Abstract

Climatic changes are significantly changing the way that earth structures, particularly clay embankments and cuttings, behave. Evidence suggests that certain regions will continue to experience hotter summers and dryer winters and that wet periods, when they occur, will consist of short heavy downpours rather than prolonged periods of light precipitation. The effect of this will be to increase the depth of water tables and the associated active zone where pore water pressures are below zero. It is therefore essential that the interactions between the atmosphere and the soil profile are better understood and the effect that these interactions have on the behaviour of earth structures are reliably measured. This paper discusses the relationships, which exist between atmospheres, different types of vegetation and pore water pressures above the water table. Measurements are presented that support the results of analyses, which illustrate the long-term effects of such changes on our infrastructure.

Introduction

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 high plasticity overconsolidated clays, which induces strain softening and this can eventually lead to collapse through a mechanism of progressive failure [KOVAČEVIĆ 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 pore water 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 pore water 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 pro-active way; to assess the serviceability and or stability of slopes it is therefore essential that they be fed with good data on pore water pressures and deformations, obtained from reliable field measurements.

In recent years infrastructure owners in the south east of the UK have attempted to gather this evidence through concentrated field monitoring of embankments and cuttings. These programmes known as “deep monitoring” have involved the installation and reading of inclinometers for monitoring horizontal displacements, extensometers for monitoring vertical displacements, open standpipes for monitoring the underlying pore water pressures and flushable piezometers for monitoring the superficial pore water pressures. This paper describes the background to this research and presents results from some of these investigations.

The development of pore pressure profiles in ground above a water table

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 has 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 full of water and the pressure in the water phase is a function of depth, the specific weight of the water (\(\gamma_w\)) and the hydraulic boundary conditions (e.g. the drainage conditions). This pore water pressure is generally positive and relatively easy to measure. The following paragraphs and figures will demonstrate how complicated pore water pressure profiles can however 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 were subjected to no other force than that due to gravity, the soil above the water table would be completely dry. However, powerful forces (e.g. molecular / physico-chemical forces acting at the boundary between the soil particles and the water, evaporation and evapotranspiration acting at and close to the surface) cause the water to be drawn into the otherwise empty void space. The combination of these forces gives soil lying above the water table an attraction for water that is termed “soil suction” and is frequently measured as a negative pore water pressure (although there is no proof that the pressure in the water is actually negative relative to atmospheric pressure). Graphically however it is customary to use the water table as a reference (e.g. zero) and to represent the pore water pressures in ground lying above the water table as negative values and an extrapolation of the positive pore water pressures that exist below the water table.

It is important to recognise that ultimately the pore pressure profile is determined by the net flow condition at the boundary. 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 (see Fig. 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.

The development of a pore water pressure profile following net evaporation from a flat horizontal surface is shown in figure 2 [adapted from Wellings and 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 pore water pressure profile at the end of a wet winter in the UK. When evaporation exceeds infiltration from the surface a zero flow plane 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 pore water pressure the zero flow plane will gradually penetrate the profile towards the natural water table and the hydrostatic profile will be re-established. If however the surface pore water pressure continues to reduce, the pore pressure profile will transcend the hydrostatic condition above the water table and the zero flow plane 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.

If infiltration at the surface again starts to exceed evaporation a second zero flow plane will develop that will also gradually penetrate towards the

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**Fig. 1 – Idealised pressure potentials during upward and downward flow.**

**Fig. 1 – Potenziale di pressione idealizzato durante il flusso verso l’alto e verso il basso.**

**Fig. 2 – The development of pore water pressures in the active zone during upward flow.**

**Fig. 2 – Sviluppo delle pressioni interstiziali nella zona attiva durante il flusso verso l’alto.**
water table from the surface (see Fig. 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.

Therefore, if the pore water pressure profile and its influence on the stability of a slope is to be correctly interpreted and understood it is therefore essential to make measurements of pore water pressure at a range of depths (above and below the water table) and locations within a slope.

