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In-situ soil moisture monitoring of a disused road embankment using commercially available sensors

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ABSTRACT: A disused historic road embankment located on the South African escarpment experienced cracking and settlement in the 2020-22 period following a long period of stability. Site observations before and during construction of a stabilising pile wall indicated the presence of voided material and seasonal water at depth. A moisture monitoring system was installed in this slope featuring sensors measuring volumetric water content and matrix suction. The purpose of this system was to evaluate the performance of relatively cheap, commercial sensors for in-situ measurements, and to investigate the seasonal variation of moisture at depth. This paper presents the results of data collected over a 21-month period at depths between 1 m and 15 m below ground level. This study found that the sensors produced data that appeared internally consistent when plotted on a semi-log soil-water retention curve plot. Furthermore, significant variations in suctions were found to occur at 1 m below ground level (0 – 2010 kPa) and 7 m below ground level (0 – 1320 kPa). Recommendations are made on the use of these sensors in future installations, as well as the need for further numerical study.

KEYWORDS: Slope stability, field monitoring, unsaturated soil, volumetric water content, matrix suction.

1 INTRODUCTION

In the last few decades unsaturated soil mechanics in geotechnical engineering has evolved from a niche field adopted from soil science to a tool making inroads into engineering practice across a host of geotechnical subspecialities (Tsiampousi et al. 2016; Vu et al. 2025; Alonso et al. 2025). This progress has been driven by a strong theoretical framework developed from experimentation and numerical modelling. However, the difficulty of measuring soil suctions accurately and widely in situ has proven to be a stumbling block to wider adoption (Houston 2019). This limitation has made it challenging to instil confidence in the application of unsaturated soil mechanics in the wider geotechnical field, as most practitioners do not have a feel for typical magnitudes of in-situ suctions, how they are measured, and their seasonal and spatial variability.

The subject of this paper is a disused road embankment located on the South African Escarpment which has been instrumented and monitored following a recent period of instability. A brief overview of the site is presented Here whereas a more complete characterisation (including stabilising works) may be found in Schulz-Poblete et al. (2024).

The embankment in question is located downslope of a major national highway, which is situated on a mountain pass with a history of problematic slopes. The disused road embankment experienced cracking and settlement in the 2021-22 period after heavy rains following a 30-year period of relative stability. A process of investigation, monitoring, and structural intervention was undertaken to protect the national highway from progressive failures which could result from downslope instability.

This paper aims to add to the existing body of work regarding unsaturated in-situ measurements (van der Raadt et al. 1987; Mendes et al. 2008; Toll et al. 2011; Puppala et al. 2012; McCartney & Khosravi 2013; Jafari et al. 2019; Vandoorne et al. 2021) by presenting moisture data in terms of volumetric water content (VWC) and soil matrix suction (henceforth referred to as suction) over a 21-month period.

2 SITE CHARACTERISATION

2.1 *Geological Setting*

The site lies at an elevation of ~1650 m MASL at the foothills of the escarpment. This area is characterised by rolling hills, small streams, and erosion gullies towards the upper escarpment. Sedimentary rocks of the Adelaide Subgroup underlay the site. This subgroup is represented by a single formation in this area, known as the Normandien Formation. This forms part of the Karoo Supergroup, which has further been intruded by dolerites of the Karoo Dolerite Suite, occurring in the form of dykes and sills.

Due to the mountainous topography, colluvium and talus have been deposited on the residual layers, with thicker deposits concentrated in gulleys. A gulley of this kind forms much of the cracked road area, running westwards under both the highway and downslope area. Based on previous experience, early and mid-20th century roadbuilders did not always take care to clear these loose colluvium/talus layers before placing fill, which has caused problems on similar slopes in the past.

2.2 *Climate*

Van Reenen experiences a climate characterised by warm summers (average midday temperature 25°C) and cold winters (average midday temperature 15°C), with occasional occurrences of snowfall. The eastern part of the province, including Van Reenen, often sees snow on the higher ranges. The region normally receives approximately 750 mm of rain per year, with most rainfall occurring mainly during the mid-summer months of January and December (Weather-and-climate 2025).

