The use of moisture probes to infer changes in suction due to controlled inundation behind a full scale trial retaining wall

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ABSTRACT: To better understand the behaviour of unsaturated clays for retaining wall design in Adelaide, South Australia, a trial soldier pile retaining wall supporting an 8 m deep excavation was constructed for a proposed 3 km long underpass. The full scale trial retaining wall was constructed prior to the start of summer to allow the soil to shrink over an extended dry period, typical of an Adelaide summer. At the end of summer, the soil was wetted up via a controlled inundation program that replicated a pipe burst or leaking water main, critical considerations for retaining wall design. As part of an extensive testing and monitoring program, in situ moisture probes were used to quantify the change in soil moisture content before, during and after inundation. This paper presents a practical means to estimate soil suction based on the calibration of moisture probe data and the use of a site specific soil-water characteristic curve. Limitations of using moisture probes to infer suction are discussed, with suggestions provided for the future use of similar moisture probes in very stiff to hard clay soils as encountered on this site.

1 INTRODUCTION

As part of an investigation into the influence of unsaturated clays on retaining structures, a trial wall was constructed in the suburb of Croydon in metropolitan Adelaide, as part of the early design stages for a lowered motorway. The purpose of the trial was to determine if the piled wall could support a deep vertical excavation when the unsaturated clay soils behind the wall were inundated. It is commonly understood that clay soils increase in volume with increasing moisture content and apply a swelling pressure to the retaining wall. Unlike rigid retaining structures that are designed to withstand the swelling pressures applied by soil acting on the wall, the soldier piles constructed as part of the this study were designed to be more flexible and deflect as the soil increased in volume, thereby reducing the soil pressures acting on the wall. Consequently, monitoring of pile movements was a critical aspect of the trial. Studies that compare measured and predicted movements at this site include Woodburn (2014) and Kuo et al. (2018); due to space constraints, this paper will not focus on this issue, but will instead focus on one key aspect of the trial, quantifying changes in soil moisture content and suction using both in situ and laboratory testing.

2 SOIL CONDITIONS

Within the general site area, published literature by Taylor et al. (1974) and Selby (1984) indicates that the soil conditions consist of deep fine-grained soils, comprising silty and sandy clays; typical of sediments washed down from the Adelaide Hills and deposited over the lower outwash plains of the Adelaide metropolitan area. As discussed by Woodburn & Herraman (2014), there have been case studies in Adelaide in similar soil conditions, where clay has been excavated as a source for brick construction, with the walls of historical pits and pug hole excavations up to 8 m deep remaining stable and able to stand nearly vertical with minimal support for several years, providing they are protected from the weather.

The location of the test site targeted natural soils deemed representative of a proposed 3 km length of lowered motorway. A summary of soil properties for the low-to-medium plasticity Sandy Clay soil that was typically encountered at the test site between depths of 1-8 m, is given in Table 1. The side walls of the excavation between soldier piles exhibited natural variability, with some fissures and defects in the exposed soil visible. The water table was located at a depth of approximately 12 m below the ground surface.

Table 1. Summary of soil properties

Soil property	
Sand content (≤ 2.36 mm, %)	26
Fines content (≤ 75 µm, %)	74
Specific gravity	2.62
Bulk unit weight (kN/m^3)	19.3
Atterberg limits	
Plastic limit (%)	17
Liquid limit (%)	37
Plasticity index (%)	20
Unified soil classification system (USCS)	CL

3 TRIAL RETAINING WALL

To better understand the behaviour of unsaturated clays for retaining wall design purposes, a full scale trial pile retaining wall was constructed within the vicinity of a proposed 8 m deep lowered motorway. Prior to excavation of the test site, a total of 47 continuous flight auger piles were cast into the ground. Two rows of embedded cantilevered soldier piles, comprising varying pile diameters and centre-to-centre spacings, were constructed to depths of 16 m. It was anticipated that data from this trial would help establish an optimum pile configuration for retaining structures associated with the proposed lowered motorway. After concrete test results showed that the piles had reached their design characteristic strength, staged excavation of the soil between the piles was undertaken, to a final depth of 8 m, as shown in Figure 1. In plan, the pile retaining wall site was 30 m in the long direction and 6.75 m wide (between the two parallel sets of piles).

Figure 1. View of excavated trial pile retaining wall.

4 EXCAVATION STABILITY

Excavation of soil was undertaken at the start of summer to allow the soil to shrink over an extended dry period. The soil was already very dry at the time of excavation between the two rows of piles. A small blade on an excavator was used to remove soil between piles. Furthermore, any large blocks of clay that could be susceptible to toppling were dislodged for safety reasons. An elevation view shortly after excavation is shown in Figure 2. The walls of the excavation were generally stable, with no reports of soil slumping from the sides of the excavation during the months of December and January. At the end of summer, the soil was wetted up via a controlled inundation program that replicated a pipe burst or leaking water main, critical considerations for retaining wall design, as discussed by Herraman (2007). A trench was excavated behind the wall as shown in Figure 3. A slotted PVC agricultural pipe was located in the trench surrounded by 6 mm sized gravel. Known volumes of water from a nearby tank located on site were added to the trench over a period of about 3 months.

