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Application and verification of the effects of soil suction in embankment stability assessment

Application et vérification des effets de l'aspiration du sol dans l'évaluation de la stabilité

Gareth Swarbrick
Principal Geotechnical Engineer, PSM, Australia, gareth.swarbrick@psm.com.au

ABSTRACT: This paper documents the development, application and to some degree verification of a, practical and robust method by which the beneficial effects of soil suction can be incorporated into stability analyses of embankments. The method uses well established methods for the extension of the effective stress principle in unsaturated environments and applied in a practical manner such that parameters may be readily inferred or estimated. The method has been applied to six operating railway embankments situated in the Southern Coalfields South of Sydney, Australia. Inclusion of soil suction effects was deemed necessary to explain the stability of these structures during extreme flooding and earthquakes recorded over the past 50 years. It has also provided stakeholders with confidence in their understanding of current stability prior to exposure to potential mine subsidence effects. Soil suctions within the embankments have since been verified using field sensors to monitor spatial and temporal variations. This paper details the method by which soil suction was measured, the limitations encountered and the implications for the application of soil suction in stability assessments.

KEYWORDS: unsaturated soil mechanics, soil suction, measurement, embankment stability.

1 INTRODUCTION

Soil suction is a phenomenon which is well known and often explained as being a principal driver behind shrink-swell phenomena, surface cracking, greater than expected stability in soil slopes and high strength of desiccated clays. Application of this principle in geomechanics, however, is limited. This is largely due to the phenomenon being either too difficult to reliably quantify, transient in nature, difficult to measure or poorly understood.

For some structures, however, there is a need to quantify the effects of soil suction as it can have a significant stabilising effect which is otherwise unquantified. Not being able to quantify these effects means that a structure cannot be properly assessed and managed.

This paper presents a methodology as applied to railway embankments to redress these shortcomings. The methodology relied upon a number of assumptions based on a lack of information at that time. Subsequently a monitoring program was initiated to test these assumptions. This paper describes the stability assessment methodology, assumptions and reviews these in light of recent monitoring.

Note that all values for soil suction in this paper are presented or assessed (e.g. higher/lower, max/min) in terms of negative values unless otherwise stated.

2 BACKGROUND

2.1 *What is Soil Suction?*

Soil suction occurs in all unsaturated porous media and is a measure of the flow potential of pore water due to surface tension and osmotic potential. Consequently, it is often termed *soil water potential* or *pore water potential.* When the pore water potential is less than the pore gas potential it is usually termed negative pore pressure or simply soil suction due to its implied vacuum state.

The mechanical differential between the pore gas (u_a) and liquid pressures (u_w) is termed *matric suction* and is dominated by capillarity and surface tension effects. There may also be changes in pore water chemistry that increase the flow potential due to osmotic effects. This is termed solute or osmotic suction. The combination of matric and solute suction is termed total suction.

As pore water attempts to flow from an area of higher to lower pore water potential these forces are balanced by increased surface tension effects as water retreats into ever tightening pore spaces. Therefore, there is a relationship between the quantity of water and solutes retained the pore space for any given value of soil suction. This relationship is termed the soil water characteristic curve (SWCC).

At low suctions a porous media will usually be able to remain saturated due to capillary and osmotic effects. The value of suction at which a fully saturated porous begins to desaturate (allows the ingress of air) is called the air entry value (AEV). Similarly, a dry soil will wet up as suction is decreased. The suction value at which an initially dry soil will completely expel all air is termed the air expulsion or exit value (AXV). The AXV and the AEV are generally not the same due to hysteretic effects with the AEV normally a lower (more negative) soil suction than the air expulsion value.

2.2 *Application of soil suction in design*

It is well known by practising geotechnical engineers that excavated soil slopes can often exhibit significant strength over short periods. For stiff clays this may be a matter of weeks or even years. This also applies to temporary excavations in sand where the walls can remain stable for a few hours or even days often providing enough time to install permanent support.

The ability of such structures to remain stable is difficult to explain without the use of unsaturated soil mechanics whereby pore pressures fall below atmospheric (i.e. 'negative') and some proportion of which is transferred to effective stress thereby increasing strength. In most cases the reliance is temporary and often design is based on experience and empiricism. Such an approach is not acceptable in permanent design without the ability to calculate and confirm the continued presence of soil suction.

