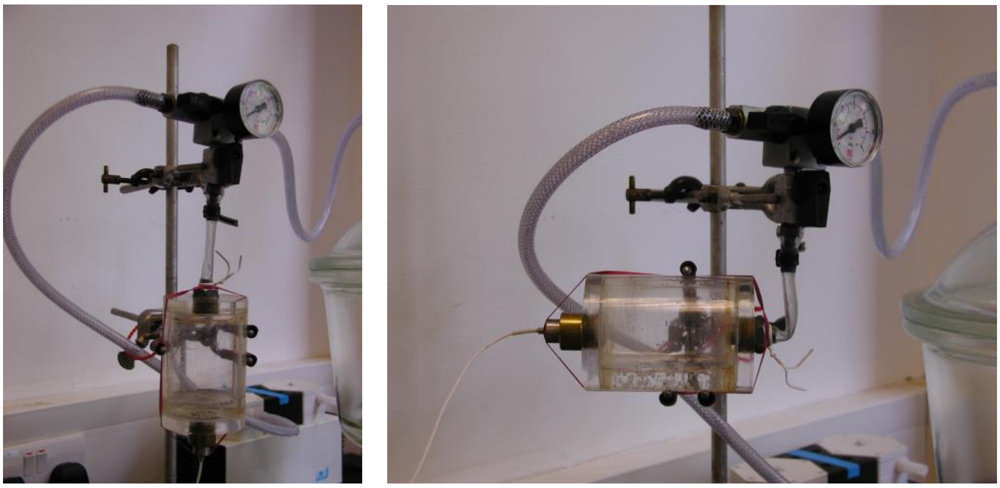


Figure 9 Vacuum equipment used for saturating suction probes

Figure 10 Hand-pump for pressurising suction probes

When placed in contact with a soil that has a high suction, the water inside the suction probe is drawn out of the device but the water that remains in the device can sustain the tension and transmits it to the strain gauged diaphragm, which deforms thereby recording the tension (Figure 11). In laboratory exercises, the tension has been sustained for many months (Monroy 2006).

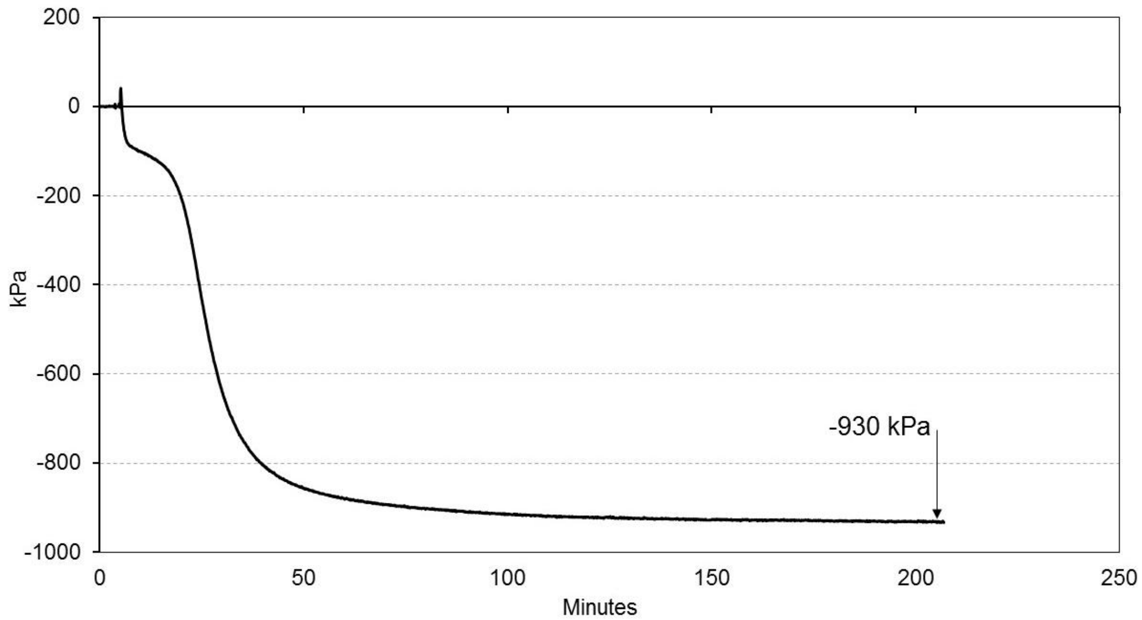
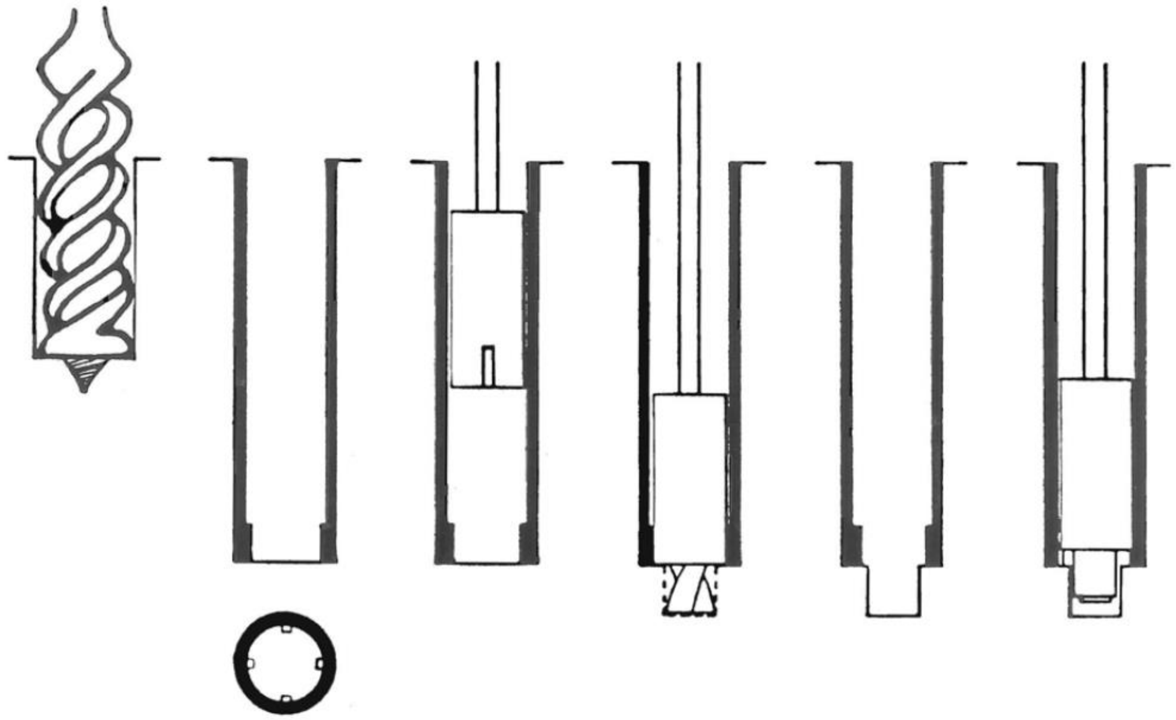