Climate determines both the mode and rate of weathering, with the effect of climate on the weathering process (i.e. soil formation) reflected by the climatic N-value defined by Weinert (1964). The site has an N-value of approximately 2.0, indicating a net surplus of water. This surplus suggests that soil profiles encountered are likely to be deep and comprise chemically altered residual soils. This low N-value also implies that rocks which are prone to degrade due to moisture inundation and fluctuation are likely to do so in this environment.

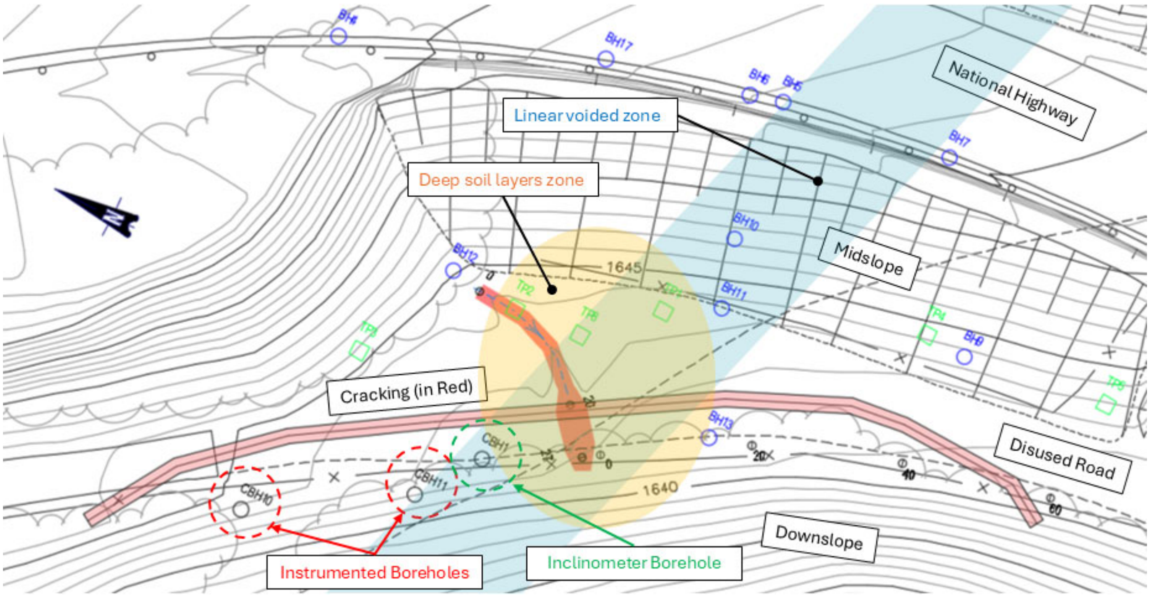

Figure 1. Site layout

2.3 *Investigation and Construction Findings*

Boreholes on the crest of the disused embankment confirmed the presence of a deep fill and colluvium (~20 m depth to very soft rock) towards the north of the site.

Borehole investigations were supplemented with geophysical surveys which identified a zone of deep fill and colluvium layers beneath the old road in the gulley area and surrounds. This zone appeared to be intersected by a linear voided zone, theorised to function as an underground drainage path. A site layout along with boreholes and identified regions of interest is presented in Figure 1.

Further evidence of a drainage path was found during construction of an anchored pile wall in 2024. Zones described by geophysical data as ‘voided’ mapped well on to areas with problematic drilling (boulders in pile auger holes, grout loss in anchor holes). Experience with the anchor holes during the rainy season confirmed the rapid recharge of the groundwater and underground flow in the area. Water would jet out of anchor holes when a drill string was inserted the morning after rain. It is believed that the theorised drainage path weakened the deeper fill and colluvium layers through years of wetting and drying cycles, ultimately triggering the eventual onset of instability.

2.4 *Laboratory Testing*

Laboratory tests were conducted on all soil and rock strata identified. Limited sample return from boreholes restricted the testing programme, necessitating careful planning to maximise the value of testing conducted on the recovered samples. The soil materials that were identified are presented in Table 1. All soils tested were categorised as CL based on the Unified Soil Classification system. It should be noted that the depths presented are as found in the gulley area (borehole CBH11).

