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Installation of a low-cost unsaturated soil monitoring system in Howick, South Africa

Installation d'un système de surveillance des sols non saturés à faible coût à Howick, Afrique du Sud

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ABSTRACT: The stability of soil embankment slopes is an important aspect of infrastructure works, as many crucial roads, buildings and runways are ultimately supported by them. As changing climate patterns affect slope stability, the infrastructure in turn is put at risk. Increasingly, studies are being undertaken worldwide to investigate the effect of harsher climatic conditions on slopes using unsaturated theory, both by modelling and monitoring unsaturated slopes. This paper presents a low-cost suction monitoring solution incorporating fixed-matrix porous sensors for a 11 m high slope on a highway embankment in South Africa that had shown signs of movement prior to mechanical stabilisation works. An overview of the equipment and techniques used to install the system is given and data obtained from the system over a dry and a wet season is presented. The analysis of this data shows how material layering in the embankment can lead to localised zones of higher and lower suction which cannot necessarily be anticipated for design purposes without the air of direct measurement.

KEYWORDS: Fixed-matrix porous sensor; unsaturated soil mechanics; field testing, fill embankment, rainfall infiltration.

1 INTRODUCTION.

The field of unsaturated soil mechanics has seen great advances over the last decade in terms of the theoretical understanding of unsaturated processes and their contribution to geotechnical engineering problems, a good summary of which is provided in Fredlund (2018). In slope stability analysis the unsaturated permeability (which is lower at higher suctions) affects rainfall infiltration, while the increased shear strength from soil suctions can aid overall slope stability. The lack of suctions present could therefore result in creep of soil layers further downslope.

Furthermore, there have been substantial developments in the equipment used to measure soil suction both in the laboratory and in the field, with some equipment allowing magnitudes of suction greater than a mega-pascal to be reliably measured (Ridley & Burland 1993; Lourenço *et al.* 2006; Jacobsz, 2019). Unsaturated soil mechanics is poised to enter engineering practice over the coming years with its adoption into codes of practice (DPTI, 2015), requiring practitioners to understand unsaturated theory. The various theoretical calculations and laboratory tests must be accompanied by a thorough understanding of how to carry out unsaturated field testing and monitoring in different soils and contexts.

The aim of this paper is to add to the body of knowledge regarding in-situ monitoring of soil suction (van der Raadt *et al.* 1987; Mendes *et al.* 2008; Toll *et al.* 2011; Toll *et al.* 2012; Puppala *et al.* 2011; Puppala *et al.* 2012; McCartney & Khosravi (2013)). In this study, specific emphasis has been placed on adopting a cheap and robust monitoring system that can be used on small to medium sized projects. In doing so, the stability of slopes under varied climatic conditions can be monitored over a prolonged period.

This study will include a discussion on the relative benefits and limitations of the implemented setup, as well as proposed improvements to the system.

2 SITE HISTORY AND CHARACTERISATION.

The subject of the current study is an embankment that supports a major highway, National Route 3, in the South African province of KwaZulu-Natal. This embankment, among others, has been the subject of continued surveying and visual inspection due to minor cracks appearing in the roadway and survey data suggesting a general trend of slope movement away from the roadway.

Initial modeling of the embankment was carried out based on soil parameters of similar nearby embankments, to be augmented by new soil parameters once core drilling had been completed.

This initial conventional saturated analysis determined that the embankment was quasi-stable under current conditions, but a change in the water regime may lead to deterioration. The embankment was therefore still standing and fulfilling its purpose, with only some subsidence and cracking in the road hinting at a problem. Subsequent models were therefore run with the inclusion of unsaturated soil parameters. The slope was modelled at an angle of 40° from the horizontal. In the model, rainfall infiltration was modelled using transient flow analysis, and hydraulic conductivity functions (HCF) using the Rocscience RS2 programme. An example of one of these models is presented in Figure 1, showing the wetting front as a result of rainfall infiltration and the associated reduction in shear strength represented by the factor of safety (FoS).