Figure 11 Typical suction probe measurement

Even in a thoroughly de-aired tensiometer, air can form in the water chamber when the difference between the tensile stress in water within the chamber and the atmospheric air pressure outside the tensiometer is equivalent to the air entry value of the porous filter, causing air to be drawn through the filter under the influence of the differential pressure. Ridley and Burland (1995; 1999) demonstrated this to be so by inserting ceramic filters with different air entry values into suction probes and allowing water to evaporate from the exposed surface of the filters. The maximum tension recorded by the suction probes increased as the pore sizes of the filters decreased. Suction probes are routinely fitted with porous filters that have air entry values that are at least 1,500 kPa, and that is a key factor in their successful measurements of high porewater tensions.

The complete removal of all air from a suction probe is practically impossible because it would require the application of an infinite positive pre-stress. The tiny amounts of air that remain inside a suction probe have sub-atmospheric pressure due to the presence of the hydraulic tension. Although the air inside a suction probe is enclosed within imperfections in the surface of the device and does not affect the ability of the water in the device to sustain tension, a diffusion gradient exists across the saturated ceramic filter and air can pass through the filter under the influence of this gradient. If sufficient air passes through the filter to form a bubble within the suction probe, the hydraulic tension in the device can be broken and if that happens, the pressure will rise instantaneously to the ambient atmospheric value. The device must then be subjected to a high positive hydraulic pressure again as quickly as possible to remove the air. This problem is particularly problematic in partly saturated soils where air at atmospheric pressure is more common.



(a) (b) (c) (d) (e) (f)

Figure 12 Method of making in situ measurements with suction probes

Ridley and Burland (1996) presented a technique for introducing suction probes into shallow boreholes. The need for routine pressurisation of suction probes, if air forms within them, means that the devices must be removable from the borehole and long-term continuous measurements are therefore not very practical. An initial borehole is sunk using a 63.5 mm diameter helical hand auger (Figure 12(a)). When the required depth is reached the borehole is cleaned out and lined with a 50.8 mm internal diameter plastic pipe (Figure 12(b)). To make representative measurements of suction it is necessary to ensure a good all-over contact between the ceramic filter and the soil. To do this a smooth, relatively undisturbed, horizontal bottom is required for the borehole. Standard hand augering tools cause considerable disturbance to the soil at the bottom of the augered borehole, particularly in the centre of the hole. A tool was therefore designed that can be placed at the bottom of the initial borehole and used to carefully drill up to 76.2 mm below the bottom of the borehole. The tool consists of a 34.925 mm diameter milling machine slot cutter that is fitted to a standard hand auger extension rod (gas pipe) using a connecting bar. The cutter is free to slide inside a metal barrel, with an external diameter of 50.8 mm that is lowered inside the plastic pipe. During the lowering operation the barrel is prevented from falling (Figure 12(c)) by a using a pin locking mechanism on the connecting bar. When the barrel arrives at the bottom of the borehole, tabs fitted to the inside of the plastic pipe locate in slots cut into the outside of the barrel (Figure 12(d)). This prevents the barrel from rotating in the borehole whilst the secondary hole is being drilled. The cutter is then rotated and advanced downwards (Figure 12(d)) until the pins in the connecting bar are flush with a stop fitted to the inside of the barrel. In clay, trimmings from the secondary hole are deposited inside the barrel and the bottom of the hole is left smooth and horizontal (Figure 12(e)). After completion, the barrel is removed from the borehole and cleaned. Any trimmings taken from the barrel can be used to estimate the in situ moisture content of the clay at the depth of the suction measurement. The cutter and connecting bar used to drill the secondary hole are replaced by another connecting bar fitted to a spring loaded mounting for a suction probe. The spring holds the suction probe proud of the mounting until the latter is resting on another flat surface, i.e. the bottom of the secondary hole. The mounting and the connecting bar are fitted inside the barrel in a similar manner to the cutter. The barrel is then lowered inside the plastic pipe and located once again by the tabs. Finally, the mounting with the suction probe is lowered to the bottom of the secondary hole (Figure 12(f)) and the spring depresses until the mounting and the suction probe are flush with the soil.

By making comparisons between the behaviour of a vacuum gauge tensiometer and a suction probe, Ridley et al. (1998) showed that air only formed in the vacuum gauge tensiometer when the suction was 25 kPa or more and that providing the tension in the tensiometer remained less than 50 kPa the volume of air remained controllable. However, when the tension was greater than 50 kPa the formation of air became uncontrollable and, if the tension of 50 kPa was maintained, the tensiometer eventually became dry. Extreme caution should therefore be exercised when using vacuum gauge tensiometers for measuring soil suctions in engineered soils, where the soil suctions can be quite high. This is not necessarily the case for agricultural soils where densities are usually much looser and the moisture condition that is most beneficial to the successful uptake of water by plants is at water contents that are closer to the field capacity, which in most circumstances is equivalent to a soil suction that is less than 25 kPa (Biddle 1998).

Aside from the limited measurement range over which air is unlikely to form in a tensiometer, the principle disadvantage of vacuum gauge tensiometers is that the sensor (the vacuum gauge) and the porous filter are separated by a vertical distance and this reduces the range of measurement further, by approximately 10 kPa per metre of separation. To avoid the reduction in operating range; therefore, the sensor and the porous filter should be placed as close as possible to each other (as is the case for suction probes). For in situ measurements, this may require the pressure sensor to be buried below the surface. In slopes and embankments, however, the pressure sensor can be located at the same elevation as the porous filter and on the surface of the slope by connecting them horizontally. If air forms in a tensiometer, it will still need to be removed and this will require a system that can introduce water into the tensiometer without removing the device from the ground. Bishop et al. (1964) used water filled tubes to flush water around a hydraulic piezometer and successfully measured suctions up to about 80 kPa, providing the porous filter and the sensors (in this case, Bourdon gauges) were located at the same elevation. Twin-tube piezometers, as they became known, suffer the same limiting factors as vacuum gauge tensiometers though when they are used in boreholes. Ridley et al. (2003) introduced a modified twin-tube piezometer (Figure 13) in which water can be circulated through tubes to remove any air if it forms, and the hydraulic system can be isolated close to the pressure sensor after the air has been removed to avoid the need for any pressure corrections caused by a head of water being above the pressure sensor. This device has been used to measure suctions up to about 90 kPa at depths of about 10 m inside boreholes. It also has the distinct advantage over the vacuum gauge tensiometer that it can measure positive porewater pressures too.