The influence of soil type on pore water pressures above a water table

Many factors, including the void ratio and the stress history, influence the relationship between water content and soil suction in a ground profile [BLIGHT, 1997] An important factor however in the development of the pore pressure profile above the water table is the soil type and in particular the influence of the soil type on the relationship between water content and soil suction (known as the soil water retention curve). When presenting the soil water retention curve it is usual to represent the water content in terms of either volumetric water content (θ) or degree of saturation (Sr). Figure 4 shows the influence of soil type on the soil water retention curve (gathered from the author’s tests). Note the shift in the position of the curve as the particle sizes reduce (silty sand – silt – silty clay) and the hysteresis that occurs in the relationship between drying (decreasing degree of saturation) and wetting (increasing degree of saturation). The suction at which the degree of saturation reduces below 100% (i.e. fully saturated) also increases as the particle size decreases. This means that theoretically the capillary zone (i.e. the zone in which the pores remain full of water and the pore water is in a state of true tension) is thicker in finer grained soils. However, fine grained soils also form cracks easier than coarse soils, so the global degree of saturation reduces even though the microfabric is still essentially saturated.

The degree of saturation will in turn influence the coefficient of permeability (or hydraulic conductivity) of the soil. 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 in accordance with Darcy’s law (for simplicity here modelled as one dimensional, in accordance with the framework presented in figures 1 to 3). When a soil desaturates it does so in a progressive manner with the water initially draining from the larger voids (as described earlier in the section on pore pressure profiles). 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 (see Fig. 5). In these circumstances there will be a net downward flow from the upper zone to the permanent water table. This situation can also occur in clayey soils when cracks exist at the surface and persistent rainfall causes the cracks to fill 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. In theory the pore pressure profile corresponding to the field capacity should be hydrostatic with a zero pressure at the surface. In the UK however there is seldom sufficient rainfall to meet this condition and a small suction is normally retained in clayey soils at the surface at the end of winter.

In coarse granular soils the saturated hydraulic conductivity is high but the degree of saturation reduces rapidly as the pore water pressures decrease and the change in hydraulic conductivity can be many orders of magnitude. Once the soil has desaturated the hydraulic conductivity can be very small and the movement of moisture to the surface from deeper in the profile will be predominantly through vapour transfer and very slow. This means that the unsaturated zone that is created by drying will often be quite shallow in granular soils. However, whilst the hydraulic conductivity of the soil may be quite low after drying, the storage capacity is high and the increase in hydraulic conductivity during wetting is also rapid. Therefore granular soils are good at absorbing intense rainfall events. In contrast clay soils have low hydraulic conductivities and remain saturated to relatively high soil suctions. Therefore, in the absence of cracks, water struggles to enter the profile at the surface and intense rainfall events result in water gathering at the surface. Saturation of the shallow layers in intact clays requires prolonged periods of low intensity rainfall.

**The relationship between climate, moisture content, pore water pressures and slope movements**

Recent research (e.g. Ridley et al., 2004) has shown that there is a good correlation between the shallow pore water pressures (and hence the depth of the zero pressure line) in clay slopes and variations of soil moisture deficit (SMD). Soil moisture deficit (measured in mm) is defined as the amount of water per unit surface area that the soil surface will absorb before further precipitation cannot be stored in the profile (i.e. the soil profile has reached its field capacity). It is measured in the UK by the Meteorological Office [Hough and Jones, 1997] from weather data, for different soils and vegetation covers, primarily for use in agriculture.

Soil Moisture Deficit and pore water suction (hence shallow pore water pressures and the position of the zero pressure line) are related through the volumetric water content (or degree of saturation). Figure 6 indicates how SMD can be calculated directly from observations of the in-situ volumetric water content (θ) profile. The total moisture deficit is the sum of the differences between the measured profile and the profile when the soil is at field capacity. The soil moisture deficit is therefore the area of the triangle shown in figure 6. Volumetric water content and soil suction are related through the soil water characteristic curve (see Fig.
In most situations the volumetric water content / suction relationship will follow a scanning curve, with the value at field capacity lying on the main wetting curve and other points tracing a hysteretic curve between the field capacity and the main drying curve.