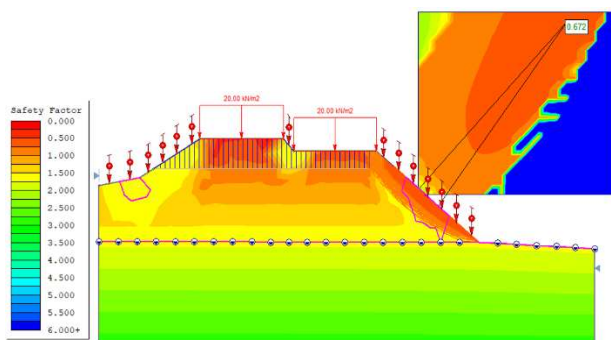


Figure 1. Unsaturated model of effect of rainfall infiltration and transient water flow on embankment

In these unsaturated soil models the Extended Mohr-Coulomb failure criteria is used to estimate unsaturated shear strength (Fredlund & Rahardjo, 2012). The addition of unsaturated theory and rainfall infiltration to the model showed a FoS < 1.0 for shallow sloughing failures occurring.

The authors were subsequently instructed to design a rehabilitation system for the embankment and prevent further movement. The slope is approximately 11 m high and 50 m wide. Stabilisation of the slope was achieved through the use of high-tensile steel mesh pinned back with a combination of soil nails and hollow bar soil nails. Sub-horizontal drill drains were also installed at the base of the slope with the intention of drawing down the water table.

The soil suction measuring system presented in the current study was conceived as a way to monitor suction changes in the embankment over an extended period of time. This would allow for the effect of rainfall, as well as the depth of the wetting front to be assessed.

A cross-section of the embankment and mechanical stabilisation measures is presented in Figure 2.

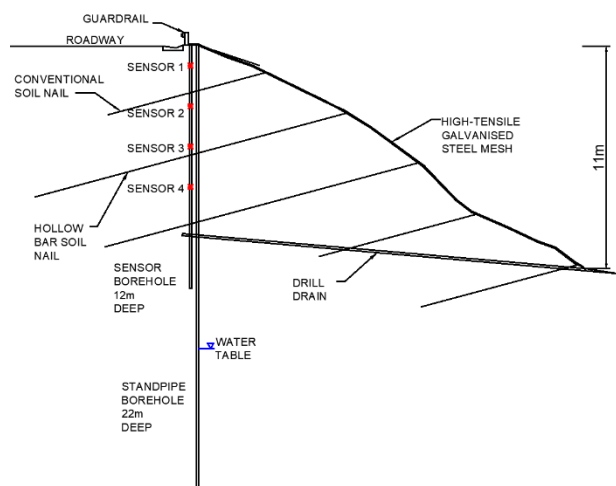


Figure 2. Cross-section of fill slope

The embankment is located in a subtropical area of the country characterised by wet summers (average 174 mm/month) and dry winters (average 15 mm/month), with overall mean temperatures of 20°C in winter and 24°C in summer (Weather Spark, 2021). The significant variation in precipitation between summer and winter in this area make it an ideal site for the monitoring of seasonal fluctuations in soil suction. The initial borehole used for core logging (22 m deep) had a standpipe installed and was used for water table monitoring. The soil suction measuring system was installed in a second borehole (drilled to 12 m) installed 1 m away from the standpipe.

Core drilling was carried out at the crest of the embankment down to 22 m. The soil profile is presented in Table 1. Water was encountered at 15.0 m below surface.

Table 1. Embankment soil profile

Soil Type	Depth (m)
Clayey SILT, Fill	0 - 2.2
Clayey SAND, Fill	2.2 - 4.5
Silty CLAY, Fill	4.5 - 16.0
Very Soft Rock, DOLERITE	16.0 - 17.3
Soft to Medium Hard Rock, DOLERITE	17.3 - 22.0+

A Shelby sample was retrieved between 4.95 – 5.45 m below surface. This sample was sent for laboratory testing. Two soil-water retention curves (SWRC) were measured on this sample at the University of Pretoria using the continuous tensiometer approach combined with discrete measurements (using a dewpoint hygrometer) in the high suction range as outlined by Gaspar *et al.* (2019). The best-fit curves established using the Fredlund & Xing (1994) method are presented in Figure 3.