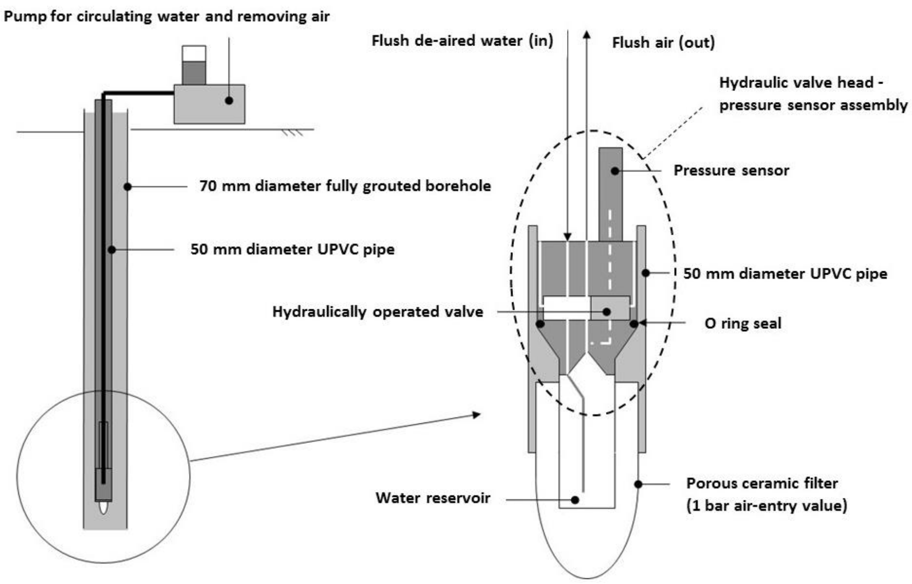
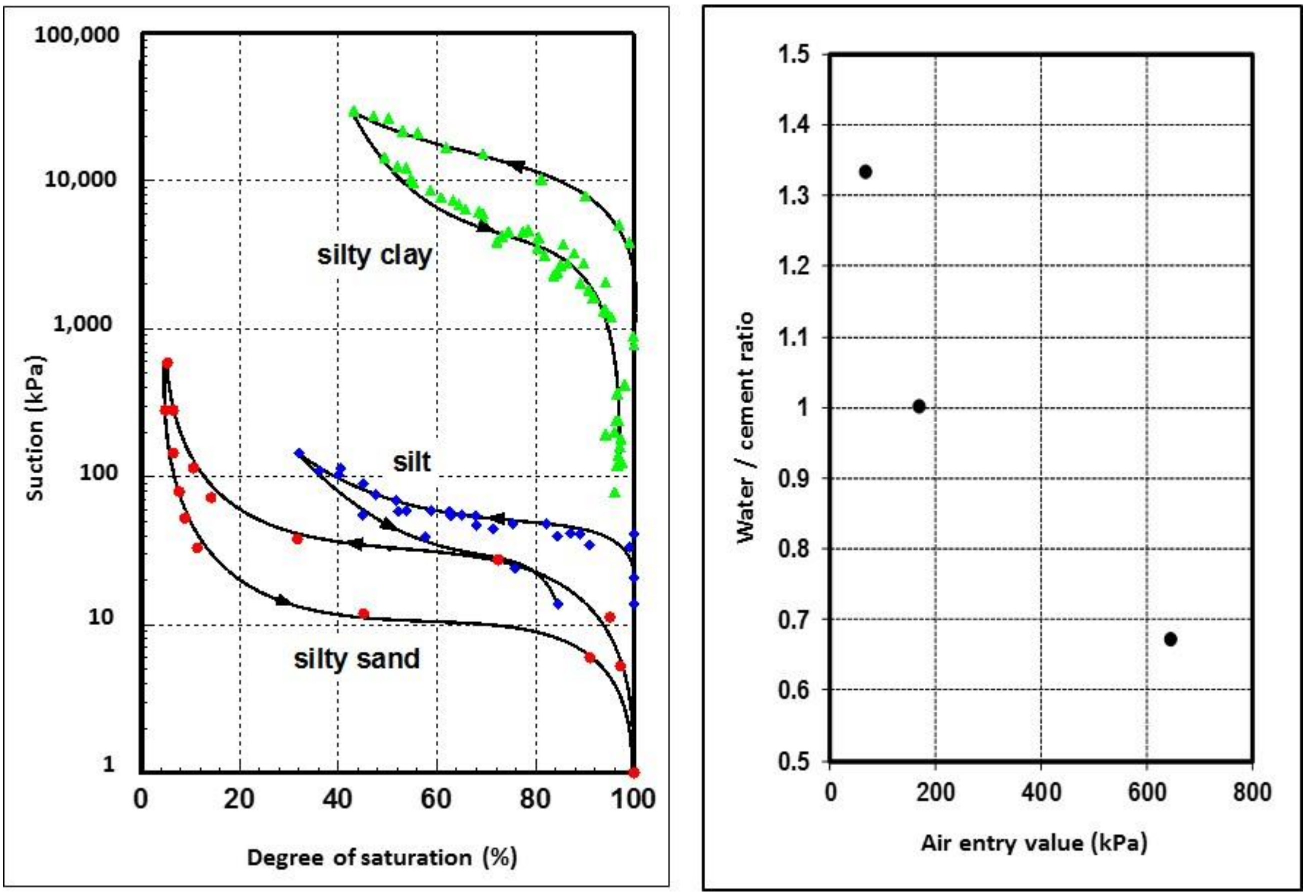


Figure 13 A flushable piezometer for measuring positive and negative porewater pressures (after Ridley et al. 2003)



(a) (b)

Figure 14 Saturation-desaturation behaviour of (a) sands, silts and clays; and (b) cement grouts