Table 1. Basic soil descriptions

Material	*Description*	*Depth (m)*	*PI (LL)*
Fill	Sandy SILT and clayey SILT with pebbles	0-12	21 (40)
Colluvium	Clayey SILT with minor traces of subangular gravels and pebbles	12-18	16 (41)
Residual mudrock	Clayey SILT with subangular and angular mudstone gravels	18-22	18 (40)

The identified soils illustrated considerable similarity, suggesting a common origin. The colluvium is comprised of weathering products from further upslope, and the fill appears to have been locally sourced. Given the commonality of the soils and the limited amount of testable material, a mixed Fill/Colluvium sample was prepared for laboratory testing. This sample was used to carry out triaxial, direct simple shear, and soil-water retention curve (SWRC) testing from a slurried sample. The current paper is primarily concerned with the SWRC test which was fitted to tested data using the Fredlund & Xing (1994) method. Tested properties are presented in Table 2.

Table 2. Mixed Fill/Colluvium properties

Shear Strength Properties	ϕ' (°)	*c' (kPa)*			
	28.5	7.2			
Drying Curve Fitting Parameters	α	n	m	ψ_r *(kPa)*	θ_s *(m^3/m^3)*
	43.11	0.67	0.62	1500	0.425

3 MOISTURE MONITORING SYSTEM

3.1 *System Details*

The moisture monitoring system used on this project comprised a full suite of sensors and data acquisition systems from METER Group. The setup included two 6-channel ZL6 Basic data loggers connected to twelve sensors placed in three discrete boreholes. Readings of all sensors were taken at hourly intervals as is standard on this model of data logger. Three sensor types were installed:

1. TEROS 12: Volumetric water content, indirect measurement (capacitance), mineral soils (0 to 0.7 m^3/m^3)
2. TEROS 21: Soil matrix suction measurement, indirect measurement (fixed-matrix porous disc), low and high suction range (0 to -100,000 kPa)
3. TEROS 32: Soil matrix suction measurement, direct measurement (tensiometer), low suction range (-85 to +50 kPa)

Sensors installed in two boreholes are discussed in this study - CBH11 and CBH10. CBH11 is the borehole positioned closest to the cracking in the old road and has the deep soil strata (22 m to bedrock), half (six) of the available sensors were therefore concentrated in this borehole. CBH10 is a shallower borehole (4.5 m depth to bedrock) 25 m to the northwest of CBH11, four sensors were placed in this borehole. Figure 2 presents the layout of sensors in boreholes CBH11 and CBH10. Note that both boreholes were drilled from the same elevation.

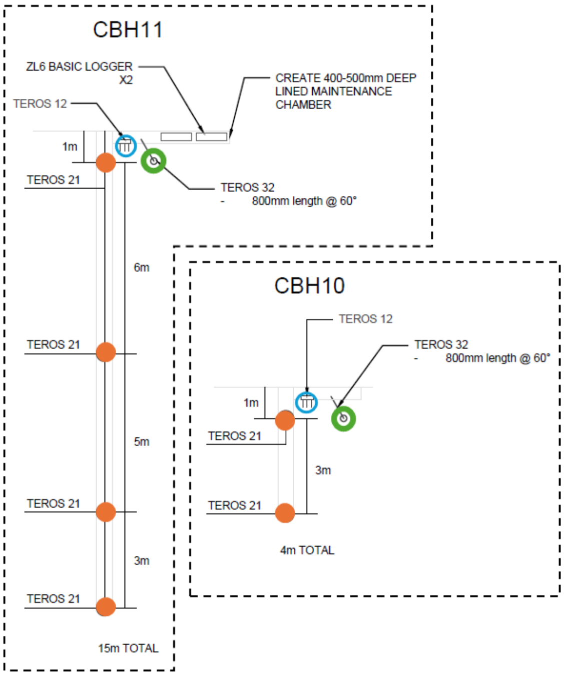

Figure 2. Moisture system arrangement

The TEROS 21 sensors were installed using the installation method described in Schulz-Poblete (2022). TEROS 12 and TEROS 32 sensors were installed as per METER guidelines.