Figure 2. Elevation view of pile retaining wall shortly after excavation.

Figure 3. Trench used to inundate soil behind retaining wall.

During the inundation period, there was evidence of soil saturation and slumping on the face of the walls of the excavation between the soldier piles. Whilst stable when dry, upon wetting up, blocks of clay were observed to topple from the walls of the excavation, as typically shown in Figure 4. Such failures are consistent with observations by Mitchell (2013) who described cases of instability in unsaturated fissured clay. Figure 5 illustrates imminent toppling failure, whereby dry soil on the face of the retaining wall moves away from wetter soil located behind the face. Such instabilities continued to occur on the face of the retaining wall as a result of inundation behind the wall; in some instances, long blocks up to 2 m high became unstable and had to be dislodged for safety reasons.

Figure 4. Evidence of block failures of clay from side walls of excavation after inundation of soil behind the wall.

Figure 5. Sloughing of clay between piles (foreground) with moisture probes located between piles (background).

5 MOISTURE PROBES

As part of an extensive testing and monitoring program, in situ moisture probes were used to quantify the change in soil moisture content before, during and after inundation. MP406 moisture probes (ICT International, 2017), as shown in Figure 6, were chosen because they were capable of being buried for long periods and did not require regular servicing once installed. They were robust, cost effective devices from which continuous readings could be taken when connected to a data logger and have been successfully adopted in earlier field studies (e.g. Salt et al., 2007). MP406 moisture probes measure volumetric moisture content using 60 mm long stainless steel needles that are typically pushed into the soil. Whilst in situ measurements of suction would have been preferable, tensiometers were not adopted due to the high suction range being tested. Through the use of both in situ moisture probes and complementary laboratory testing, the aim was to analyse soil-water interactions such that suction could be predicted based on a raw (voltage) readings obtained from the moisture probes.

Figure 6. MP406 Moisture Probe (ICT International, 2017).

Moisture probes were installed prior to the commencement of wetting up after pre-drilling a horizontal hole, 1400 mm in length, into the face of the excavation. Soil samples were collected from the end of the pre-drilled hole and tested in the laboratory for total suction and gravimetric moisture content, which were later converted to volumetric moisture content after measuring soil density. Soil samples were taken during the initial installation of the moisture probes and, each time the moisture probes were shifted to a new location. The moisture probes were moved periodically down the face to monitor the progression of the wetting front behind the wall. Each moisture probe was installed into the face of the retaining wall between the soldier piles, using a 2 m length of 25 mm diameter PVC pipe, as shown in Figure 5. In many cases, the needles of the moisture probes could not be pushed into the very stiff to hard clay soils, so a dummy probe was hammered into the end of the hole prior to probe installation.

During the inundation period, moisture probe readings were captured every 30 minutes using a data acquisition system that could be monitored via remote communication. In the clay soils at this site, it was found that the moisture probes were sensitive to changes in soil density, moisture content and the needle length that was inserted into the soil. Consequently, correct installation of the moisture probes was critical to obtaining meaningful results, as the full length of the needles needed to be in intimate contact with the surrounding soil to yield reproducible and reliable readings.

6 RESULTS

Raw data from one typical moisture probe installation are shown in Figure 7; the raw output from the probe is in units of milli-volts (mV). It can be observed that an initial 2300 L of water added to the soakage trench located behind the retaining wall located 1 m above the moisture probe wasn't detected by the moisture probe; however, subsequent water releases caused an increased voltage reading, consistent with a higher volumetric moisture content.

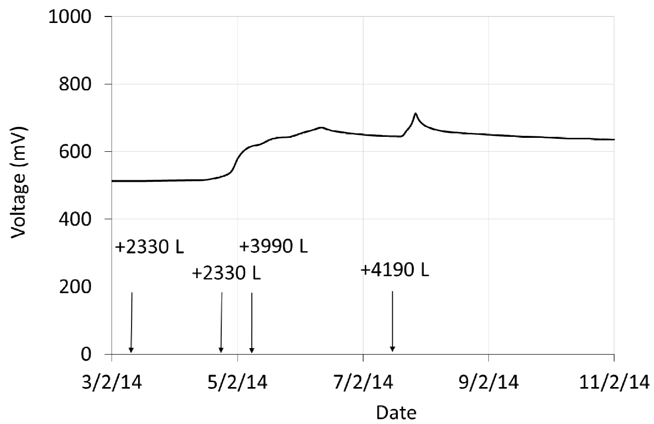

Figure 7. Example of raw readings from moisture probe located at 1 m depth showing increasing voltage due to inundation.