Periods of low SMD (and therefore low soil suction and high pore water pressures) correlate well with the major landslips recorded on the rail network in the South East of England between 1988 and 2002. Figure 8 shows the SMD for London calculated by the Meteorological Office [Hough and Jones, 1997] for a clay soil and two crop types; grass and deciduous trees. This is a useful graph for identifying wet and dry periods. Generally, SMD for grass fluctuates between zero and 135 mm with an annual cycle. Occasions when the SMD for grass remains high through the wettest periods of the year (e.g. winter in the UK) indicate a particularly dry winter. SMD for trees rarely drops to zero. This is because trees extract much more moisture from the ground than grass, and hence more moisture is required to bring the soil back to its field capacity. Therefore periods when the SMD for trees reaches zero will be associated with particularly prolonged wet weather and hence high pore water pressures.

Figure 8 also shows the occurrence of landslips (sliding at shallow depth) on the railway network during the same period. Landslips are frequently seen to be associated with periods when the SMD is low (often zero). Furthermore, landslips have also been associated with prolonged dry periods (often several seasons) followed by a, sometimes, short but intense wet period. Problems of serviceability (e.g. uneven track level on railways) usually occur when SMD for trees is high.

Soil moisture deficit therefore provides a useful indicator of periods when the pore pressures in clay slopes are likely to be high. This can be used in an effective way to predict periods when slope movements are likely to be a problem. Figure 9 shows SMD, pore water pressure measured by a single piezometer located close to the depth of a shear zone and down slope displacements along a shear plane within a natural slow moving landslide. Accelerations in the displacement are associated with reductions of the SMD and associated increases in the pore water pressure. The former gives a good early warning of when the latter can be expected to occur and hence when the displacement can be expected to accelerate. Even at shal-
low depth, accelerations don’t always occur when the water level rises above the level shown but they only occur when it does so. SMD can therefore be used to indicate when to increase the frequency of slope monitoring.

The influence of vegetation on the pore water pressures in slopes

In this section the effect of vegetation on pore water pressures will be discussed and in particular the likely range of pore water suctions that can be developed by vegetation will be demonstrated.

Of the water that is absorbed by roots 99% is transpired and 1% is stored for use in metabolism and maintenance of turgor (rigidity of cells) within the buds and leaves. Since water will flow from a point of high hydraulic potential to one of lower hydraulic potential and for a tree the flow occurs above the water table, flow towards tree roots will occur across negative hydraulic potentials. Some typical values for a small tree in moist soil are (after Moore et al., 1995):

- $\Psi_{\text{atmosphere}} = 100,000$ kPa (at 50% relative humidity and 22 °C)
- $\Psi_{\text{leaf}} = 1,500$ kPa
- $\Psi_{\text{stem}} = 500$ kPa
- $\Psi_{\text{root}} = 200$ kPa
- $\Psi_{\text{soil}}$ depends on the soil type

Water can move from the soil to the leaves at velocities of up to 0.75 m/sec. Moreover, it has been reported [Helliwell, 1993] that a large tree can take 900 litres of water from the soil each day, from a root area of up to 300 m$^2$.

Roots can only take up water when the suction they impose is greater than that of the suction in the soil. The values shown suggest that roots can operate easily where the soils suctions are up to 200 kPa, and should be able to struggle up to 1500 kPa. Moreover, it can be seen that if the suction in the soil is equal to 1500 kPa (i.e. the suction at the leaf) there is no potential for flow. This is known as the “permanent wilting point.” It also follows that the presence of roots whilst not guaranteeing the existence of suction, at least suggests that the soil was, at some time, subjected to suction.

Roots have difficulty penetrating soils with (i) a high clay content, (ii) strengths greater than 2.0 to 2.5 MPa or (iii) 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 very dependent on the soil type.

Increases in soil suction close to the root will eventually lead to a stress condition that causes cracks to develop in the soil. This has a number of benefits for the vegetation. Firstly, the roots can penetrate deeper into the soil and obtain water at a lower suction. And secondly roots acquire oxygen for the vegetation and this is easier to obtain from cracks. Once a crack has formed the mass permeability of the soil will increase considerably. This facilitates the ingress of water, improves the availability of water and reduces the need for further root penetration.