To an extent, operational limitations dictated which sensors could be installed. As this was an ongoing project with budget constraints and restrictive deadlines it was decided to use a single family of sensors and logger, which would allow for ‘plug-and-play’ usage. Furthermore, it was decided to focus the available budget on developing two parallel systems of monitoring: a ‘shallow’ and a ‘deep’ system.

The shallow system is present in both boreholes CBH11 and CBH10 and consist of parallel installations of TEROS 12, 21, and 32 sensors in the zone 0.5 – 1.0 m BGL. The shallow system was designed to provide comparative in-situ data for three complementary suction sensors over a long period. Unfortunately, problems have persisted with the TEROS 32 sensors since installation, and therefore only the volumetric water content and suction data of the TEROS 12 and 21 sensors respectively, will be presented here.

The sensors in CBH11 form the deep system and are intended to monitor suction changes at depth in the fill/colluvium gulley area near the zone of cracking (sensors at 1 m, 7 m, 12 m, 15 m BGL). A long-term aim of this system is to determine if a theorised underground drainage path is present and affecting the stability of the embankment. The deep system was limited to using TEROS 21 suction probes at depth since TEROS 12 and 32 sensors require more careful installation to ensure hydraulic contact between sensor and surrounding soil. As a result, these sensors are better suited to near-surface installations.

3.2 *Sensor Discussion*

While it is not the purpose of this paper to present detailed descriptions of the sensors, it is important to highlight their practical limitations. Note that both sensors used manufacturer calibrations, rather than site-specific calibrations.

3.2.1 *TEROS 21 (Suction sensor)*

The TEROS 21 sensor is the most widely used in the present study. It is a fixed-matrix porous sensor with a stated measurable matrix suction range of 0 – 100 000 kPa. Its ability to measure suctions over a wide range with effectively no maintenance requirements make it a very attractive tool for in-situ measurements. The sensor infers suction based on the water content of the fixed-matrix ceramic disc by means of a set water-suction relationship (i.e. a SWRC for the disc). Tripathy et al. (2016) presented an overview of this type of sensor that can be reviewed for more information. For the purposes of this study, four points should be noted:

1. As suction measurements are dependent on the water content in the disc, readings may lag in the time it takes for water to infiltrate/exfiltrate the disc during moisture changes in the parent soil.
2. Errors in the TEROS 21 sensor have been noted to increase in the high suction ranges (100 – 100 000 kPa) (Vandoorne, 2020). In these suction ranges small variations in measured disc water content cause large changes in inferred suction due to the shape of the ceramics’ retention curve.
3. Hysteresis occurs between wetting and drying of the ceramic disc (Vandoorne, 2020).
4. Previous experience indicates equilibration of this sensor type can take 1-2 weeks (Tripathy et al. 2016, Schulz-Poblete et al. 2022).

3.2.2 *TEROS 12 (Volumetric water content sensor)*

The TEROS 12 sensor is a capacitance type sensor used to measure volumetric water content. In an assessment of four different water content sensors, Mittelbach et al. (2012) noted that the tested capacitance type sensor (Decagon 10HS) was prone to errors on the wetter end of the moisture spectrum. This erroneous behaviour appears to carry over to the TEROS 12 sensor as noted by Fajire et al. (2025). Based on this information, it is logical treat volumetric water content values with caution when the soil tends towards saturation.

4 IN-SITU MOISTURE DATA

4.1 *Shallow Suction-Water Content Data*

This section discusses the relationship between the TEROS 12 and 21 measurements (VWC and suction, respectively) in the near-surface layer. Figure 3 and Figure 4 present data from two boreholes over a 21-month period. Discrete drying cycles have been identified and named chronologically for later reference.