In order to convert the raw readings from mV into volumetric moisture content, calibration using a polynomial factory calibration was undertaken in accordance with the manufacturer's manual (ICT International, 2017). The results of inferred volumetric moisture content versus laboratory measured values are given in Figure 8, whereby it can be observed that the inferred and measured values were in reasonable agreement.

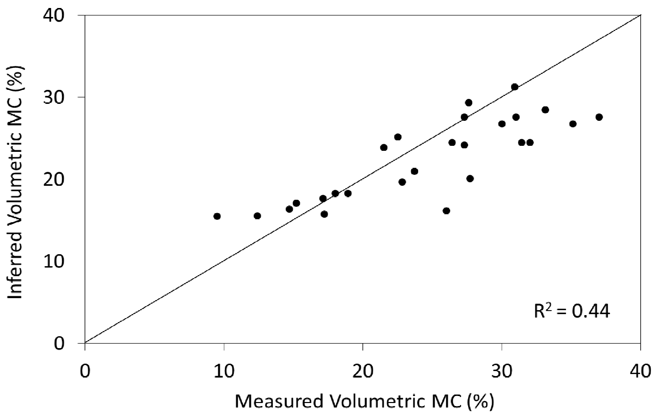

Figure 8. Inferred Volumetric Moisture Content versus Measured based on polynomial factory calibration.

A site-specific calibration for the moisture probes was determined from laboratory testing of soil samples obtained directly from site from adjacent locations, these values were compared against in situ moisture probe measurements. Figure 9 illustrates an improved relationship between inferred and measured values as a result of the recalibration. The moisture probes provided useful information regarding the progression of a wetting front and were deemed to produce reliable volumetric moisture contents below 30%. Both measurement error and the heterogeneity of the soil at the site are likely to have contributed to the variability observed in Figures 8 and 9. Further work would be required to separate the two effects.

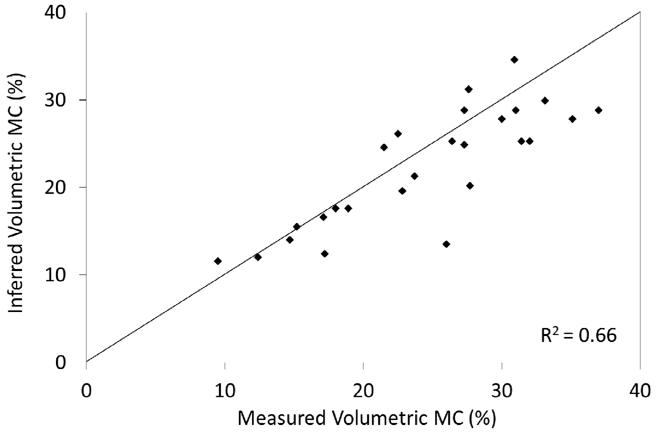

Figure 9. Inferred Volumetric Moisture Content versus Measured based on laboratory calibration on soil samples from site.

A laboratory determined drying Soil Water Characteristic Curve (SWCC), plotted as degree of saturation versus suction is shown in Figure 10. The SWCC was generated using an unsaturated triaxial machine with a 5-bar high air entry ceramic disk, in conjunction with a WP4C Dew Point Potentiameter (Meter Group, 2017) on samples taken from site.

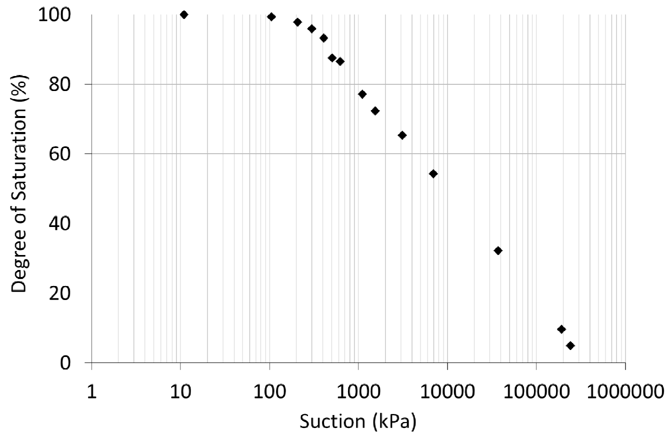

Figure 10. SWCC (Degree of Saturation versus Suction) generated from laboratory testing from site soil samples.