2.3 *The role of soil suction in railway embankment stability*

Australia has been constructing and extending railways since 1830. Currently in Australia there is around 33,000 kilometres of track on three major track gauges. The oldest railway lines, such as the Main Northern Line (MNR) to the north of Sydney and the Main Southern Line (MSR) to the south, have typically seen these modifications over time:

- initial widening of the embankments and cuttings accommodate line duplication (undertaken in the 1920s)
- further widening to accommodate service roads on at least one side but generally both sides of the rail tracks (undertaken in the 1980s).

Consequently, many of the oldest railway embankments on the MNR and MSR have over steepened batter angles typically around 36 degrees and sometimes up to 40 degrees to the horizontal. A typical embankment section showing these features is shown in Figure 1.

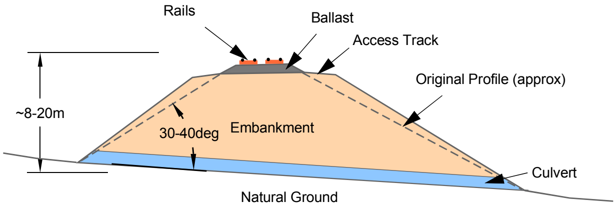

Figure 1. Typical rail embankment section

Strength parameters inferred from back analysis or even measured for the embankment materials suggest modest friction angles of 30 to 33 degrees and cohesions of only a few kPa based on traditional geotechnical sampling and testing including triaxial and shear box testing. These strengths are expected given these materials are derived from sandstones and shales won from adjacent cuttings and placed by end tipping without controlled compaction. A typical particle size distribution is provided in Table 1. Atterberg limits were typically a liquid limit of 30 to 40%, plastic limit of 11 to 20% and linear shrinkage of 7 to 11%. In-situ moisture contents were typically 10 to 20%.

Table 1. Typical particle size distribution

Sieve Size (mm)	% Passing
4.75	100
2.36	93
1.18	88
0.6	84
0.425	82
0.3	81
0.15	78
0.075	76

It is, therefore, not expected that traditional slope stability analyses will suggest such embankments are unstable (Factor of Safety below one) given batter angles of 36 degrees and greater. However, very little instability has been observed in any of these historical railway embankments made of these materials over their 150 year history including relatively high recorded seismic and flood loading. The logical measure ensuring the stability of these embankments is soil suction.

In most cases the omission of the effect of soil suction is accepted as this will usually make the design more conservative. For railway embankments studied here, however, their current level of risk cannot be determined using traditional stability theory and therefore risk assessment of these structures is problematic. This deficiency in geomechanics to explain the observed performance needs to be overcome to facilitate a reliable and effective assessment of these structures.

3 INCLUSION OF THE EFFECTS SOIL SUCTION IN STABILITY ASSESSMENT

3.1 *Previous Studies*

It has long been recognised that the stability of over steepened slopes and embankments is explained by the effects of soil suction. Pioneering work in this area began in Hong Kong in the 1980s where very high steep slopes could not be explained by traditional soil mechanics and were found to be very susceptible to rainfall (Ching *et al.* (1984); Fredlund (1987)). Subsequent research was undertaken to extend the effective stress relationship to incorporate soil suction as described in Rahardjo *et al.* (1991); Ng and Pang (2000); Fourie (2016). The beneficial aspect of negative pore pressure on slope stability is shown schematically in Figure 2.

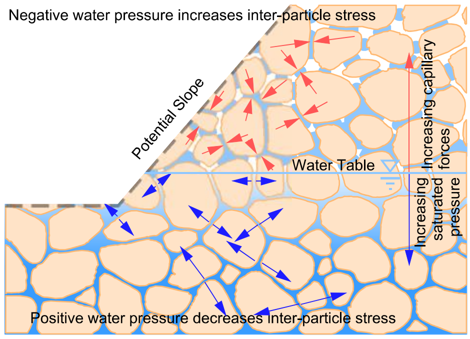

Figure 2. Stabilising forces of negative pore pressure

The consideration of soil suction in slope stability analyses requires the following:

- an understanding of the magnitude and distribution of soil suction within the embankment
- modification of effective stress to incorporate soil suction
- use of modified effective stress in shear strength

These elements are expanded below.