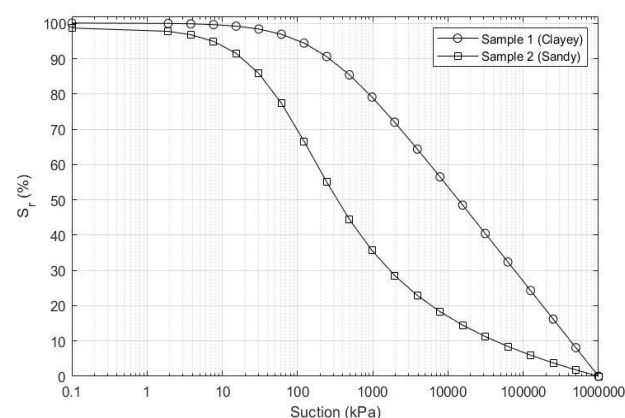


Figure 3. Degree of saturation SWRCs for two fill samples

The difference in the two measured curves may be accounted for by the fact that the Shelby sample was retrieved at an interface between two different grades of fill (clayey sand above and silty clay below). The two samples tested were taken from the top and bottom of the Shelby sample respectively, and there is therefore a likely difference in grading between these two samples.

3 SUCTION MEASUREMENT SYSTEM.

The suction measurement system used in this study comprised a Data Acquisition System (DAQ) designed by the University of Pretoria. The DAQ can accommodate four internally connected Teros 21 sensors. The Teros 21 (previously known as MPS-6) sensors are made by METER Group and were selected for ease of use/installation relative to high-capacity tensiometers, as well as their low cost. Fixed-matrix porous sensors such as the Teros 21 were initially developed for agricultural uses, but studies have been undertaken to assess their use for geotechnical engineering purposes (Tripathy *et al.*, 2016; Jones *et al.* 2019; Vandoorne, 2021).

Both the DAQ and the Teros 21 sensors are presented in Figure 4 below.



Figure 4. Closed DAQ with four ports for Teros 21 suction sensors

The DAQ consisted of an Arduino based system connected to a lithium polymer battery that can theoretically support readings taken for 10 years depending on the sampling interval chosen. The data was then recorded to an internal SD card which was manually switched out with an empty SD card when the battery was due to be changed. This DAQ was designed to be waterproof as it was intended to keep the DAQ below the ground surface. Burying the DAQ was necessary to safeguard the equipment against potential vandalism and theft.

A feature of this monitoring system which was deemed crucial by the authors was its low cost and ease of installation. By prioritising these aspects, similar setups can be adopted by industry relatively easily, thereby facilitating the wider adoption of unsaturated soil mechanics in practice. The UP DAQ cost USD1860 and the sensors used in this study were purchased for USD280 (2018 price) each. The total price of the system was therefore approximately \$3000. The cost of this system could be even further reduced if the suction sensors were replaced with low-cost tensiometers, where material costs have been noted to amount to just \$27 (Jacobsz 2018).

The UP high-capacity tensiometers were considered for this study, however, tensiometers are better suited for long-term monitoring in high moisture environments (e.g. tailings dams) or in dryer environments where tensiometers can periodically be retrieved and rotated with newly saturated ones for best performance. This is due to the susceptibility of tensiometers to cavitate when their capacity is exceeded. In the present study suction readings were to be measured over a long period of time in an uncertain suction environment. Fixed-matrix porous sensors were therefore seen as the safer choice owing to their ability to measure suctions over a wide range without the need for replacement or maintenance.

4 INSTALLATION METHOD.

The logging system was planned to measure suctions at four discrete depths in the embankment using the Teros 21 sensors at 1 m, 3 m, 5 m and 7 m below the surface of the embankment crest. Taken together with the water table level obtainable from the neighbouring standpipe, this data would provide information on the changes in suction state with depth during successive wetting and drying cycles.