Attention is drawn to four respective zones in these graphs, colour coded as follows:

- Green – Period of equilibration of TEROS 21, VWC and suction measurements not yet correlated.
- Grey – Varying VWC measurements in high VWC range, corresponding with periods of very low suction.
- Yellow – Periods of increasing suctions corresponding to decreasing VWC.
- Red – Only present in CBH10, an error apparent in TEROS 12 data from late 2024. Reading jumps from in-situ values of approximately 0.3 to 0.8 m^3/m^3.

The behaviour of the TEROS 12 in wet conditions (high VWC) appears erratic and unrelated to the corresponding suction readings. While it is difficult to confirm measurements in the grey zone are erroneous, literature does suggest these sensors have limitations in the high-water content range. High variance in the grey zone, as well as the error in CBH10 highlighted in red may support this view.

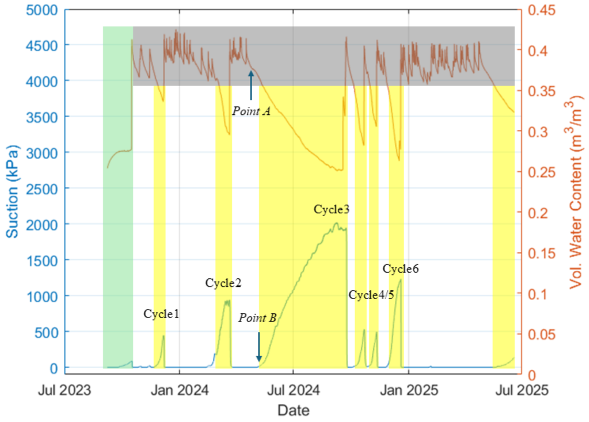

Figure 3. CBH11: Volumetric water content and suction

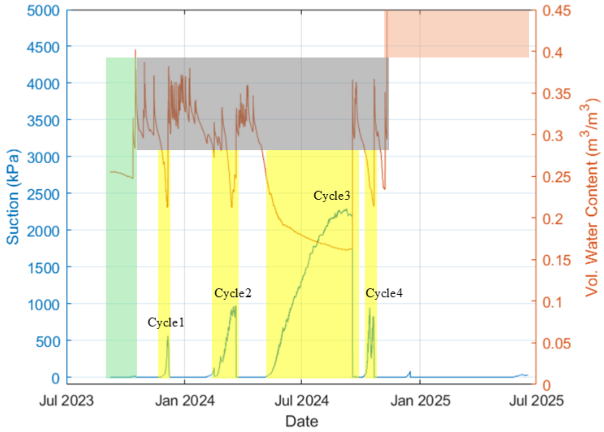

Figure 4. CBH10: Volumetric water content and suction

It was expected that there may be a response lag between the sensors, as the operating principle of the TEROS 21 means it may be slower to respond than the TEROS 12. Furthermore, the two sensors are not located at the same depth below ground level (~500 mm level difference).

There is evidence of suction response lag compared to VWC during drying cycles; however, wetting appears to register simultaneously. The clearest example of both phenomena is Cycle 3 in CBH10 as suction increase lags a VWC decrease that has been discernible for more than a week (Points A and B in Figure 3). However, when wetting occurred at the end of this cycle, both sensors registered the moisture change within the hour.

Based on the above, the TEROS 12 and 21 sensors appear complementary, if imperfect. The suction lag while drying is a limitation but appears to vary by cycle and by borehole. This may indicate that it is in part a function of hydraulic conductivity in the parent soil (which is in turn dependant on the suction/moisture state of the parent soil).

The relationship can also be evaluated directly by plotting in-situ VWC and suction on a semi-log graph. Ket et al. (2018) carried out a similar procedure using older versions of similar sensors (Decagon 10HS and MPS-2). The raw data plot for both boreholes is presented in Figure 5 alongside the laboratory measured SWRC described in Section 2.4.

In a perfectly coupled system of water content and suction, one would expect the path of the plot to reflect the wetting, drying, and scanning curves that make up a SWRC. Due to the imperfect nature of the sensors (and in-situ monitoring in general) unusual responses, as shown in Figure 5 can result. Clearly incorrect sections of the plot appear to be either vertical (changes in VWC at constant suction) or horizontal (changes in suction at constant VWC). Horizontal suction changes at constant VMC may be occurring in the capillary regime, but reviewing the data shows these horizontal lines are often he result of brief jumps in the suction signal. Many of these sections reflect the areas of data presented in the grey zone in Figure 3 and Figure 4. There may however be other undefined causes for some of these errors.