3.2 *Methodology for the inclusion of soil suction*

The methodology described below was presented in Swarbrick and Piper (2019). The method is an extension of the Mohr-Coulomb shear strength model:

$$\tau = \sigma' \tan \phi' + c \tag{1}$$

where σ' is effective stress, ϕ id the effective angle of friction and c is cohesion, for use in unsaturated soils. It utilises the widely accepted Bishop (1959) equation of effective stress for unsaturated soils:

$$\sigma' = (\sigma - u_a) - \chi(u_w - u_a) \tag{2}$$

Where σ is total stress, u_w is pore water pressure and u_a is pore air pressure and the parameter χ equals one while the soil remains saturated but reduces towards zero with desaturation.

Use is also made of the Khalili and Khabbaz (1998) empirical relationship for χ:

$$\chi = \begin{cases} \left[\frac{(u_a - u_w)}{AEV}\right]^{-0.55} & , u_a - u_w > AEV \\ 1 & , u_a - u_w \leq AEV \end{cases} \tag{3}$$

Combining the above derives unsaturated shear strength as:

$$\tau = (\sigma - u_a) \tan \phi' + c - \begin{cases} \frac{(u_w - u_a)}{(|(u_w - u_a)|)^{0.55}} AEV^{0.55} \tan \phi' \,, \; u_w - u_a < -AEV \\ (u_w - u_a) \tan \phi' \,, \; u_w - u_a \geq -AEV \end{cases} \tag{4}$$

It can often be assumed that u_a is constant (e.g. atmospheric pressure) and the reference pressure, in which case Equation 4 becomes:

$$\tau = \sigma \tan \phi' + c_a \tag{5}$$

Where:

$$c_a = c - \begin{cases} \frac{(u_w)}{(|(u_w)|)^{0.55}} AEV^{0.55} \tan \phi' \,, \; u_w < -AEV \\ u_w \tan \phi' \,, \; u_w \geq -AEV \end{cases} + \tag{6}$$

Equations 5 & 6 allow shear strength to be calculated under both saturated and unsaturated conditions. Shear strength is derived from strength parameters by knowing the AEV and the distribution of negative pore pressure. The combined parameter c_a is constant for a given soil suction and often termed *apparent cohesion*. Written in this form it is evident traditional analyses can be used using total stress parameters and a modified cohesion as long as soil suction can be assumed to be a constant or at least a minimum.

4 APPLICATION TO RAILWAY EMBANKMENTS

4.1 *General*

The inclusion of soil suction effects in embankment stability assessments was undertaken in the expectation it would explain observed performance where traditional soil mechanics had failed. This was initially done, however, without any direct evidence of the magnitude, spatial or temporal distribution of soil suction in these embankments and relied largely upon other published studies and the authors own experience in the study of partially unsaturated soils.

Inclusion of soil suction was undertaken using a number of key assumptions designed to apply the effects cautiously. These assumptions were:

- the embankments would be able to shed the bulk of directly intercepted rainfall due to their above ground profile and steep sides,
- any accumulation of floodwater adjacent to the embankment would only result in a loss of suction of the outer 1 m or so before floodwaters receded as shown diagrammatically in Figure 3,
- infiltration into the embankment would only result in a loss of suction within the outer 1 m or so due to runoff as shown diagrammatically in Figure 3,
- elsewhere within the embankment the soil suction could be estimated by assuming hydrostatic conditions, that is, pore pressure decreasing (soil suction increasing) at the same rate as the rate of increase in gravitational head; and
- the AEV, being unknown, could be assumed to be at least 25 kPa being based on the lower bound of published values for similar soils (Khalili and Khabbaz (1998)).