The challenge in performing the installation is due to the requirement of almost all suction measurement equipment and methods to be in close contact with the soil being measured if matric suction is to be measured accurately (Schulz-Poblete, 2019). In some systems using tensiometers in instrumented embankments, the tensiometers are fitted into a specially fabricated pipe allowing the user to push the tensiometer face

into direct contact with the soil (Toll *et al.* 2011). A similar method was deemed infeasible with the Teros 21 sensor due to its geometry.

The chosen method of installation that was decided upon is similar to the method of installation recommended in the Teros 21 manual (METER Group 2017). In this manual the operator is instructed to perform a field installation by moistening native soil and firmly packing it around the sensor's ceramic discs. This packed sensor is then to be lowered into the hole to the required depth and a slurry of native soil poured after it. On this site there were concerns over the variability of the native soil including soil/gravel/roots that may affect readings if pressed against the sensors.

It was therefore decided to adjust the above method by substituting the native soil packed around the sensor by packing moistened silica flour around the sensor ceramic before lowering. Silica flour and other fines have previously (Oliveira & Marinho, 2008; McCartney & Khosravi, 2013) been used in unsaturated testing to provide a thin layer of transition material, which effectively hydraulically couples the parent soil skeleton with the sensor (be it tensiometer, filter paper, or other) by eliminating large air pockets around the sensor face, which may affect suction readings.

The process for preparing and installing the system was therefore as follows:

1. Drill hole in ground using an uncased rotary core method and undertake SPT-N tests.
2. Mist Teros 21 with water.
3. Press each disc into silica flour.
4. Repeat Steps 1 and 2 until a sufficient bulb of silica flour has formed around the Teros 21 ceramic discs.
5. Pour native soil at its in-situ moisture state into borehole until the first sensor level has been reached (7 m).
6. Pour a predetermined volume of silica flour into hole as a bedding layer (approximately 100 mm thick).
7. Lower coated sensor into hole until sensor is resting on bedding layer.
8. Pour another predetermined volume of silica flour for a cover layer (approximately 100 mm thick).
9. Pour native soil into hole until next sensor level is reached and repeat steps above until hole is filled.

The steps above are based on an inherent assumption. It is assumed that the silica flour packed around the sensor plus the 200 mm thick silica flour layer will not affect suction readings. When silica flour (or any other material) is present in a tiny quantity in a much larger volume of other material it is reasonable to assume that the suction characteristics of the large volume of material governs, and through equilibration the small quantity will have the same suction value as the greater whole. This will be true if the air-entry value of the silica is higher than that of the surrounding material. If the air-entry value is lower than the surrounding material, the silica will desaturate in an unsaturated soil, resulting in poor hydraulic connectivity between the sensor and the material being monitored. Poor hydraulic conductivity will slow down the rate of suction equalization between sensor and soil. This is however not considered a major problem for data logging taking place over an extended period of time.

In the present study the volume of silica flour used is miniscule compared to the amount of native soil along the sides of a 7 m run of borehole. Therefore, in the present study the silica flour around the sensor is assumed to act as a conduit to transmit the suctions of the surrounding native soil to the Teros 21 ceramic disc. This is a secondary concern due to the disturbed native soil being a relatively small volume when compared to the

surrounding soil and therefore has a negligible effect on suctions due to the process described previously.

Once all four sensors had been installed, the DAQ was placed in a pre-dug hole beside the borehole, the sensor cables were connected into the DAQ and the DAQ was switched on. The hole was then covered with native soil and left to collect data.

Figure 5 below presents key steps from the system installation.



Figure 5. System installation (a) Site overview with DAQ located at white standpipe, (b) Teros 21 sensor coated in silica flour, (c) pouring premeasured volume of silica flour down borehole and, (d) DAQ placed beside filled in borehole.

The DAQ system was installed on 19/08/2019 and data logging commenced immediately. The data was then retrieved on a second site visit on 07/12/2019 whereupon the battery and SD card were replaced. A third site visit was conducted on 09/03/2020. In total, data had been recorded for 141 days as unfortunately data collection had terminated on 06/01/2020 – shortly after the second site visit. An inspection of the DAQ system found some water pooled in the bottom of the DAQ box (not in direct contact with the electronics) and a generally humid environment within, which was the likely cause for the DAQ malfunctioning.

