

# Monitoring Volumetric Water Content and Matric Potential in Variably Saturated Platinum Tailings

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**ABSTRACT:** The stability of Tailings Storage Facilities (TSFs) is critically influenced by saturation levels, as liquefaction susceptibility is directly related to the degree of tailings' saturation. A desaturated outer prism is typically recommended for TSFs to function as a structural shell, providing resistance against undrained loading conditions. However, a high degree of saturation within this shell can compromise the facility's stability. Understanding and monitoring saturation dynamics, especially during saturation events such as hydraulic deposition and rainfall, is essential for maintaining the structural integrity of TSFs. To monitor these dynamics, Time Domain Reflectometry (TDR) probes and Heat Dissipation Matric Potential (HDMP) sensors were installed in the outer shell of an upstream-constructed platinum TSF. These tools offer complementary measurements: TDR probes assess in-situ moisture content, while HDMP sensors measure matric pressure within the unsaturated zone. The TSF employs hydraulic deposition using cyclones and has reached a height of 35 m, with a planned final height of 115 m. Probes and sensors were installed at two locations along the TSF's length and at varying depths (1 m, 7 m, and 14 m below the surface). Data collected during hydraulic deposition and rainfall events could be used to reveal changes in saturation and flow patterns within the facility. This study presents the sensor responses to these events and discusses the observed trends. The findings provide insights into the transient nature of flow entering the TSF during infiltration/evaporation sequences, helping to define the impact on saturation levels and inform design and operational strategies to enhance stability.

**KEYWORDS:** Saturation monitoring, tailings, unsaturated soil mechanics

## 1 INTRODUCTION

Tailings Storage Facilities (TSFs) are critical components of mining operations. However, improper management of these facilities poses significant risks, with liquefaction-related failures among the most severe. Liquefaction can occur when tailings materials become sufficiently saturated and subjected to a trigger event (such as a seismic event, overloading or general slope instability). Numerous high-profile TSF failures worldwide have been attributed to undrained loading of saturated tailings, underscoring the need for careful management of saturation conditions within these structures.

To mitigate such risks, current best practices advocates maintaining a desaturated structural outer shell (or prism) of a TSF (Wates, 2023), as illustrated in Figure 1. According to Wates (2023) a supporting prism that forms a triangle extending downstream from the final crest (illustrated by triangle ABC) will be adequate in most cases while optimisation may reduce the requirement to triangle ABD. Ongoing performance monitoring of saturation levels in the outer shell is essential for ensuring operational safety and minimizing the potential for catastrophic failure.

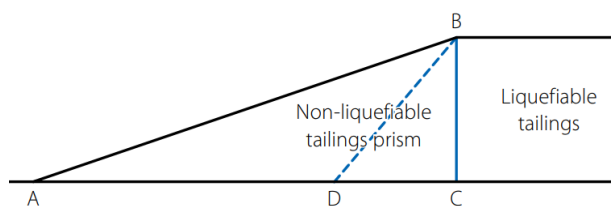


Figure 1. Illustration of non-liquefiable tailings prism (Wates, 2023).

Effective monitoring of saturation in TSFs requires robust and reliable measurement tools which can characterize moisture content, matric pressure and piezometric pore water pressure within the structure. Various types of measurement devices exist for this purpose. Two types of instruments which are widely used for this purpose are: Time Domain Reflectometry (TDR) probes and Heat Dissipation Matric Potential (HDMP) sensors. TDR probes estimate the volumetric water content (VWC) of soils by measuring the dielectric constant in the soil, which is influenced by moisture. HDMP sensors assess the

soil's matric pressure by measuring the rate and magnitude of temperature changes in a porous cylinder of the sensor following a controlled heating pulse, allowing for indirect estimation of the soil's water retention capacity and VWC.

This paper presents a methodology for monitoring the VWC and matric pressure in the structural zone of a TSF using TDR probes and HDMP sensors respectively. By integrating these monitoring tools with other available monitoring data (such as drain flows, vibrating wire piezometer data, deposition cycles, etc.), the study aims to provide a robust framework for assessing the saturation state of the TSF outer shell, thereby enhancing facility safety and informing both design and operational decision-making.

## 2 BACKGROUND AND LITERATURE REVIEW

### 2.1 TSF Stability and the Role of Unsaturated Mechanics

Tailings storage facilities (TSFs) can be constructed using three principal methods: upstream, downstream, and centreline. In all configurations, the stability of the facility critically depends on the integrity of the material forming the outer shell, which is designed to act as a structural zone. For centreline and downstream designs, these embankments utilise engineered materials which are purposely constructed to be non-liquefiable and exhibit dilative behaviour, thereby reducing the risk of instability and liquefaction. In upstream facilities, however, the outer shell is constructed predominantly from the tailings being stored, which may be susceptible to liquefaction.