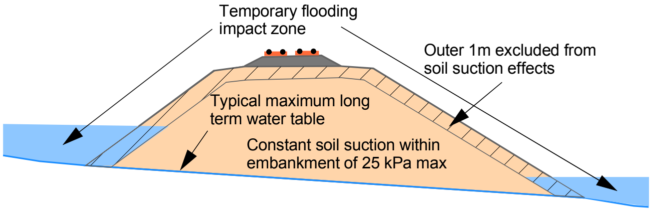

Figure 3. Application of soil suction within an embankment.

4.2 *Assumed suction distribution*

It was assumed that the bulk of the material within the embankment would be in equilibrium above the water table in the same manner it would be below it; i.e. a linear reduction in pore pressure with increasing height such that total head would be constant as shown in Figure 2. This can be described simply in terms of elevation as:

$$(u_w - u_a) = (z_{wt} - z)\gamma_w \tag{7}$$

Where z is elevation of the point at which soil suction is being determined (mRL) z_{wt} is the elevation of a water table (mRL), and γ_w is the unit weight of water.

This approach is similar to the long term wetted condition under an impermeable barrier (such as a concrete slab) recommended by AS 2870-1996 (1996) to approach wet of optimum in eastern coastal areas. AS 2870-1996 (1996) also foreshadows further increases in moisture in the presence of a permanent water table. Similar equilibrium moisture contents are recommended by AUSTROADS (1996) which also notes the potential for significant wetting in the presence of a groundwater table.

The methodology used here is designed to represent the most adverse moisture content likely to exist within the embankment at any time given the presence of a permanent water table. However, there can be short term increases above this condition during extreme infiltration events, particularly in combination with preferential flow through fissures and cracks. These impacts, however, significantly reduce with depth. The severity of such events is also limited through continued maintenance to limit the formation of areas were runoff can collect and infiltrate.

Using Equation 7 in Equation 4 eliminates all unknowns except σ, ϕ' and c (noting that AEV was assumed to be 25 kPa) and assuming u_a was the reference pressure and at atmospheric.

4.3 *Stability assessments*

Stability assessments are provided in more detail in Swarbrick and Piper (2019). In summary the inclusion of soil suction effects as described here resulted in an increase in factor of safety of around 0.2 to 0.3 for the embankments under assessment. While this increase was relatively small, it was sufficient to explain observed performance over time and during extreme events given the over steepened geometry of these embankments. A section of an embankment included in the analysis and soil suction monitoring program is shown in Figure 4.

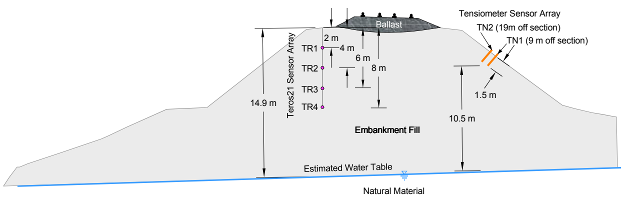

Figure 4. Rail embankment section analysed and instrumented

5 VALIDATION

5.1 *General*

Verification of the actual factor of safety for the embankment studied here is not considered possible given the embankment is in current use. Validation, therefore, has focussed on establishing the existence of soil suction in the embankment including magnitude and its distribution spatially and temporally. This was determined by installation of devices to measure or infer soil suction.

5.2 *Measurement of soil suction*

The measurement of suction has been a challenge ever since it was identified by agronomists and soil physicists over 100 years ago. The reasons for this are many:

- soil suction varies considerably from 0 kPa (saturated) to around 10,000 kPa,
- it is comprised of different components, these being matric and solute suction,
- as soil suction decreases instrument contact becomes more difficult and equilibrium rates are very slow.

Most methods fall into two categories – direct and indirect. Direct methods, measure soil suction directly, either by a field instrument that directly records the negative pressure or by applying a known soil water potential to sample in the lab and measuring its response. Indirect methods rely upon the measurement of a surrogate property that is known to change with changing soil water potential. These surrogate properties include the soil moisture content and the soil gas humidity.

Useful summaries of the available methods for measuring soil suction contained in Richards (1980) and Scanlon *et al.* (2002).

Field methods are generally limited to tensiometers, psychrometric methods or filter papers (see Swarbrick (1995)). At the commencement of this study the only direct method for field measurement that could be continuously logged was by tensiometers.