Assuming that the soil is unable to sustain true tension, vertical cracks will appear when the horizontal total stress reduces to zero. The magnitude of

![Fig. 9 – Soil moisture deficit, pore water pressure and displacement along a shear surface in an active clay landslide.](image-url)
the suction required to cause this can be estimated, for level ground, using the following equation [after Marsland et al., 1998]:

\[ u_c = \sigma_v (1 - 1 / \sin \Phi^r) \cdot OCR \sin \Phi^r \]

where \( u_c \) = critical pore water suction (kPa), \( \sigma_v \) = total vertical stress (kPa), \( \Phi^r \) = drained angle of friction and OCR = the overconsolidation ratio.

In the case of a clay fill that was loose dumped and collapsed following inundation (typical of the type of material used during the construction of old railway embankments): \( \Phi^r = 21^\circ, \gamma = 19 \text{ kN/m}^3 \) and an overconsolidation ratio likely to be close to 1.0. In such a material a suction of 48 kPa will allow cracking to develop to a depth of 1.5 metres, whilst a suction of 195 kPa will initiate cracking to a depth of 6 metres. Therefore it is feasible, in a soil of this type, that roots do not need to generate high suctions, because low suctions cause cracking and allow precipitation to penetrate the soil profile directly. Furthermore, it is relatively easy for the roots to penetrate the clay fill and obtain water from deeper and at a lower suction.

In natural slopes, \( K_s \) is usually greater than 1.0 and a high overconsolidation ratio means that much higher suctions are required to cause cracking. Therefore the extent of the root zone is likely to be much shallower in natural and cut slopes in clay.

The magnitude of the pore water depression will also be heavily influenced by the local climate. For example, the Eucalyptus tree is native to eastern Australia and the pore water suction close to the trees can be many thousands of kiloPascals [Blight, 1997]. However, the same species of tree grows well in the Northern Europe where the pore water suctions are normally quite low.

Not all of the water present in a soil is available for abstraction by vegetation. Observation suggests that the amount of water that is available to vegetation is in the range 20-40% less than the field capacity [Morecs, 1995]. If evaporation and/or evapotranspiration exceed rainfall the amount of water within the soil will fall below the field capacity. As introduced previously, the soil suction when the vegetation can no longer remove water from a soil is known as the permanent wilting point. Figure 10 shows the relationships between gravimetric water contents and soil suctions for two samples of clay fill taken from an old railway embankment. The soil has a void ratio of 0.95 and a gravimetric water content of 35% at the field capacity. In a cubic metre of such a soil there is approximately 0.49 m³ of water and 0.51 m³ of solids. Based on the above observations evapotranspiration could continue until the quantity of water in the soil is say 0.34 m³ (i.e. 30% less than the field capacity). This is equivalent to a gravimetric water content of about 25% and a soil suction of about 1500 kPa. This supports the values presented earlier and suggests that the permanent wilting point occurs at a suction of about 1500 kPa.

Field measurements in clay embankments and fills

Fills and compacted soils (such as those used in embankments) have an inherent suction when they are first compacted. The magnitude of this suction can be a few hundred kilopascals even under normal compaction conditions. Empirical methods exist for estimating the likely magnitude of the initial suctions in clay fill materials [Ridley and Perez-Romero, 1998]. Figure 11 shows examples of suctions measured in London Clay following compaction in the laboratory and in the field. Similar suctions (also shown in the figure) have been measured on samples recovered from an old, heavily vegetated, railway embankment constructed of compacted London Clay.