It is very important to remember that it is not just the porous filter in a piezometer that lies between the water inside the device and the water inside the soil, it is also the material that is used to backfill the borehole. Sands, which are a common backfill material for diaphragm piezometers, have very low air entry values. This means that they de-saturate quickly when they are in contact with soils that have a suction. Typically this occurs at suctions that are less than 10 kPa and a piezometer sand can be practically dry when the surrounding soil has a suction in excess of 50 kPa (see Figure 14(a)). If the sand is dry, it is not possible for the tension in the water in the surrounding soil to be transmitted to the water that is inside the piezometer, so even if the piezometer remains saturated it will not correctly measure the soil suction in the ground. Grout is a much better backfill material if soil suctions are likely to be encountered because it can remain saturated (see Figure 13(b)) when it is in contact with soils that have high soil suctions, e.g. greater than 100 kPa. Flushable piezometers, such as the one shown in Figure 13, are therefore installed in fully-grouted boreholes. In addition, the process of flushing a piezometer can be very aggressive to the pressure sensor and to the sealing mechanism in the piezometer, so the flushable piezometers are replaceable in situ. To do this the porous filter is first installed with a follow-on plastic casing and the hydraulic valve head — pressure sensor assembly is inserted into the porous filter component through the plastic casing.

The measurements presented in the following sections of this paper were made using either suction probes or flushable piezometers.

4 Measurements of soil suctions in clay cuttings

When clay ground is excavated to form a cut slope, the reduction in effective stress can induce negative porewater pressures if the clay remains undrained. This can give a clay slope temporary stability in the short term, which can, in some construction situations, be advantageous. Monitoring of the porewater pressures and/or suctions coupled with analysis can be a cost-effective solution to temporary works constructions in clay excavations. Figure 15 shows porewater pressures measured using flushable piezometers shortly after the excavation in a 20 m deep excavation for the construction of Heathrow Airport's Terminal 5.

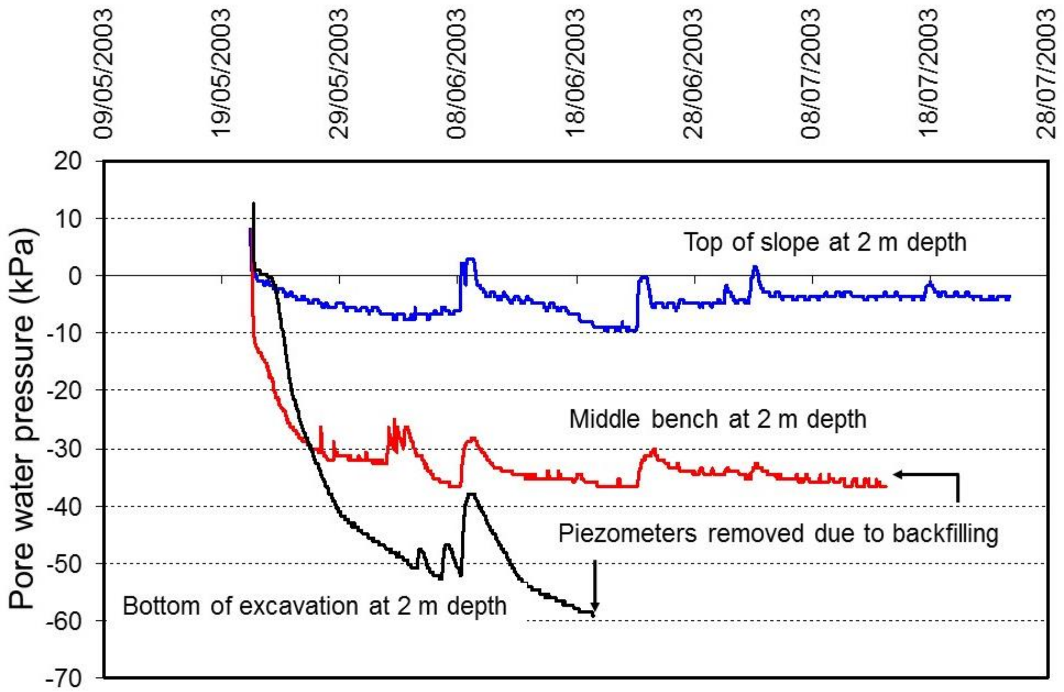


Figure 15 Porewater pressures measured at Heathrow Airport Terminal 5 after excavation of clay

Negative porewater pressures with a similar magnitude were predicted using finite element analyses (Kovacevic et al. 2007) and were shown to give temporary stability for a period that was sufficient to undertake the construction. Note how the negative porewater pressures near the surface are on occasions rapidly lost. These events were closely linked to rainfall events and the presence of cracks in the surface of the slopes. Temporary instability to shallow depths as a result of these short increases in porewater pressure was predicted by the finite element analyses and was observed.

If a clay cutting remains open for too long the temporary stability resulting from the negative porewater pressures be can be lost if the porewater pressures increase (as observed at Heathrow). Failure may be because the slope angle and geology are such that stability in the static sense is lost or because softening of the clay near the toe of the slope leads to a progressive failure in an apparently stable slope (Potts et al. 1997). The delayed failure of cut slopes is a common occurrence in stiff plastic clays and the time for failures to occur is frequently many years and difficult to predict precisely using analytical methods. Figure 16 shows the difference between porewater pressures measured within the footprint of an already failed plastic slope and the porewater pressures measured outside the failure zone. All of the measurements were made using flushable piezometers.