5.2.1 *Tensiometers*

Tensiometers were invented by the American soil physicist Wilford Gardner in 1912. They are a sealed column of water connected to a porous ceramic tip. When the ceramic tip is buried in the soil it acts as a membrane allowing the column of water to come into equilibrium with the soil suction at the tip. The column of water is connected to a pressure sensor which provides a reading.

Advantages of tensiometers are that they are simple, accurate and measure soil suction directly. The disadvantages are that their range is limited by the air entry value of the porous membrane, and this is typically 70 to 80 kPa. Higher air entry membranes are available, however the response time reduces with increasing air entry value such that for normal field applications they cannot react quickly enough to record abrupt changes in conditions, such as rainfall.

This study used tensiometers installed in the batters of an embankment. The depth was chosen to target the soil below the upper 1 m to detect the continued presence of soil suction as assumed in Section 4. An installed tensiometer is shown in **Error! Reference source not found.** with a negative pressure seen in the dial gauge. The gauge is situated vertically around 0.8 m above the tip connected by a water column (allowing for the angle of installation). This further reduces the tensiometer measurement range to around 60 to 70 kPa.

Figure 5. An installed soil suction tensiometer.

Results for two tensiometers, TN1 and TN2, are presented in this paper. Their location on section, separated by 28 m in plan, and installation depth of around 1.5 m is shown on Figure 4.

5.2.2 *Indirect Measurement by Ceramic Capacitance*

Additional instruments were installed in the embankment to measure soil suction at depth. Unfortunately, tensiometers were not considered suitable as they could not be readily extended vertically without further loss of their measurement range. Other options, such as horizontal installation or buried gauges, presented other challenges that were not readily overcome. Instead a use was made of indirect measurement methods.

The adopted device was the Teros21 sensor which estimates the water content of a buried, ceramic disc by measuring the electrical conductivity by the capacitance method. The disc is put into close contact with the soil region of interest such that the ceramic disc and surrounding soil, should, over time, reach the same soil water potential (i.e. suction). The measured water content of the ceramic disc at equilibrium is converted to an apparent soil suction using a calibrated table. Calibration is undertaken by the manufacturer prior to installation by applying soil suction to the disc in 5 stages from a saturated to a dry state. This relationship between moisture content and soil suction is the SWCC as described above.

A schematic of the Teros21 sensor taken from the manual is provided in Figure 6.

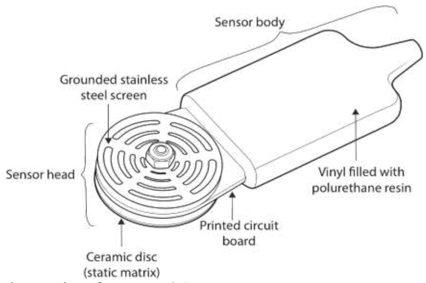

Figure 6. Schematic of a Teros21 sensor

Results for four Teros21 devices, TR1 to TR4, are presented in this paper installed at depths of 2, 4, 6 and 8 m respectively. Their location of these sensors within the embankment are shown on Figure 4.

5.3 *Other Observations*

During the study one of the embankments under observation experienced a storm event, estimated to be a 1 in 100 AEP, that resulted in significant flooding. The event lasted around 6 hrs and was observed to engulf the embankment at least 4 m above the toe. While no suction devices were in operation at the time, post inspections did not reveal any slumping or localised failures and no evidence of significant ingress of water.

The assumptions made for this study as listed under Section 4.1 would suggest that localised failures should have occurred during this extent of flooding. However, soil strengths are likely to be higher than that chosen for design purposes and this, in combination with the presence of vegetation, is likely to have prevented slumping during this event. Small slumps have been observed at other embankments but a direct link to flooding cannot be readily established as these observations have been made well after the event.

5.4 *Results*

Readings for all devices over a period of about 8 months are shown in Figure 7. Tensiometer TN2 reaches it measurement limit on a number of occasions as indicated on Figure 7. Note that soil suction has been shown as positive on this figure so it can be plotted in log scale.