Figure 12 summarises the in-situ pore pressures measured in clay fill embankments in the south east of the UK (e.g. London Clay) that are overlain with a variety of surface vegetation. The results are derived from the author’s own records and those of Wallance [1976]. The measurements confirm many of the aspects discussed previously. The magnitude of the pore water depression is influenced by the type of vegetation. The maximum pore water 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). Moreover the shape of the pore pressure profile in the root zone is considerably distorted from that of the hydrostatic condition.
The maximum pore water pressures that were measured are 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 where many of these pore pressure measurements were made. Finite element analyses [Kovacevic et al., 2001] suggest that such movements could also decrease stability through a mechanism of progressive failures. In order to improve overall stability it is therefore necessary to minimise any seasonal changes that may occur in vegetated slopes. To many infrastructure owners (particularly railway operators) the disruption caused by seasonal variations of pore water pressure induced by vegetation and the associated shrinkage and swelling of the plastic clay from which the embankments are constructed can be very disruptive. Speed restrictions imposed by a loss of level in the railway line result in inconvenience to the travelling public and revenue loss to the operator of the railway. It is therefore tempting for railway operators to remove trees from clay embankments in an attempt to restrict the damaging seasonal variations. In doing so however they risk allowing the pore water pressures to increase and the stabilising suctions to be lost, leading to potential failure if the slope is oversteepened.
In a recent study [«Ground Engineering», 2010] to investigate the effects of removing vegetation from a clay embankment, inclinometers and magnet extensometers were used to measure the lateral and vertical displacements respectively, flushable piezometers were used to measure the pore water pressures within the embankment fill and deep open standpipes were used to measure the level of the underlying ground water. The chosen embankment had a history of poor line quality and was heavily vegetated with high water demand Oak trees. During the first year of the investigation moderate pore water suctions were measured in the embankment fill (see Fig. 13), vertical displacements near the top of the slope were seasonal in nature, extending to depths that were below the base of the embankment (approximately 4.5 m) as shown in figure 14 and lateral displacements at the top of the slope were minimal (see Fig. 15). After approximately one year the Oak trees were removed and the roots were killed. Thereafter the pore water pressures gradually increased and eventually the negative pore water pressure increased rapidly to about zero (Fig. 16). Local measurements of volumetric water content (Fig. 16), measured using a Neutron Probe [SMETHURST, 2009], indicated that at about the same time and depth a wetting front was passing through the soil profile. Over the following three seasons the vertical (Fig. 14) and lateral (Fig. 16) displacements were both consistent with swelling occurring within the clay fill. Such swelling could, if it continued, eventually lead to the development of a zone of sheared material and, in a high plasticity overconsolidated clay such as the one presented here, it could also lead to a loss of overall stability.
Field measurements in clay excavations and cuttings

When clay ground is excavated to form a cut slope the reduction in total stress can induce negative excess pore water pressures in the short term. This can give a clay slope temporary stability, which can be advantageous for construction. Monitoring of the pore water pressures coupled with analysis can therefore be a cost effective solution to temporary works construction in clay excavations. Figure 17 shows pore water pressures measured shortly after the excavation in a 20 m deep excavation for the construction of Heathrow Airport’s Terminal 5. Negative pore water 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 pore water pressures near the surface show occasional short term in-
increases, which were associated with rainfall events. Temporary instability to shallow depths as a result of these short increases in pore water pressure was successfully predicted by the finite element analyses and was observed. Prolonged infiltration and increases in the in-situ pore water pressures including loss of the stabilizing soil suctions is however a concern and well maintained drainage is an important aspect of this type of temporary works design.

Moreover, if a cutting in clay remains open for too long the temporary stability resulting from the negative pore water pressures can also be lost if the pore water pressures increase. Failure may occur because the slope angle and geomechanics are such that either stability mobilizes the peak strength or because softening of the clay (starting at the toe of the slope) leads to a progressive failure. The delayed failure of cut slopes is a common occurrence in stiff high plasticity clays and the time to failure is frequently many years. Figure 18 shows the difference between pore water pressures measured within the footprint of an already failed cut slope in Gault Clay and the pore water pressures measured in a nearby section of the cut.
slope outside the failure zone. Note the deep seated nature of the mass movement. Detecting instability prior to the failure of such slopes can however be difficult. Failures may be immediate, with displacements occurring rapidly after a slow evolution of the progressive failure mechanism. Frequently careful examination of the in situ water contents to identify zones of softened material (particularly near the toe of the slope) is the best way of identifying if a failure is likely to occur. Pore pressure measurements will be of limited use for predicting when a cut slope will fail because most failures occur before the long-term pore water pressures are reached. The potential for instability in clay cuttings can be assessed by measuring the in situ pore water pressures (which are likely to be negative) and comparing them with the long-term expected pore water pressures. This can be supported by numerical analysis of the particular slope concerned or by using published parametric studies (e.g. Ellis and O’Brien, 2007) to make an engineering judgment of the stability problem accounting for monitoring data gathered during a relatively short period of time.