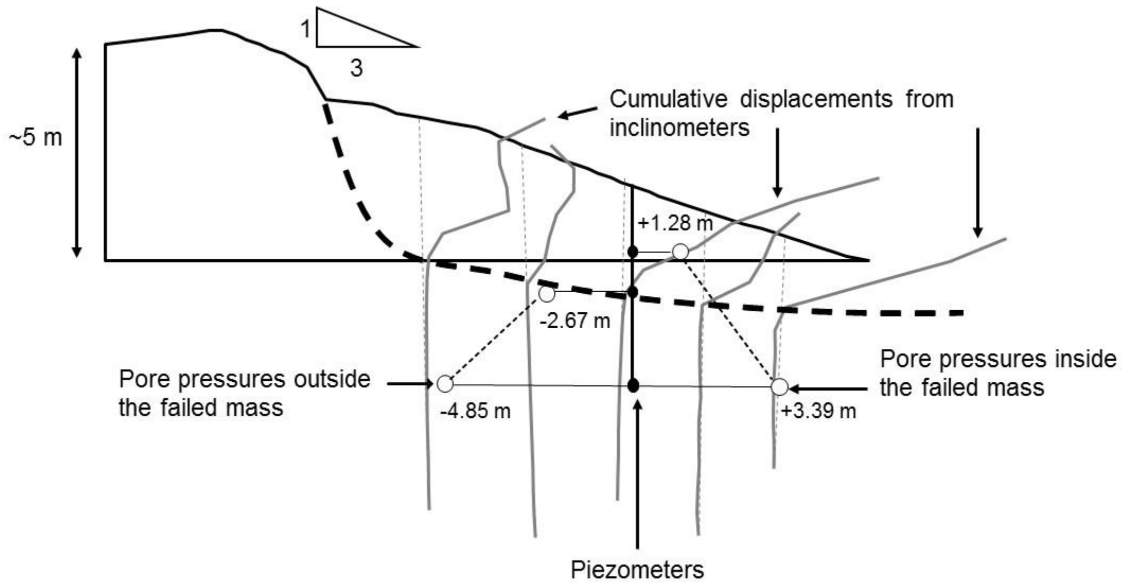


Figure 16 Porewater pressures measured inside and outside a failed clay slope

Note the deep-seated nature of the mass movement. Detecting instability prior to the failure of such slopes using displacement measurements (e.g. inclinometers) can be difficult because failures are normally brittle in nature with displacements occurring rapidly as the progressive failure mechanism evolves. Monitoring the negative porewater pressures, detecting rises in the porewater pressures and feeding the observations back into numerical analyses is; therefore, a better way of predicting when clay slopes might become unstable.

The time to failure in clay cuttings can be significantly extended and, in some cases, might even be prevented by the presence of vegetation. Figure 17 shows the porewater pressures measured nine years (using twin-tube piezometers) and 30 years (using flushable piezometers) after the construction of a 14 m high heavily vegetated London Clay cutting with a slope angle of 1:4. Numerical analyses suggest that a slope of this height and angle should be at risk of instability. The presence of vegetation on the surface of the slope has slowed the rise in the deeper porewater pressures and it is likely that this is improving the stability of the slope. Shallow seasonal variations of the porewater pressures were also observed, and these may have consequences for the shallow stability of such slopes because net down slope displacement may occur as a result of shrinkage and swelling. Such displacements have been observed and are reported elsewhere (Ridley 2013).

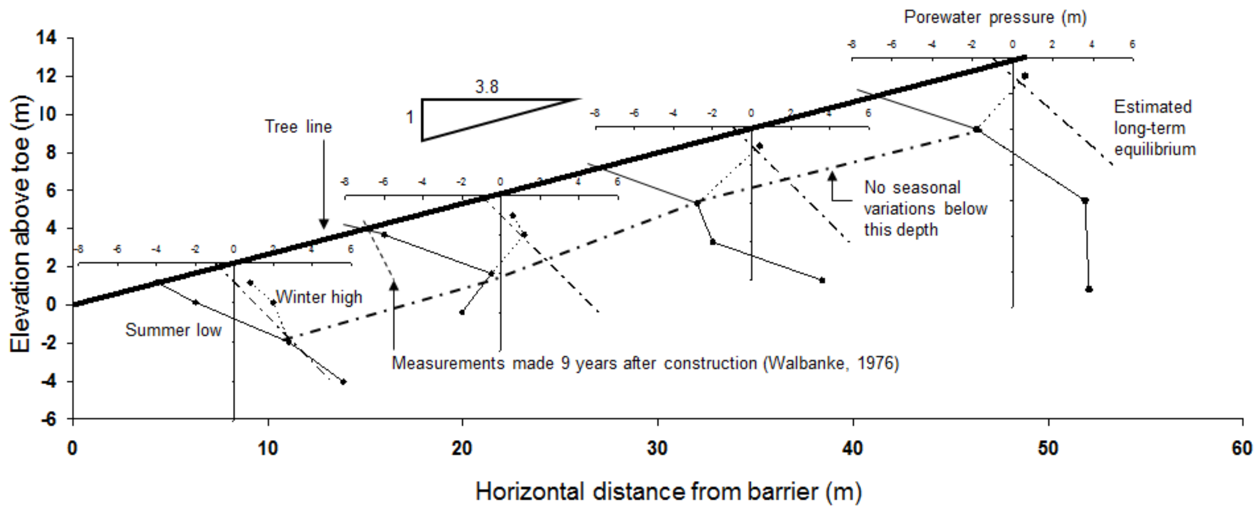


Figure 17 Long-term measurements of porewater pressures in a vegetated clay cutting

5 Measurements of soil suctions in clay fills and embankments

Fills and compacted soils, such as those used in embankments, have an inherent suction when they are first compacted. Empirical methods exist for estimating the likely magnitude of the initial suctions in clay fill materials (Ridley & Pérez-Romero 1998). Suctions measured in London Clay following compaction in the laboratory and in the field have been measured using suction probes (Ridley 2013) and have been shown to be about 1,000 kPa at the optimum water content and maximum dry density. Similar suctions have been measured with suction probes on samples recovered from old, heavily vegetated, railway embankments constructed of compacted London Clay.

Figure 18 summarises the long-term in situ pore pressures measured in clay fill embankments in the UK that are overlain with a variety of surface vegetation. The measurements on grass slopes (Walbancke 1976) were made using twin-tube piezometers and those where shrubs and trees were present were measured using flushable piezometers. The magnitudes of the porewater suctions are influenced by the type of vegetation. The maximum porewater suction is quite low even in the case of tall deciduous trees. In addition, the maximum depth of influence of the root zone lies close to the bottom of the embankments (e.g. 6-8 m) and the shape of the pore pressure profile for the deciduous trees is distorted from that of the hydrostatic condition and reflects flow of water to the root zone, i.e. upward flow from the water table and downward flow from the surface, which is of course important for the survival of the vegetation. The maximum porewater pressures that were measured are, however, close to the hydrostatic profile and could result in slope instability. Shallow seated slope failures are a common occurrence when vegetation is removed from slopes. However, large seasonal track movements have been detected in the old railway embankments and finite element analyses (Kovacevic et al. 2001) suggest that such movements could also decrease stability through a mechanism of progressive failure.