However, there are multiple parts of the plot which resemble curves on an SWRC. These tend to reflect the drying cycles highlighted in Figure 3 and Figure 4 where it was noted that VWC and suction change appear correlated.

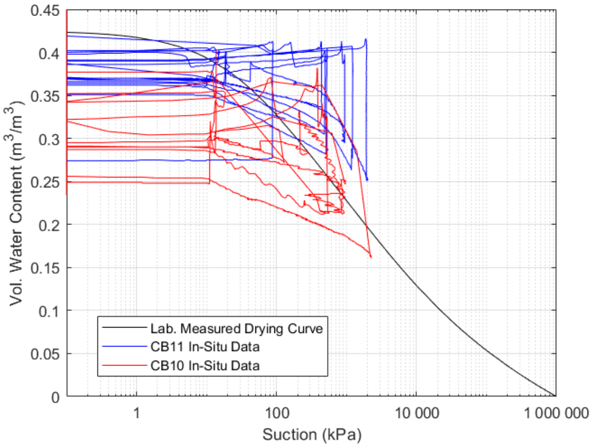

Figure 5. In situ data and laboratory measured drying curve

Processing the data and removing the anomalous results mentioned above produces the plots presented in Figure 6 (CBH11) and Figure 7 (CBH10). An effort has been made to estimate where a bounding 'in-situ drying curve' may be located (accounting for the effects of in-situ soil structure). Note that this curve is not equivalent to a primary drying curve determined in the laboratory with a slurried (non-structured) sample. The difference in soil structure between a slurry prepared sample and in-situ soil create a different family of SWRC curves. The presented curve is merely meant to present a possible bounding curve for in-situ data.

The interpreted in-situ drying curve for both CBH11 and CBH10 were fitted based on data from Cycle 2, as well as the higher suction data from Cycle 3. The remaining cycles appear to represent scanning curves – plotting between the drying curve and a theoretical wetting curve along a flatter slope.

Errors inherent in the sensor types used have been discussed in Section 3.2. Despite these errors, suction and VWC readings appear to create repeatable cycles that agree with unsaturated theory. It is noted that for both boreholes, Cycle 2 begins following a long wet period (Figures 3 & 4) and therefore begins from a higher VWC. A short drying period follows Cycle 2 before Cycle 3 begins the long winter drying period form a lower starting VWC. Cycle 3 therefore traverses a scanning curve (flatter gradient), before meeting the data from Cycle 2 on the interpreted in-situ drying curve, thereafter, following a steeper gradient.

Following the logic above, further scanning curves are present based on short drying cycles (Cycles 1, 4, 5). For future investigations, it is recommended that evapotranspiration data is included in the analysis, as it may therefore be possible to better interpret full wetting and drying cycles.

Accepting that the SWRC measured in the laboratory was a 'mean' sample, created from various remoulded silty layers, there is some variability between the laboratory measured curve and the drying cycles measured in situ. The implications of this must be carefully considered when using laboratory measured SWRC's to model in-situ behaviour.

In the present study, it appears that any modelling done using the laboratory SWRC would have been conservative over a wide VWC range, since the laboratory curve is positioned left of many in-situ measurements (Figure 6 – CBH11) thus underpredicting suction at a given VWC. However, the data at CBH10 (Figure 7) shows that scanning curves (in addition to primary curves) should also be modelled, or suctions could be overpredicted.