To ensure the stability of upstream TSFs, the risk of liquefaction in the outer shell must be mitigated. This can be achieved either by ensuring the tailings behave in a dilative manner or by maintaining a desaturated state in the outer prism. Thus, continuous, reliable monitoring of the saturation state is essential to confirm that the design basis is upheld and to minimize liquefaction risk throughout the facility's operational life.

### 2.2 Monitoring in Variably Saturated Soils

Monitoring the pore water regime within tailings and embankment materials involves measuring three principal variables: moisture content, matric pressure, and piezometric

pore water pressure to ensure storage and hydraulic gradient status. Used in combination, these variables allow for full characterization of the range of saturation states and for delineating the capillary, transition, and residual zones within the outer shell.

Moisture content provides a direct indication of saturation in the soil. When combined with matric pressure measurements, the results can be plotted on a Soil Water Characteristic Curve (SWCC). The SWCC describes the relationship between soil water content and matric pressure and is a critical tool for identifying saturated and unsaturated zones.

Of key interest, for this study, is the location of the capillary fringe. In this study, the capillary fringe is defined as the extent of the saturated porous media above the phreatic surface where the pore water pressure is negative. It is important to consider this zone in assessing liquefaction potential as this zone may be sufficiently saturated for liquefaction to occur, despite exhibiting negative pore pressures.

Once the air entry pressure in the soil is exceeded, water loss decreases as matric pressures increase. For coarse porous media, this may occur rapidly, but less so for fine textured porous media. This is known as the transition zone. At higher suction values, most of the remaining water remaining is held tightly within the pores between soil particles. In this region, even large increases in suction only cause small changes in water content, causing the curve to flatten out. This is known as the residual zone (Fredlund, 2006). Figure 2 has been included for illustrative purposes only to show the general location of the saturated, transition and residual zones on a typical SWCC.

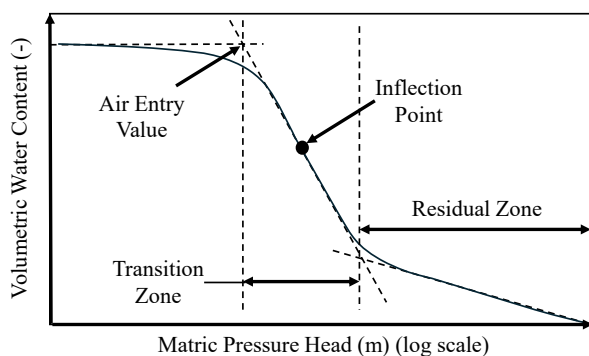


Figure 2. Soil Water Characteristic Curve.

Accurate definition of these zones in TSF shells is fundamental for understanding the structural shell's ability to resist liquefaction and to guide daily operational management.

For any given soil, an infinite family of SWCCs exists, bound by major drying and wetting curves which exhibit hysteresis (Fredlund, 2006). Figure 2 presents a typical initial drying curve. The main wetting curve would plot below the main drying curve with scanning curves in between if the drying or wetting process is stopped partway and reversed. This hysteresis must be accounted for when interpreting field data. In TSF applications, the full range of wetting and drying cycles is rarely achieved due to continuous hydraulic deposition, potentially limiting the degree of hysteresis observed and simplifying field interpretation.

For detailed measurement and confirmation of the unsaturated state, direct suction measurement is preferred. SWCCs can nonetheless be measured in-situ by simultaneously monitoring both moisture content and matric pressure, assisting with real-time identification of the prevailing soil water regime and evaluation of saturated versus unsaturated behaviour.

### 2.3 Review of Instrumentation for TSF Saturation Monitoring

Numerous instrument types are available for measuring VWC and pore water pressure in TSFs, each with distinct advantages and limitations. Selection of suitable technology for TSF conditions depends on operational, installation, and environmental constraints as well as the mechanical and hydraulic properties of the tailings. A brief overview of the instruments investigated for this study is provided below.

#### 2.3.1 Tensiometers

Tensiometers are used to directly measure matric pressure in soils, typically using a saturated high air entry (HAE) ceramic tip, and a pressure transducer (le Roux and Jacobsz, 2021). The reliability of tensiometers depends strongly on maintaining saturation of the ceramic; if the air entry value of the ceramic disk is exceeded, air entry and cavitation may occur, necessitating reinstallation or replacement. Since tensiometers of any type may ultimately require replenishment, they were not selected for long-term monitoring, in this case.