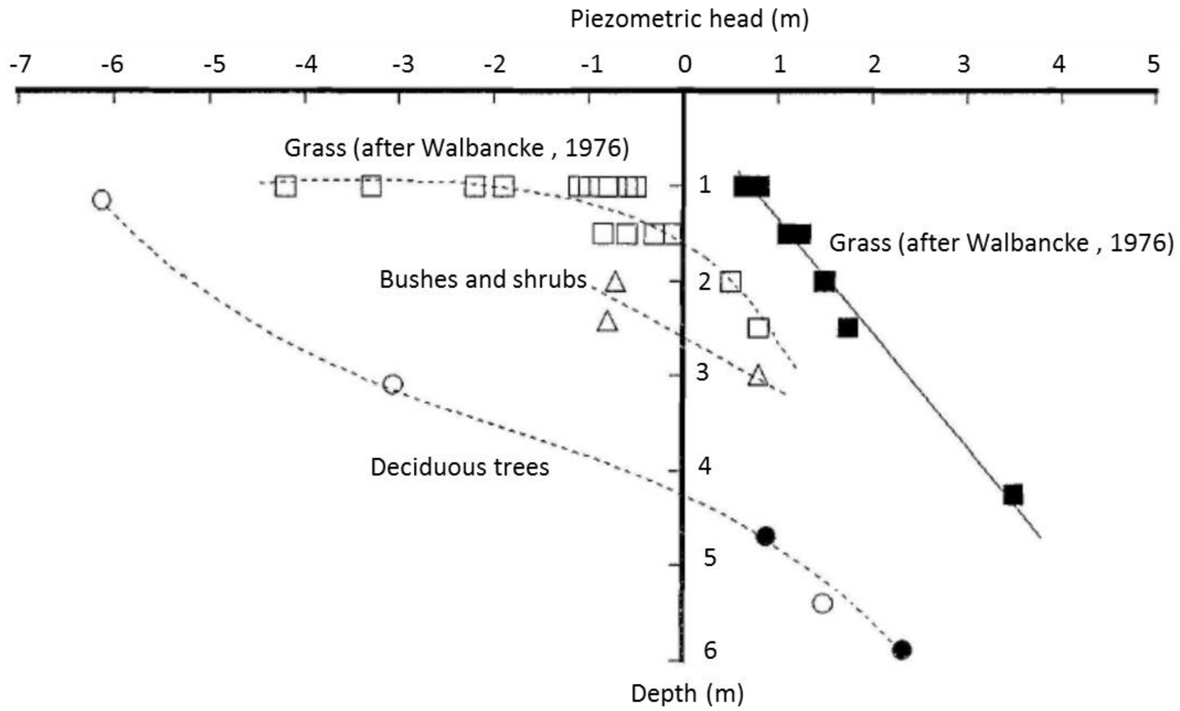


Figure 18 Porewater pressures measured in vegetated clay embankments

Evidence for the potential damage that can be caused by the existence of seasonal variations of porewater pressure in vegetated clay embankments is shown in Figure 19. Note the large lateral and vertical displacements recorded when the porewater pressures increase to zero. The displacements were less dramatic in subsequent seasons when the seasonal variations of porewater pressure were also smaller.

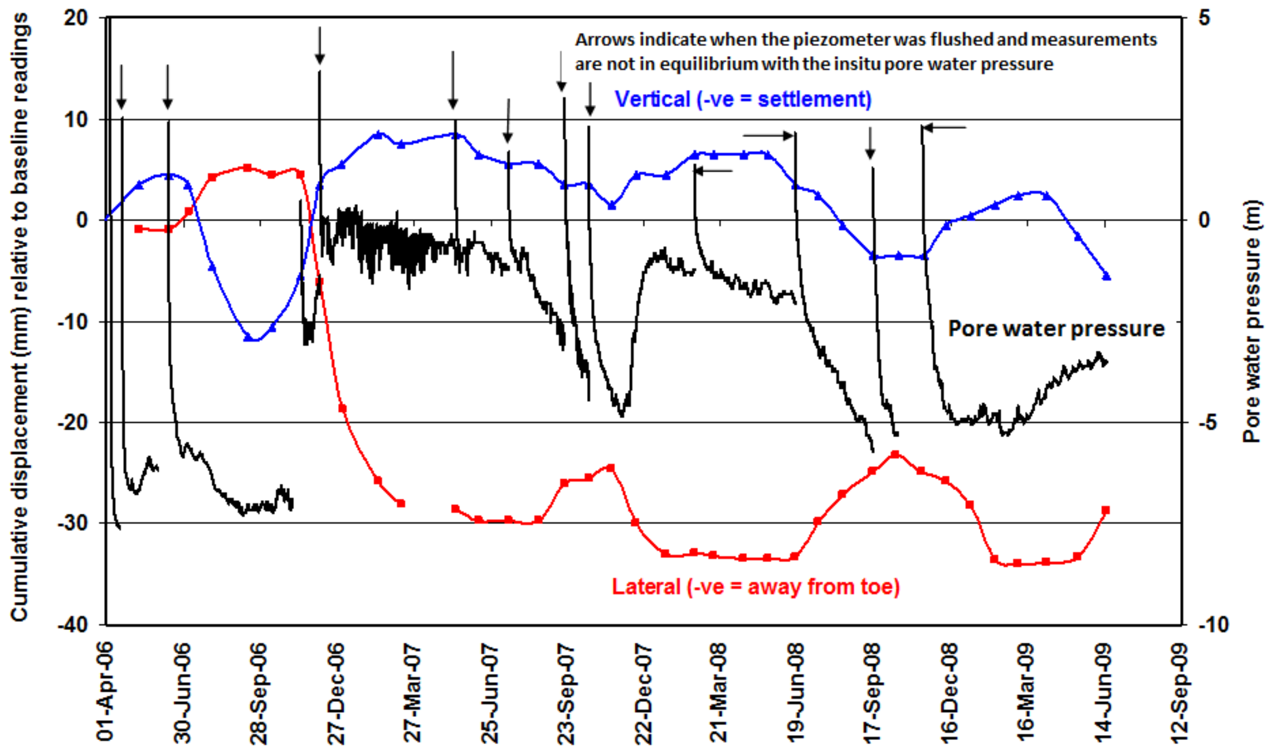


Figure 19 Link between damaging displacements and seasonal variations of porewater pressure

6 Measurements of soil suctions in other (natural) slopes

Soil suction is not only present in clay slopes. There are many natural slopes formed of coarser, more permeable materials where soil suction has an important, stabilising effect. Examples are found all over the world and the author has been involved in making measurements in locations such as Brazil and Hong Kong. Ridley et al. (1997) reported in situ measurements made with suction probes in a weathered granite slope close to Porto Alegre in southern Brazil. The suction probes were installed in the slope using the method described by Ridley and Burland (1996) and Figure 12. Although the measurements were much smaller than expected (Figure 20), the suction probes and the method of installation performed well at depths of up to 4 m below the top of the slope. Measurable changes of suction recorded 1 m below the surface were linked to changes of water content brought about by heavy rainfall and measured because the installation method allows small samples of material to be removed from the borehole as described earlier.