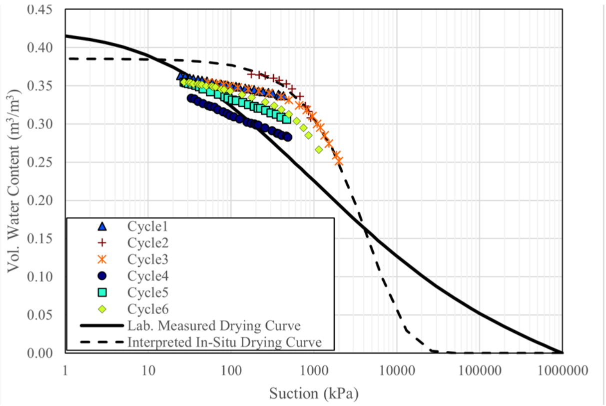

Figure 6. CBH11: Processed in-situ data and interpreted drying curve

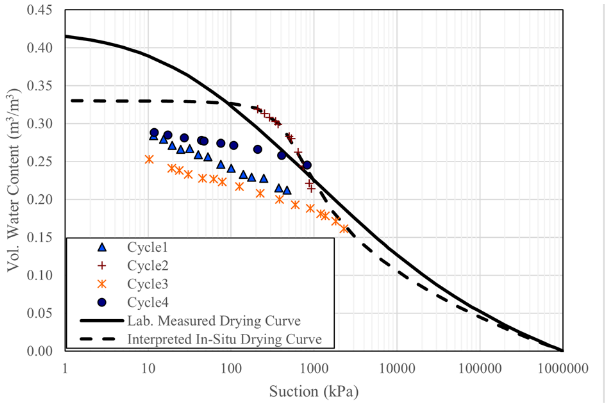

Figure 7. CBH10: Processed in-situ data and interpreted drying curve

4.2 *Deep Suction Data*

This section discusses the seasonal variation of suction measurements at depth in borehole CBH11. TEROS 21 sensors were installed at 1 m, 7 m, 12 m, and 15 m BGL. The three deepest sensors were placed at these depths (in the bottom Fill and Colluvium layers) as it was believed that the slip surface may pass through a zone located 12 – 15 m BGL. This assumption was later verified by inclinometer data near CBH11 (CBH1 – see Figure 1) showing a zone of movement between 9 – 14 m BGL. Furthermore, this slip surface was thought to be influenced by the seasonal fluctuation of the water table, believed to be around the same depth.

Figure 8 presents a 3-dimensional matrix suction plot over a span of 21 months. The same data for 1 m and 7 m BGL is presented in 2D in Figure 9. During this timeframe, two full wet seasons are captured (Summer – November to February), while only one full dry season is captured (Winter – May to August).

As would be expected, the shallowest sensor at 1 m best correlates with seasonal environmental conditions. Generally low suction conditions in the wet season, punctuated by brief periods of increasing suctions. The maximum suction (2010 kPa – September '24) is built up over the entire dry winter season starting in early May and dissipating all at once in late September with the onset of the first rains. Although no rainfall and evapotranspiration data were available at time of writing, the timing of rains can be assumed based on typical weather patterns in the area (Weather-and-climate 2025).

The sensor at 7 m shows large variations in suctions throughout the year with a maximum suction of 1320 kPa recorded in September '24. However, suctions at this depth are less correlated with seasonal fluctuations. The source of suction seasonal variation at 7 m BGL is however difficult to quantify with the data alone. More detailed investigations and modelling required to answer question about the role of surface rainfall infiltration and the influence of the theorised underground drainage path.