5 RESULTS & ANALYSIS.

The 141 days of data recorded fell in the transition from the dry season to the rainy season. However, before the rainy season started the Teros sensors had to equilibrate with the surrounding soil. For the sake of comparison, time to equilibration was determined by the same method as in Tripathy *et al.* (2016), whereby suction results are compared in 6-hour intervals until suction in an interval differs by <2 kPa. Table 2 presents the time from installation for each sensor to equilibrate.

Table 2. Teros 21 sensor days to equilibration

Sensor No.	Depth (m)	Days (Hours) to Equilibration
1	1	3 (75)
2	3	3 (74)
3	5	3 (70)
4	7	8 (197)

Tripathy *et al.* (2016) reported equilibration times for various clay mixes between 12 h to 2 weeks depending on the soil used and initial moisture state of the soil and sensor respectively. The

time to equilibration presented in Table 2 certainly falls within this range. The soils in this study are not clean clays and one would therefore expect their equilibration times to be on the lower end of those measured by Tripathy *et al.* (2016). The consistency of suctions after these equalisation points suggest that self-compaction had ceased by the time suctions showed apparent equalisation. These post-equalisation suction values are presented in Figure 6a.

The most immediately apparent trend in the data presented in Figure 6a is the sharp drop in suctions experienced in Sensor 1 at 1 m below surface level. These sharp drops in suction may be explained by two periods of heavy rainfall at the start of the rainy season, presented in Figure 6b. The periods of November 10-16 and December 7-16 received, at their peak 21.6 mm/day and 21.4 mm/day rainfall. These rainfall events coincide with these drops in suction at the uppermost sensor. It should be noted here that 10 kPa is the minimum suction that the Teros sensor can measure, and may therefore effectively be considered saturated, as Sensor 1 appears to be after the December rain. Furthermore, Sensor 2 at 3 m and Sensor 3 at 5 m below surface also show a general decrease in suctions over the period, although the response is delayed owing to the time required for the wetting front to reach these sensors.

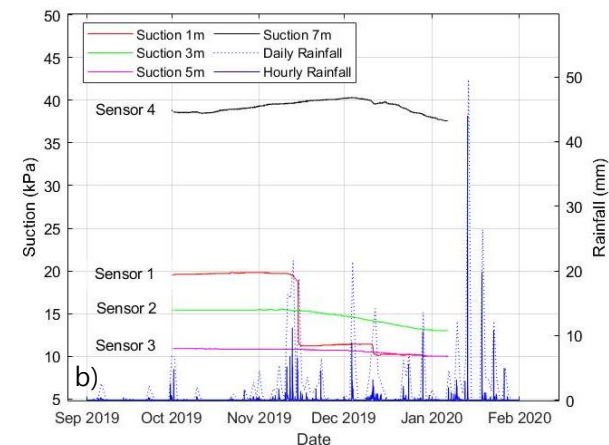
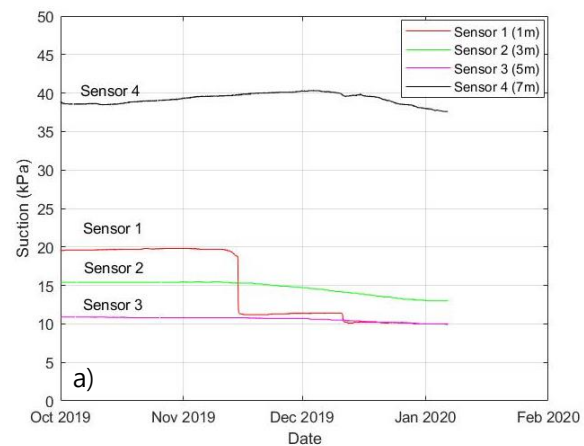


Figure 6. a) Post-equilibration suction data with b) hourly/daily rainfall data

The behaviour of the two lowest sensors at 5 m and 7 m below ground surface show little reaction to rainfall events, as would be expected at depth. The changes occurring at these depths may be better visualised by plotting sampled points by depth. Figure 7 presents the suctions profiles recorded at midnight of the first of each month against each sensor's respective depth.