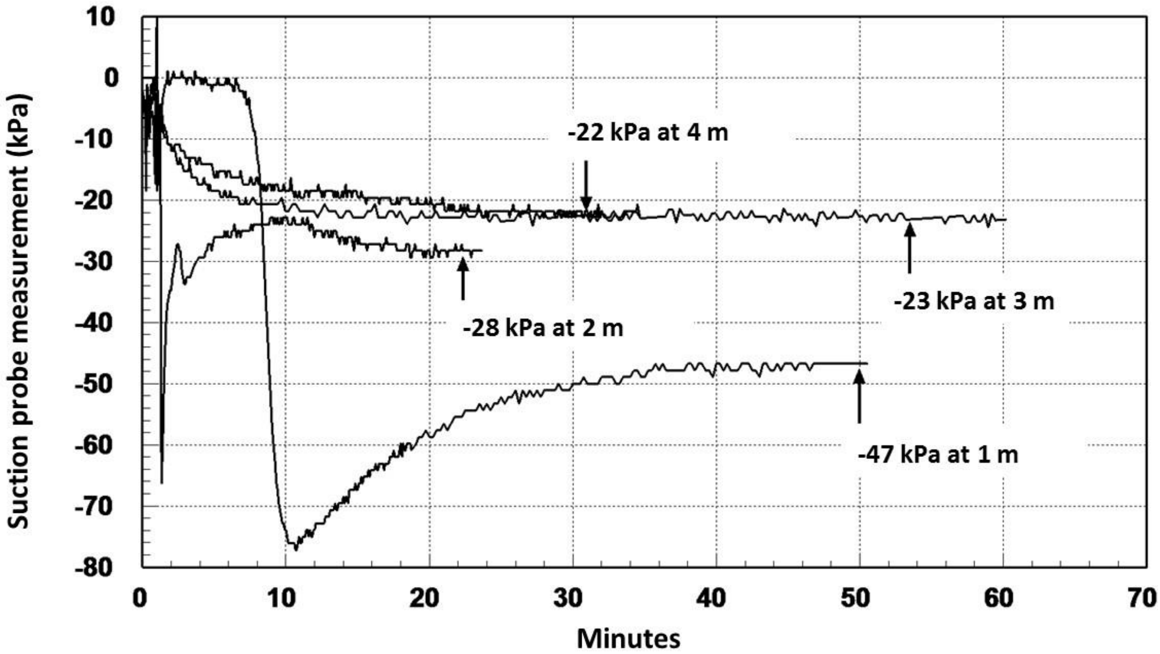


Figure 20 In situ suction probe measurements in a residual soil slope in southern Brazil (after Ridley et al. 1997)

Previously unreported results from a colluvium slope in Hong Kong are shown in Figure 21. These were made with flushable piezometers that were grouted into shallow boreholes at different locations (high, middle and low) on a slope where superficial failures had occurred. Seasonal variations were observed and were closely related to intense rainfall events. The maximum measured porewater pressures were close to the hydrostatic profile at all levels of the slope and during the dry season the porewater suctions were seen to increase rapidly at shallow depths, eventually exceeding the range of the flushable piezometers.

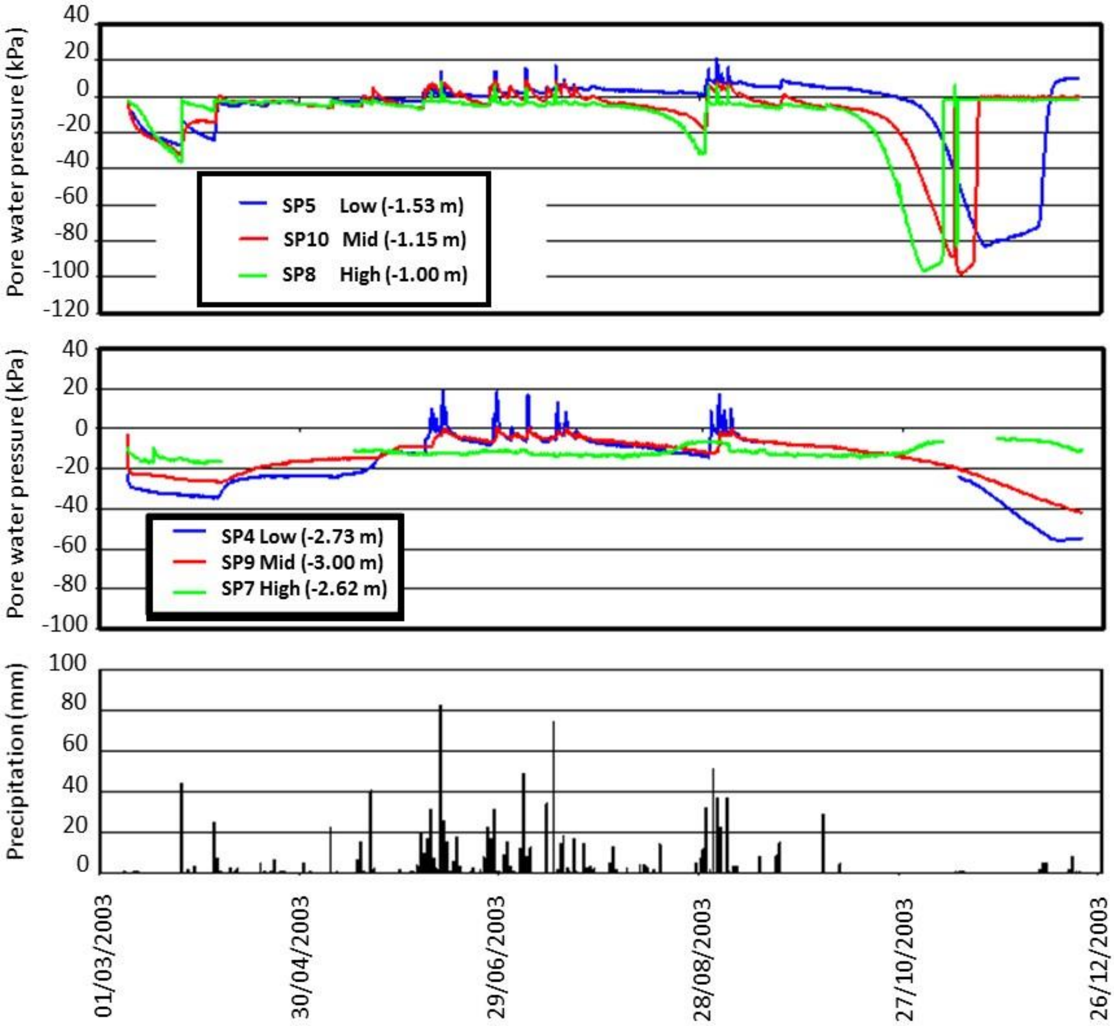


Figure 21 Variations of porewater pressures measured using flushable piezometers in a slope in Hong Kong