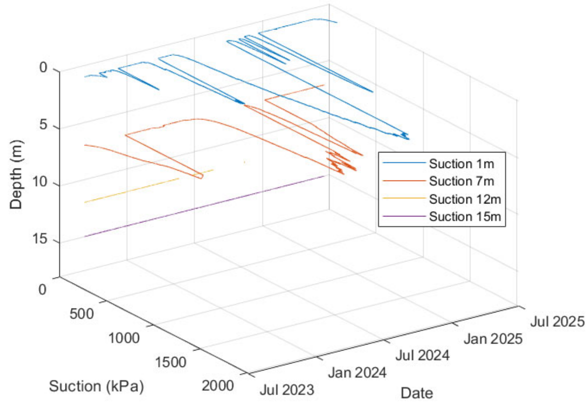

Figure 8. 3D plot of CBH11 suctions by depth and date

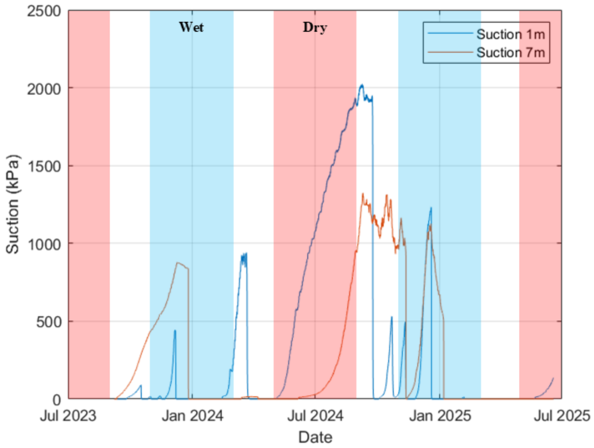

Figure 9. 2D plot of CBH11 suctions by depth and date

Data at 12 m is incomplete as a gap is present around June – July '24, and no further data was recorded from August '24. The sensor appears to be problematic, but it is unclear what the cause may be. For the little data that is available in the August – June '24 period, near saturated conditions were measured. In the same period suctions at 7 m BGL were steadily increasing.

Data at 15 m BGL is complete, and near saturated throughout the year, implying the presence of a year-round water table near at or above this depth. The degree to which this water table fluctuates throughout the year is unclear, as observations during construction suggest that it does.

Transient numerical modelling, incorporating precipitation and evapotranspiration data is considered as the next step to further understanding of this behaviour.

5 DISCUSSION

This study focused on in-situ monitoring of water content and suction within a disused road embankment. These measurements have been interpreted along with the strengths and limitations of relatively cheap commercially available soil sensors, with the goal of better understanding the moisture regime in a soil embankment.

Despite limitations of the TEROS 12 and TEROS 21 sensors used, in-situ soil moisture data appeared to produce patterns of drying cycles which were different for each borehole, but internally consistent and in agreement with unsaturated theory. When plotted in semi-log space, VWC and suction data created an apparent bounding in-situ drying curve during certain periods (first drying cycle in autumn after long wet summer, long drying cycle in winter), and in other periods produced apparent scanning lines (during small drying cycles in spring and summer).

Investigation into suctions at depth was aimed at determining how moisture varies seasonally at depth in the embankment. Site observations suggest some level of seasonal water table fluctuation. However, available suction data at 7 m, 12 m and 15 m BGL cannot confirm the degree of this variation besides the fact that 12 – 15 m BGL appear to be saturated for large parts of the year. This depth of apparent water table fluctuation agrees with preliminary numerical modelling and inclinometer measurements which indicate that the embankment failure is linked to soil weakening in this zone.

However, without further in-situ measurements or more sophisticated transient numerical analyses it is not possible to isolate whether water content variations at depth are due to surface infiltration, or the theorised drainage path present in the colluvium at depth. Further analysis of this site aims to incorporate meteorological data obtained from nearby weather stations. Furthermore, a future installation of a similar system would do well to consider adding continuous water table monitoring, and 2-3 more suction sensors at depth, for a more complete picture.

6 CONCLUSIONS

Following in-situ measurements of matrix suction and soil water content over a 21-month period, the following conclusions can be made:

1. Accepting some limitations, commercially available sensors appear to be able to produce consistent in-situ data which can produce drying and scanning curves.
2. Further study is needed to better identify the magnitude of error in the sensors under different moisture conditions. Such an investigation should consider the performance of each sensor in isolation (e.g. hysteresis, high VWC data scatter), and the relationship between sensor measurements (e.g. lagged suction response).
3. Importantly, the implications of any error highlighted in the above step with respect to design and modelling should be considered.
4. Transient modelling is required to understand seasonal moisture flows, into and out of the slope. This will help answer the question of whether water is infiltrating through the embankment surface or being channelled in by an underground drainage path.
5. As per the discussion in Section 5, future in-situ installations should include additional sensors at depth (water table sensor, and additional suction sensors).

7 ACKNOWLEDGEMENTS

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