During the dry season the evapotranspiration from the surface leads to higher suctions in the surface layer, while the wet season lowers the suctions as the surface takes up water. This effect

decreases with depth, which can be seen by lower sensors being affected to a lesser extent.

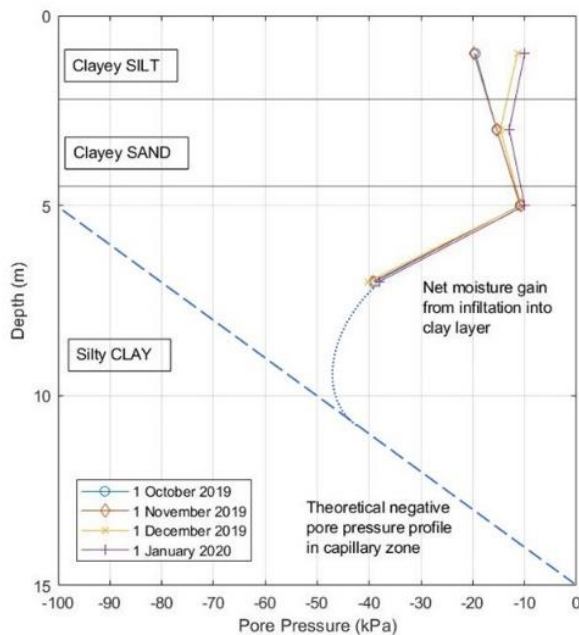


Figure 7. Suction profiles at sampled dates pre- and post-rainfall

Comparing this plot by depth with the embankment soil profile given in Table 1 shows that, while Sensors 1 (1m) and 2 (3m) are located in silty and sandy layers respectively, Sensors 3 (5m) and 4 (7m) are both located in a clayey layer. Water that infiltrates the slope appears to percolate through the overlying silty and sandy layers before stopping at the surface of the clay layer (starting at 4.5m below surface). This clay layer acts as a perched water table, leading to the near-saturated pore pressures measured at Sensor 3 (5m).

To explain the behaviour of Sensor 4 (7 m) one must consider how suctions act in the capillary zone above the water table. In a body of soil with the water table at 15 m below surface (as in the present study) one would reasonably expect negative pore pressures in the capillary zone to decrease linearly by -10 kPa for every 1 m above the water table in the capillary zone. This would hold true only if there is no environmental influence of evapotranspiration and infiltration on the pore pressures. As detailed in Table 1, the layer from 4.5 m down to the water table at 15 m is a clayey layer, overlain by a sandy layer. This sandy layer acts as a capillary break and the capillary zone does therefore not extend above 4.5 m below surface. The suction measured at 7 m below surface (40 kPa) and the suction expected at that level above the water table (80 kPa) are not equal and the difference is likely due to the infiltration of water from the perched water table into the clay layer. This infiltration produces a net moisture gain that lowers the suctions in the uppermost part of the capillary zone (Fredlund, 2018), an approximation of which is given by the curved line in Figure 7. The surface of the clay layer at 4.5 m is most likely sloped to some degree. If the surface of the clay layer was level, the perched water would not be able to flow laterally and drain away. The perched water would then either:

1. Accumulate on the surface of the clay layer, lowering the suctions in upper layers to near saturated or,
2. Infiltrate and saturate the clay below, leading to suctions at 7 m below surface being near saturated.

It is unclear what is causing the slightly erratic behaviour of Sensor 4 when compared to the stable readings of the other three sensors (Figure 6a). It is possible that the decrease in suctions in Sensor 4 starting in early December may be as a result of water from the mid November rainfall events slowly percolating through the layers, but this cannot account for the variation seen from October to December. Long-term monitoring is required to determine where these variations in Sensor 4 originate from, and will be invaluable to demonstrate how suctions (and water levels) build up and dissipate over successive seasons, particularly as the sub-horizontally drilled drain at 10 m below surface begins to extract water in the clay layer.