#### 2.3.2 Volumetric Water Content Probes (VWCPs)

Volumetric water content probes, most commonly those utilising Time Domain Reflectometry, measure the soil's dielectric constant by tracking the propagation velocity of an electromagnetic pulse through the soil (Quinones et al., 2003). This dielectric constant correlates strongly with water content, providing a reliable and robust indication of VWC if the probes are fully surrounded by soil and correctly calibrated. Probe reliability may be affected by factors such as soil texture, variable density, and installation quality. TDR probes can be installed at various orientations and depths and support frequent, automated data collection, making them suitable for TSF monitoring applications.

#### 2.3.3 Heat Dissipation Matric Potential (HDMP) Sensors

HDMP sensors measure matric suction using a heated ceramic element and thermistor. The rate of heat dissipation is affected by soil moisture and is calibrated to yield soil water potential. HDMP sensors measure tension indirectly through the saturation status of the sensor ceramic and thus do not require replenishment. For reliable readings, careful installation and proper contact with the surrounding soil are essential (Campbell Scientific, 2009).

#### 2.3.4 Vibrating Wire Piezometers (VWPs)

VWPs are used primarily to measure positive pore water pressure below the phreatic surface and are less effective for matric pressure measurement due to risks of desaturation. With careful installation and the use of high air entry value filters, VWPs may provide some indication of negative pore pressure, however their application in unsaturated zones is limited compared to tensiometers and HDMP sensors.

#### 2.3.5 Selection Rationale and Best Practices

Given the operational environment of a TSF and the need for long-term, reliable data from the unsaturated zone, TDR probes and HDMP sensors were selected for in-situ monitoring. TDR probes are robust and suitable for remote monitoring in tailings environments, while HDMP sensors offer indirect, accurate and stable measurement of matric pressure without requiring re-saturation. Tensiometers and VWPs are less suited due to their dependence on full saturation and/or mechanical limitations in unsaturated environments.

### 3 SITE DESCRIPTION AND MATERIAL CLASSIFICATION

#### 3.1 Site Overview

The facility being monitored is an upstream-constructed TSF located within the Bushveld Igneous Complex in South Africa. The facility consists of hard rock-derived rock-flour platinum tailings deposited hydraulically using cyclones. Cyclone technology is utilised to separate the coarse tailings fraction (underflow), used to provide a partially saturated outer wedge of tailings material, separate from the interior fine tailings fraction (overflow). The facility follows a phased construction approach and is constructed against a hillside, with an underlying HDPE geomembrane to mitigate seepage.

The regional climate is classified as arid to semi-arid and falls within the Highveld climatic region, which is characterized by warm temperatures and distinct summer rainfall. Long-term meteorological data indicates a mean annual precipitation of 688 mm, whereas the average annual Class-A pan evaporation is approximately 1450 mm, indicating that potential evaporation substantially exceeds rainfall. The site experiences mean monthly maximum temperatures ranging from 17°C (July) to 27°C (January), with extremes reaching 38°C.

#### 3.2 Tailings Characteristics

The tailings is classified primarily as ML (inorganic silt, very fine sand, rock flour) and, less frequently, as SM (silty sands and sand mixtures) according to the Unified Soil Classification System (USCS). Laboratory analysis shows the tailings to be generally non-plastic (NP) to slightly plastic (SP), with very low potential for expansiveness. The specific gravity of the material ranges from 3.1 to 3.8 (average 3.5). The critical state friction angle, based on triaxial compression testing, ranges between 34° and 36°.

The engineered design of the TSF emphasizes the formation and maintenance of a desaturated outer prism (or wedge) to serve as a structural shell, thereby significantly reducing the risk of liquefaction and instability, particularly in the outer slopes constructed from cycloned underflow tailings.

### 4 INSTRUMENTATION INSTALLATION METHODOLOGY

#### 4.1 Instrumentation Layout and Installation

A site-wide sensor installation program was developed to ensure the continuous monitoring of saturation and suction states within the TSF's structural shell. The complete installation plan along a single monitoring line is provided in Figure 3.