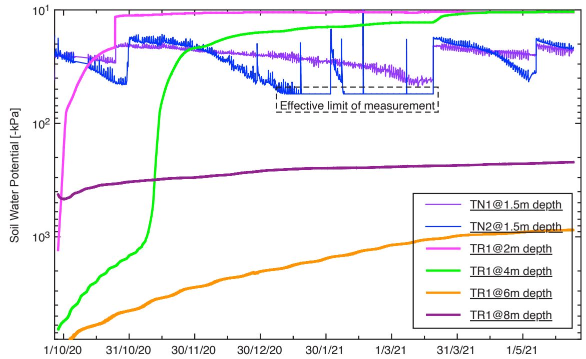

Figure 7. Collated readings from for all devices

Readings of near surface devices (in the top 2 m) are shown in Figure 8. Included are the daily rainfall and potential evaporation recorded nearby.

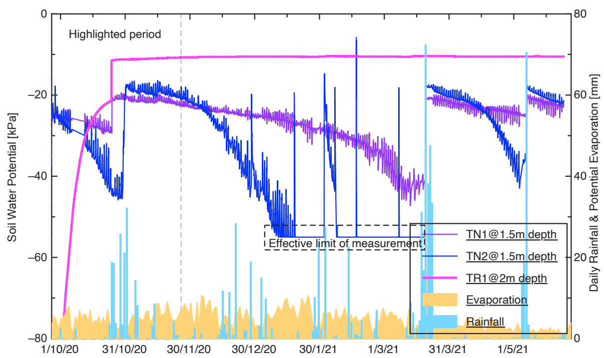

Figure 8. Readings from near surface tensiometers and Teros21 devices

A period of about 10 weeks was extracted from this record and provided in Figure 9. The duration of this period is indicated on Figure 8 as a shaded region.

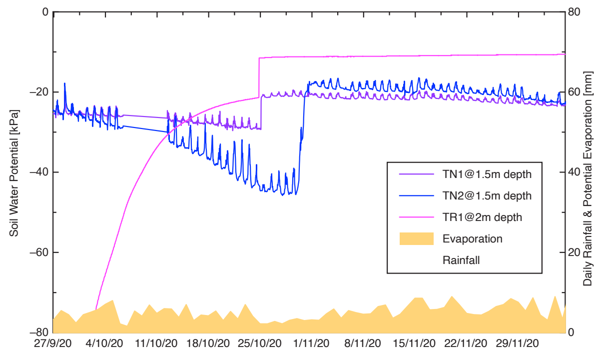

Figure 9. Highlighted monitoring period for surface suction devices

6 DISCUSSION OF RESULTS

6.1 *General*

Monitoring provided a number of insights. Firstly it was clearly established that suction was present at depth and in significant magnitude, Figure 7 verifying the conservatism of the assumed equilibrium suction profile. There also a number of effects that were expected such as daily fluctuations in suction, increases in suction after rainfall and decrease in dry periods as shown in tensiometer readings. However, there were a number of discrepancies in the Teros21 readings, such as:

- the Teros21 devices at 2 and 4 m depths recorded higher soil suctions than the tensiometers at 1.5 m depth,
- none of the Teros21 instruments reflected daily fluctuations,
- Teros21 sensors showed increases in suction following daily rainfall events greater than 20 mm or so but did not exhibit any recovery.

The reasons for these discrepancies are not well understood. What is well known is the proven reliability of the tensiometers which suggests that issues were related to the Teros21 instruments.

Despite these discrepancies there are several important conclusions that can be made concerning the validity of the methodology described in sections 3 and 4. These are:

- the depth of influence of rainfall in particular is much greater than originally anticipated with the Teros21 devices showing a rainfall response to a depth of 4 m; and
- the soil suctions measured below a depth of 4 m appear to be significantly lower than assumed in Section 4.2 (i.e. Equation 7).

Unfortunately there are also a number of complicating factors that make further interpretation of this data difficult. These are described below.

6.2 *Site specific variability*

Tensiometers and Teros21 devices were located in separate areas of the embankment where they would be subject to differences in terms of rainfall runoff and even localised evaporative effects such as solar aspect.

Even for the tensiometers, known for their accuracy, there is a significant difference between TN1 and TN2 in terms of magnitude, response time to rainfall and rate of recovery even though they were installed in nominally the same material, to the same depth and slope position, and only 28 m apart in plan as seen in Figure 8 and Figure 9.