6 CONCLUSIONS.

The present study was carried out to assess the feasibility of using a low-cost suction measurement system in the context of a slope that had been showing signs of shallow failure occurring due to rainfall infiltration.

The resulting system was built to a total cost of approximately \$3000 including sensors and DAQ. Suction results gathered over a three-month period, spanning the transition from the dry season (winter) to the wet season (summer), have shown the effect of rainfall infiltration on the soil suctions and have given an indication of the depth of infiltration, with the top 2-3 m of the embankment profile becoming near saturated. This observation supports the findings of the initial unsaturated limit equilibrium analyses with rainfall infiltration that showed shallow sloughing failures from the effect of rainfall infiltration and the subsequent loss of shear strength when the surficial layers became saturated.

Post-rehabilitation and stabilisation works (soil nails and high-tensile steel mesh), the embankment is considered stable against the shallow slip failures previously considered a possible failure mode. For this reason, the embankment in this study was considered a good candidate for trialing the suction measurement system discussed in this study. In this regard the trial may be considered a success as the suction results returned by the measurement system are reasonable when considered in conjunction with the embankment material layers. These results therefore validate the design of the system as well as the method of installation.

The following aspects were found to be crucial to the correct functioning of the system and interpretation of its results:

3. Additional measures must be in place to protect the DAQ from water, particularly so if it is installed underground.
4. Soil data gathered from ground investigation and laboratory testing is essential to successfully interpreting the suction data found by the system. The following tests are deemed essential:
 - a. Embankment ground profile (borehole logging, sampling),
 - b. Water level determination,
 - c. Laboratory testing (foundation indicators, moisture content, soil grading),
 - d. Soil Water Retention Curves (SWRC).
5. Rainfall data from nearest weather station.

The points above can benefit any suction measurement system, as once the major soil layers in the embankment have been defined, they can be sent to the laboratory for testing to establish their gradings, soil properties, and shear parameters with triaxial testing if budget allows. The suction behaviour can then be determined by the SWRC and soil suction changes seen in the monitored data can thereby be translated into shear strength parameters useful for determining the factor of safety against failure with limit equilibrium methods.

The interpretation of the results in this study clearly underlines the fact that theories describing suction change with depth must take into account the local conditions such as environmental (rainfall intensity, evapotranspiration) and geological (soil types, layering, bedding) factors that cannot always be anticipated from the outset. In this regard direct measurement is an invaluable tool and will aid any analysis that follows.