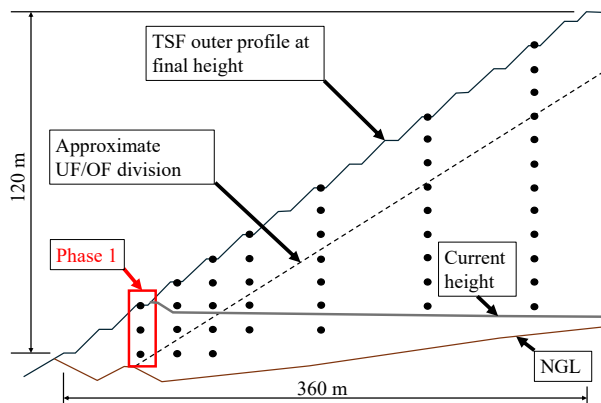


Figure 3. VWC and matric pressure monitoring installation plan.

As a first phase, sensors were installed along two monitoring lines (profiles), targeting three vertical depths: 1 m, 7 m, and 14 m below ground surface within the outer prism. This stratified depth approach allows for profile characterisation of the moisture regime from near-surface to deeper within the prism.

Each depth at both monitoring stations was fitted with:

- A CS635 Campbell Scientific TDR probe for VWC measurement
- A 229-L Campbell Scientific HDMP sensor for matric pressure measurement

All instruments were installed in the outer slope of the TSF predominantly in cycloned underflow (UF) tailings representing the coarser fraction of deposited material. Boreholes were used for instrument installation. For the 14 m installations, temporary steel casings were used to prevent collapse during drilling and instrument placement. Drilling fluids were not used to avoid influencing the in-situ moisture regime or affecting sensor readings.

The prongs of the TDR probes were pressed into undisturbed tailings. Where necessary, an 80 mm bedding layer of moist, compacted tailings was introduced to promote good probe-soil contact matching in-situ density. For HDMP sensor installation, the ceramic tip was pre-soaked in water and coated with moist tailings slurry. The HDMP sensors were then gently inserted into the bottom of the borehole, backfilled by approximately 250 mm of additional tailings slurry.

Backfilling of boreholes proceeded in 200 mm compacted lifts with in-situ tailings, ensuring density compatibility with surrounding material and minimal disturbance to the installed sensors and their cables. The steel casings for deep boreholes were progressively withdrawn during backfill.

#### 4.2 Data Acquisition and Logging

The network of TDR probes and HDMP sensors was brought online in February 2025, with all sensors connected to Campbell Scientific CR1000 data loggers. This configuration enables automated, high-frequency time series collection at each monitored depth, with data recorded and stored at hourly intervals to capture short-term changes in moisture and suction during both routine operations and saturation events (such as rainfall and hydraulic deposition). The data acquisition system was set up for remote download and time-based event recording, facilitating continuous monitoring. At the time of writing, the system had generated a comprehensive five-month record covering both operational activities and environmental wetting events.

#### 4.3 Instrument Calibration Procedures

To ensure reliable, site-specific readings, all VWC and HDMP sensors underwent rigorous calibration in the target porous medium. The calibration routine consisted of the following steps:

1. Representative tailings samples were collected from the TSF, air-dried, and then incrementally re-wetted to pre-determined VWC targets.
2. Samples were compacted to densities and salinities representative of in-situ conditions.
3. Laboratory calibration of the selected sensors (CS635 for VWC and 229-L HDMP sensors for suction) was performed in packed columns using the prepared tailings, with bulk dry density ranging from 1.7 to 1.8 t/m<sup>3</sup> and VWC ranging from 0.097 to 0.326.
4. Calibration curves relating to measured electrical or thermal output to VWC and matric pressure were developed.

- At the end of the calibration process, sub-sampling was performed to confirm final density and moisture states, and the unsaturated hydraulic characteristics (SWCC) of the compacted tailings were established.

Results from the calibration showed strong correspondence between observed and measured values, with all VWC calibration curves achieving an  $R^2 > 0.98$ . Calibration of the sensors was done according to the Campbell Scientific calibration manual (Campbell Scientific, 2009, 2017).

#### 4.4 Data Processing and Quality Assurance

##### 4.4.1 Raw Data Handling

The observation period programmed into the logger is 1-hour which is continuously uploaded to an online platform. Time-series data for volumetric water content and matric pressure from each depth and location are periodically reviewed and aligned with climatic and deposition data for the facility. The data is then processed by removal of any obvious outliers and smoothing of diurnal fluctuations where appropriate.

##### 4.4.2 Validation and Error Analysis

Quality control checks were implemented to detect and address potential measurement artifacts, sensor drift, or installation-related anomalies. These included:

- Cross-verification of simultaneous measurements from adjacent sensors to identify outliers or noise;
- Diurnal fluctuations, possibly due to temperature or barometric fluctuations, have been retained, to be investigated further at a later stage;
- Visual inspection of time-series continuity, with abrupt step-changes (unrelated to known site activities or rainfall) flagged for further investigation;
- Where anomalies were found, the data was either corrected using calibration equations or excluded from further analysis, with records kept of all adjustments. Ongoing data are compared with established site-specific SWCCs to verify consistency of sensor trends with expected soil hydraulic behaviour.