As can be observed in Figure 11, the near-surface readings of suction changed from 4.8 pF prior to inundation, to 3.6 pF after wetting. This change in total suction of 1.2 pF which occurred during wetting is coincidentally the same as that required for footing design in Adelaide as stipulated by AS 2870 (2011). The depth of about 8 m to which the suction change and desiccation has occurred was considered consistent with the previous use of the site, which was almost completely covered by timber-floored dwellings (with ventilated under-floor space) with nearby trees. This is much deeper than the 4 m depth required for design in AS 2870 (2011). The total suction of about 4.0 pF measured at 8 m is recognised as the equilibrium value for Adelaide. The decrease in suction below 8 m is due to the presence of the relatively shallow water table.

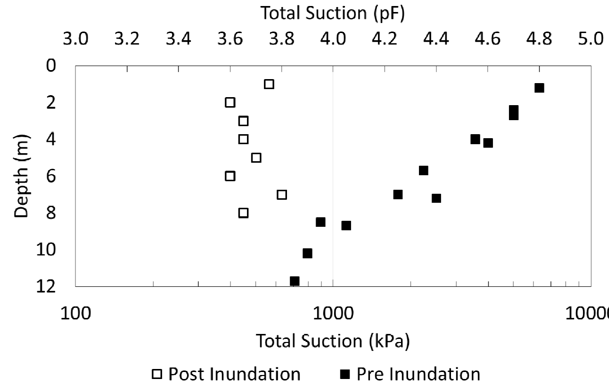

Figure 11. Suction change versus depth for pre- and post-inundation cases.

An inferred SWCC using moisture probes was developed using volumetric moisture content obtained in situ from the MP406 probes, with suction measured in the laboratory using a WP4C Dew Point Potentiameter on adjacent soil samples collected from site. The laboratory SWCC drying curve (Figure 10), was produced using representative soil samples taken from site (with soil properties as per Table 1). Figure 12 shows both the inferred SWCC determined from moisture probe data and laboratory determined drying curves, plotted as volumetric moisture content versus suction. As summarised by Fredlund et al. (2012) the moisture content versus suction relationship for any porous material is not the same during wetting and drying, therefore, it must be recognised that SWCCs inferred from both moisture probe and lab data would not be coincidental.

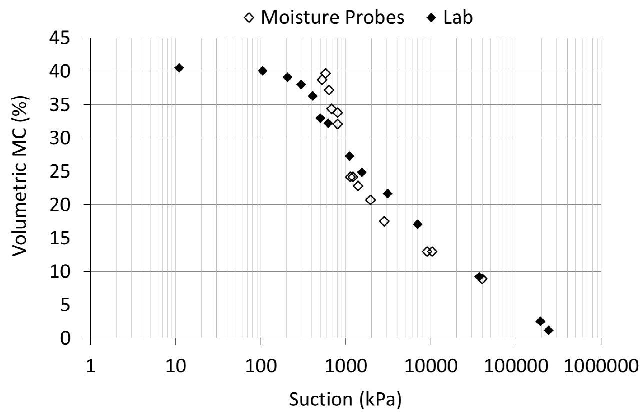

Figure 12. Comparison of SWCCs (Volumetric Moisture Content versus Suction) as generated from laboratory testing and inferred from moisture probe readings.

As a result of soil wetting, lower suctions were generally inferred from the use of moisture probes, as observed in Figure 12, whereby the SWCC generated from the moisture probe data, is generally located on the left-hand side of the laboratory drying curve, an expected result. However, for moisture contents greater than 30% it was evident that volumetric moisture contents (and corresponding inferred suction values) were far less reliable, and were in-consistent with laboratory results. Therefore the probes could be considered useful for inferring suctions corresponding to volumetric moisture contents less than 30% for the low-to-medium plasticity clay soils encountered at this site.

7 CONCLUSIONS

This study presents a practical means to estimate soil suction based on the calibration of moisture probe data and the use of complementary laboratory testing. When installing the moisture probes at this site, it was necessary to use a dummy probe as the needles could not be readily inserted into the very stiff to hard clay.

MP406 moistures probes were successfully used throughout the trial to continuously monitor moisture change as the soil behind the wall was wetted-up. Inundation of the soil caused raw moisture probe readings, in mV, to increase. Recording moisture probe data at 30 minute intervals for the duration of the trial provided sufficient data resolution to infer the progress of the wetting front behind the wall.

Converting raw data to volumetric moisture content via the use of both factory and laboratory calibrations was undertaken. Whilst the latter was superior, arguably the greatest source of error between inferred and measured moisture contents was due to soil variability at the trial site. For volumetric moisture contents less than 30%, the MP406 moisture probes gave good agreement with laboratory results; however, for higher moisture contents, the results were far less reliable for the low-to-medium plasticity clay soils encountered.

This study demonstrates the use of moisture probes as a useful and efficient means for estimating high-range suctions in the field; however, the limitations of the probes, designed and manufactured to measure moisture, not suction, must be recognized. It is possible, however, that in more uniform soil conditions better agreement may be possible in the low suction range.

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