The time to failure in clay cuttings can be significantly extended by the presence of vegetation. Figure 19 shows the pore water pressures measured 30 years after the construction of a 14 m London Clay cutting with a slope angle of about 1:4 and still stable at the stage of monitoring. Initially bare the slope became densely populated by Larch trees beyond an elevation approximately 4 m above the toe of the slope. Seasonal variations of the pore water pressures could be measured at shallow depths. This type of pore water pressure variation may have consequences for the shallow stability of such slopes, because net down slope displacement may occur as a result of shrinkage and swelling. Figure 20 shows the seasonal lateral displacements recorded in a heavily vegetated clay cutting where shallow instability has been observed. Note that the underlying trend is down the slope to depths of about 3 m. The longer-term monitoring of pore water pressures and displacements in clay cuttings can be of benefit in identifying the likelihood of shallow slips occurring as a result of seasonal variations of pore water pressure.

Conclusions

This paper has discussed the development of in situ pore water pressures and in particular the influence of climate, vegetation and soil type on the pore water pressures (suctions) within ground that lies above a natural water table. Variations of pore water pressures at shallow depths have been shown (through field measurements) to significantly affect the serviceability and ultimate stability of clay slopes.
Based on the observations presented in this paper a recommended regime for the monitoring of embankments can be proposed. It will require placing piezometers capable of measuring both positive and negative pore water pressures throughout a cross-section of the embankment and into the underlying foundation. These should be set up to record continuously for two (possibly three) full seasons. Placing an inclinometer and a magnet extensometer close to the toe of the slope will detect swelling that could lead to softening and a slope failure. A magnet extensometer placed at the shoulder of the embankment will detect the shrinkage and swelling that causes serviceability problems. If there is concern about the shallow stability of the embankment’s shoulder, inclinometers can be placed there but it is important that these penetrate a sufficient depth to ensure that the bottom of the inclinometer casing is not moving. Inclinometers and extensometers can be read manually at regular intervals to suit the monitoring programme for the piezometers. The data should be used in the first instance to make a judgment on the likelihood of a failure surface developing and if necessary as the input to a numerical analysis of the embankment. Depending on the results of the latter, the monitoring of the inclinometers can be continued at less frequent intervals beyond the initial period and used as (i) a means of recording the progress of any movements and (ii) feedback to refine the analyses.

A recommended regime for the monitoring of cut slopes is to place piezometers capable of measuring both positive and negative pore water pressures throughout a cross-section of the slope. It is not essential for these to penetrate to depths below the elevation of the bottom of the slope, but if one (positioned in the lower part of the slope) was to do so, samples taken from the borehole could be used to examine the water content profile, which could be indicative of localized shear straining. The piezometers should be set up to record continuously for as long as is required to establish the pore pressure regime and if there are any seasonal variations. If seasonal variations exist it may be necessary to record the pore water pressures for two (possibly three) full seasons. If the potential for a deeper-seated failure exists, because the geometry, ground conditions and pore pressures are appropriate, movements along a rupture surface may be detected with vertical inclinometers placed in the lower part of the slope, which can be read initially at intervals to suit the programme of pore pressure monitoring and in the longer term perhaps only quarterly or bi-annually. Numerical analyses however show that significant displacements along the rupture surface will only occur in the few years prior to a failure of the slope, so one must prepare for a long-term monitoring programme.

References

Relazioni tra clima, vegetazione, pressioni interstiziali e durabilità di pendii in argilla

Sommario

I cambiamenti climatici stanno significativamente mutando il comportamento delle strutture in terra, con particolare riferimento a dighe e scavi in argilla. L’evidenza suggerisce che in determinate regioni si avranno estati più calde ed inverni più secchi e che i periodi piovosi, quando presenti, saranno caratterizzati da brevi ed intensi acquazzoni piuttosto che da periodi prolungati di piogge leggere. Questo produrrà un approfondimento della superficie di falda ed un’estensione della corrispondente zona attiva, dove le pressioni interstiziali sono negative. È pertanto essenziale che le interazioni tra atmosfera e terreno siano meglio comprese e che gli effetti di tali interazioni sul comportamento delle strutture in terra vengano affidabilmente misurati.