7 ACKNOWLEDGEMENTS

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8 REFERENCES

- Average weather in Howick South Africa*, Weather Spark, viewed 27 May 2021, <https://weatherspark.com/y/96297/Average-Weather-in-Howick-South-Africa-Year-Round>
- Fredlund, D. G., Rahardjo, H., & Fredlund, M. D., 2012. Unsaturated soil mechanics in engineering practice, Wiley
- Fredlund, D.G. and Xing, A., 1994. Equations for the soil-water characteristic curve. *Canadian geotechnical journal*, 31(4), pp.521-532.
- Fredlund, D.G., 2018. Role of the soil-water characteristic curve in unsaturated soil mechanics. In *Proceedings of the 19th International Conference on Soil Mechanics and Geotechnical Engineering* (pp. 17-22).
- Gaspar, T. A. V., Jacobsz, S. W., Schulz-Poblete & Toll, D. G., 2019. Measurement of the soil water retention curve: practical considerations. *Proc. Of the 17th African Regional conference on Soil Mech. And Geotech. Eng., Cape Town*, pp. 227-232
- Jacobsz, S.W., 2018. Low cost tensiometers for geotechnical applications. In *Proceedings of 9th International Conference on Physical Modelling in Geotechnics* (pp. 305-310).
- Jones, B.R., van der Merwe, F.H., Schulz-Poblete, M.V. and Pequeno, F.P., 2019. Harvesting from agriculture: Evaluating the in-situ measurement of matric suction for geotechnical applications using a water potential sensor. In *Proceedings of 7th African Young Geotechnical Engineers' Conference* (pp. 189-194)
- Lourenço, S.D.N., Gallipoli, D., Toll, D.G. and Evans, F.D., 2006. Development of a commercial tensiometer for triaxial testing of unsaturated soils. In *Unsaturated Soils 2006* (pp. 1875-1886).
- McCartney, J.S. and Khosravi, A., 2013. Field-monitoring system for suction and temperature profiles under pavements. *Journal of performance of constructed facilities*, 27(6), pp.818-825.
- Mendes, J., Gallipoli, D., Toll, D. G. and Augarde, C. E. 2008. A system for field measurement of suction using high capacity tensiometers. *Unsaturated Soils: Advances in Geo-Engineering. Proceedings of the 1st European Conference on Unsaturated Soils*, CRC Press/Balkema, Durham, UK, pp. 219-225.
- Oliveira, O.M.D. and Marinho, F.A.M., 2007. Suction equilibrium time for a high capacity tensiometer. *Geotechnical Testing Journal*, 31(1), pp.101-105.
- Puppala, A. J., Manosuthkij, T., Nazarian, S. and Hoyos, L. R. 2011. Threshold moisture content and matric suction potentials in expansive clays prior to initiation of cracking in pavements, *Canadian Geotechnical Journal* 48(4), 519-531.
- Puppala, A. J., Manosuthkij, T., Nazarian, S., Hoyos, L. R. and Chittoori, B. 201. In situ matric suction and moisture content measurements in expansive clay during seasonal fluctuations, *Geotechnical Testing Journal* 35(1), 74-82.
- Ridley, A.M. and Burland, J.B., 1993. A new instrument for the measurement of soil moisture suction. *Géotechnique*, 43(2), pp.321-324.
- Schulz-Poblete, M.V. 2019. On the effective measurement of soil suction and related parameters in granular material: A case study. In *Proceedings of 7th African Young Geotechnical Engineers' Conference* (pp. 55-60)
- Teros 21 User Handbook, Gen 1. METER Group., Pullman., WA, United States., 2017. Accessed on: 05, 29, 2021.. Available: http://publications.metergroup.com/Manuals/20428_TEROS21_Gen1_Manual_Web.pdf
- Toll, D.G., Lourenço, S.D.N., Mendes, J., Gallipoli, D., Evans, F.D., Augarde, C.E., Cui, Y.J., Tang, A.M., Rojas, J.C., Pagano, L. and Mancuso, C., 2011. Soil suction monitoring for landslides and slopes. *Quarterly Journal of Engineering Geology and Hydrogeology*, 44(1), pp.23-33.
- Toll, D.G., Mendes, J., Hughes, P.N., Glendinning, S. and Gallipoli, D., 2012. Climate change and the role of unsaturated soil mechanics. *Geotechnical Engineering (SEAGS)*, 43(1), pp.76-82.
- Tripathy, S., Al-Khyat, S., Cleall, P.J., Baille, W. and Schanz, T., 2016. Soil suction measurement of unsaturated soils with a sensor using fixed-matrix porous ceramic discs. *Indian Geotechnical Journal*, 46(3), pp.252-260.
- Van der Raadt, P., Fredlund, D.G., Clifton, A.W., Klassen, M.J. and Jubien, W.E., 1987. Soil suction measurements at several sites in western Canada. *Transportation Research Record*, (1137).
- Vandoorne, R. 2021. Characterisation of railway formation materials for the application of unsaturated soil mechanics. *PhD Thesis*, University of Pretoria, Pretoria, South Africa.
- DPTI 2015, *Design Standard: Retaining Walls*, viewed 27 May 2021, https://dit.sa.gov.au/_data/assets/pdf_file/0003/167187/Design_Standard_Retaining_Walls.pdf.
- Jacobsz, S.W., 2019. TUKS tensiometer measures to -1.7 Mega Pascal. *Civil Engineering*, 27(1), pp.24-26.