7 Summary

This paper has discussed what soil suction is and how to successfully measure it. The complex nature of porewater pressures in ground lying above the natural water table, i.e. the vadose zone, was discussed. Devices that have been developed over the last 25 years were presented and how they work was explained. Field measurements have been presented, and used to show why the study of soil suction is assuming greater importance in soil mechanics. Such measurements are by no means simple, but hopefully the paper will widen the appreciation that they are indeed possible and when done properly they can help further our understanding of the behaviour of slopes.

Acknowledgement

The author is grateful to the numerous people who have assisted him in making the measurements presented here over the last 25 years or so. Particular gratitude goes to Professors John Burland and Peter Vaughan who gave the author the inspiration to study this fascinating subject.

References

Biddle, PG 1998, *Tree root damage to buildings*, Willowmead Publishing Ltd, Wantage, UK.

Bishop, AW, Kennard, MF & Vaughan, PR 1964, 'Developments in the measurement and interpretation of pore pressure in earth dams', *Proceedings of the 8th International Congress on Large Dams*, International Commission on Large Dams, vol. 2, pp. 47-71.

Black, WPM, Croney, D & Jacobs, JC 1958, 'Field studies of the movement of soil moisture', *Road Research Technical Paper*, no. 41.

Buckingham, E 1907, 'Studies on the movement of soil moisture', *US Department of Agriculture, Bureau of Soils Bulletin*, vol. 38.

Harvey, EN, Bames, DK, McElroy, AH, Whiteley, AH, Pease, DC & Cooper, KW 1944, 'Bubble formation in animals, 1. Physical factors', *Journal of Cellular and Comparative Physiology*, vol. 24, no. 1, pp. 1-22.

Kovacevic, K, Potts, DM & Vaughan, PR 2001, 'Progressive failure in clay embankments due to seasonal climate changes', *Proceedings of the 15th International Conference Soil Mechanics Geotechnical Engineering*, CRC Press, vol. 3, pp. 2117-2130.

Kovacevic, N, Hight, DW & Potts, DM 2007, 'Predicting the stand-up time of temporary London Clay slopes at Terminal 5, Heathrow Airport', *Géotechnique*, vol. 57, no. 1, pp. 63-74.

Monroy, R 2006, 'The influence of load and volume suction on the volumetric behaviour of compacted London Clay' PhD Thesis, Imperial College London.

Potts, DM, Kovacevic, N & Vaughan, PR 1997, 'Delayed collapse of cut slopes in stiff clay', *Géotechnique*, vol. 47, no. 5, pp. 953-982.

Ridley, AM 2013, 'Recent experiences of monitoring clay slopes', in A Anagnostopoulos, M Pachakis & C Tsatsanifos (eds), *Proceedings of the 15th European Conference on Soil Mechanics and Geotechnical Engineering – Geotechnics of Hard Soils – Weak Rocks*, IOS Press, Amsterdam, vol. 4, pp. 265-270.

Ridley, AM & Burland, JB 1993, 'A new instrument for the measurement of soil moisture suction', *Géotechnique*, vol. 43, no. 2, pp. 321-324.

Ridley, AM & Burland, JB 1995, 'Measurement of suction in materials which swell', *Applied Mechanics Reviews*, vol. 48, no. 10, pp. 727-732.

Ridley, AM & Burland, JB 1996, 'A pore pressure probe for the in-situ measurement of a wide range of soil suctions', in C Craig (ed.), *Proceedings of the International Conference on Advances in Site Investigation Practice*, Thomas Telford Ltd, London, pp. 510-520.

Ridley, AM & Burland, JB 1999, 'Discussion to: use of the tensile strength of water for the direct measurement of high soil suction', *Canadian Geotechnical Journal*, vol. 36, pp. 178-180.

Ridley, AM & Pérez-Romero, J 1998, 'Suction – water content relationships for a range of compacted soils', *Proceedings of the 2nd International Conference on Unsaturated Soils*, International Academic Publishers, vol. 1, pp. 114-118.

Ridley, AM & Wray, WK 1996, 'Suction measurement: a review of current theory and practices', in EE Alonso & P Delage (eds), *Proceedings of the 1st International Conference on Unsaturated Soils*, A. A. Balkema, Rotterdam, vol. 3, pp. 1293-1322.

Ridley, AM, Dineen, K, Burland, JB & Vaughan, PR 2003, 'Soil matrix suction: some examples of its measurement and application in geotechnical engineering', *Géotechnique*, vol. 53, no. 2, pp. 241-254.

Ridley, AM, Marsland, F & Patel, A 1998, 'Tensiometers – their design and use for civil engineering purposes. Geotechnical Site Characterisation', in PK Robertson & PW Mayne (eds), *Proceedings of the 1st International Conference on Site Characterisation*, Balkema, Rotterdam, vol. 2, pp. 851-856.

Ridley, AM, Schnaid, F, da Silva, GF & Bica, AVD 1997, 'In situ suction measurements in a residual soil of southern Brazil', in TMP de Campos & EA Jr Vargas (eds), *Proceedings of the 3rd Simpósio Brasileiro sobre Solos Não Saturados,* Editora Freitas Bastos, vol. 2, pp. 537-542.

Schofield, RK 1935, 'The pH of water in soil', *Transactions of the 3rd International Congress on Soil Science*, T. Murby & Co., London, vol. 2, pp. 37-48.

Walbancke, HJ 1976, 'Pore pressure in clay embankments and cuttings', PhD Thesis, Imperial College London.

Wellings, SR & Bell, JP 1982, 'Physical controls of water movement in the unsaturated zone', *Quarterly Journal of Engineering Geology*, vol. 15, pp. 235-241.