This is likely to be influenced by the non-homogeneity of pore network due to density difference, cracking etc. giving rise to the likelihood of preferential flow paths. Tensiometer TN1 responds more rapidly under both wetting and drying, which would not be the case if there was short circuiting down the instrument. Fluctuations become greater at higher suctions which is due to the non-linear nature of the SWCC.

It should be remembered that pore water in unsaturated soils is always interconnected except at very high suctions (i.e. above the wilting point). The soil suction sensor is responding to changes in soil suction within the water surrounding it and not directly to the infiltrating water above.

Another issue that arose after the installation of devices was the realisation that the depth of railway ballast adjacent to the Teros21 device string was likely to be significantly deeper than originally anticipated. This is due to the way that railways are repaired where the settlement of existing ballast is ongoing and routinely topped up and recompacted. This is likely to form a depression at the embankment / ballast interface where rainfall can pool and continue to infiltrate over extended periods. This is likely exacerbated by additional subsurface lateral flow as the section being monitored was the low point across the entire embankment.

6.3 *Hysteresis effects*

It is well known that devices that infer soil suction from their SWCC are prone to hysteresis. This is because all porous media, including ceramics, will follow a slightly difference SWCC when wetting as opposed to drying. This effect for such devices is well documented in Feng (1999); Scanlon *et al.* (2002).

Saha *et al.* (2020); Oguz *et al.* (2021); Sharma *et al.* (2021) suggest the SWCC of Teros21 sensors would take the general form as shown in Figure 10 indicating that:

- the Teros21 sensor would give the most accurate values for soil suction when on the drying path used in calibration,

- at low suctions the response to change in soil suction is minimal and their stated lower limit is 10 kPa,
- if the Teros21 was to then dry out it would not change in water content until it reached the drying path,
- detecting suction change is worse at low soil suctions

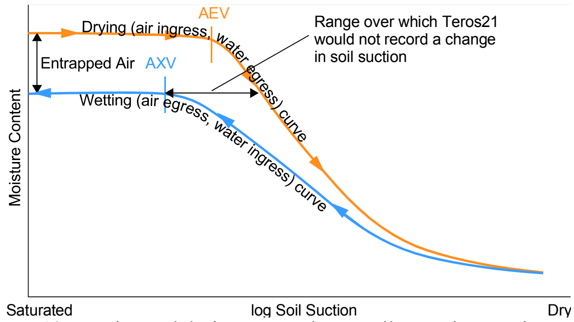

Figure 10. Wetting and drying curves due to soil water hysteresis

6.4 *Teros21 accuracy*

There are many studies that have shown the Teros21 devices (and their predecessor the MPS-6) to be reasonably accurate (Malazian *et al.* (2011); Saha *et al.* (2020); Sharma *et al.* (2021)). However, it is also recommended that each instrument should be calibrated or at least checked prior to installation.

The Teros21 instruments used in this study were not calibrated prior to installation as this process can take weeks to months to complete. This lead time was not available for this study. Some limited testing was undertaken prior to installation which resulted in some modifications the installation method to try to limit in accuracies. However, overall the accuracy of the Teros21 devices used in this study is unknown.

7 CONCLUSIONS

The measurements and assessment undertaken here have shown that appreciable soils suction exists in the study railway embankments. This was further supported by other instrumented sites within the same rail network region. Is it expected these suctions explain the satisfactory performance of these structures over 150 years whereas tradition soil mechanics has been unable to do so.

The results show, however, that caution must be exercised in the following areas should soil suction be relied upon in is design or analysis:

- establishment of the depth below which soil suction can be relied upon being likely uninfluenced by climatic effects; this depth was found to be around 4 m for this study,
- consideration of the potential for significant differences within an embankment due to spatial variability and possible climate effects
- care must be taken in the choice of soil suction instruments used to understand their potential for error and limitations.

The measurement and reliance on soil suction is still and emerging field in geotechnical engineering. It is hoped the findings of this study will assist in the development and interpretation of similar studies by others.

8 ACKNOWLEDGEMENTS

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