## 5 RESULTS

Results were obtained for two monitoring lines. This section presents the results obtained from the instrumentation installed along the more critical of the two. Time series data of VWC and matric pressure, as well as rainfall records and deposition periods, are provided for the period from February to July 2025.

### 5.1 Temporal Variation in Volumetric Water Content

Figure 4 shows the time series of VWC at 1 m, 7 m, and 14 m depths. A 24-hour moving average was plotted with lines connecting the actual datapoints shaded in the background. Rainfall data and deposition periods have been included on the plot for ease of reference. During deposition periods the rate of slurry (solids mixed with water) deposition was approximately 100 mm/day, which roughly equates to a dry layer thickness of 36 mm/day. The rate of rise of the facility over the reporting period was approximately 4 m/year.

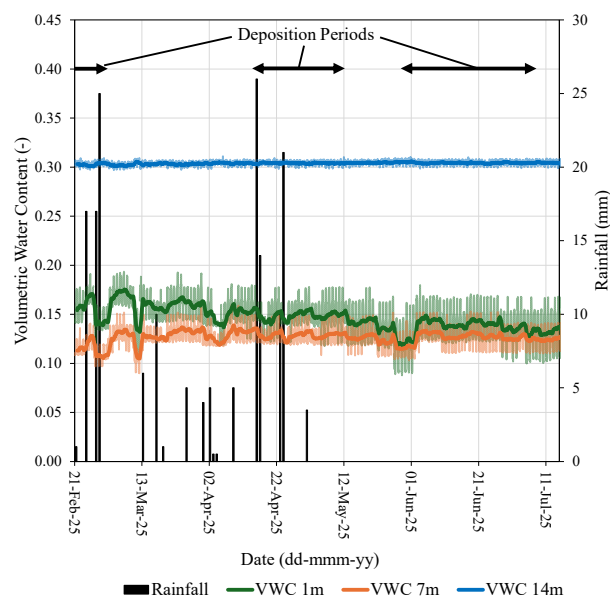


Figure 4. Time series of VWC, rainfall and deposition.

### 5.2 Temporal Variation in Matric Pressure

Figure 5 presents the corresponding time series of matric pressure head for each depth. A 24-hour moving average was plotted with actual datapoints shaded in the background. Rainfall data and deposition periods have been included on the plot for ease of reference.

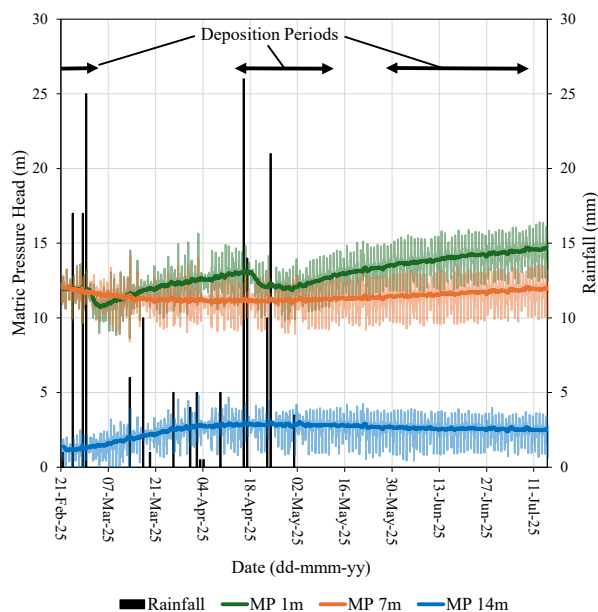


Figure 5. Time series of matric pressure, rainfall and deposition.

### 5.3 Ancillary Information

Drain flow measurements, available for drains in the vicinity of the sensors within the outer prism of the TSF, were used to verify results.

Continuous flows were observed in the toe drains located within the TSF starter wall. The presence of water in the toe drains is consistent with localized areas of high saturation in the tailings immediately above and adjacent to the drains (14 m deep sensors, Figures 4 and 5).

CPTu tests were conducted in the vicinity of the instrumentation a few months prior to installation. These results were used to define the location of the phreatic surface and

saturated zones. They were also used to verify installation in cycloned underflow tailings. Figure 6 presents a cross section through the tailings prism along the monitoring line for which results are presented. Indicated on the cross section are the probe locations, with the phreatic surface and material zones derived from CPTu results.

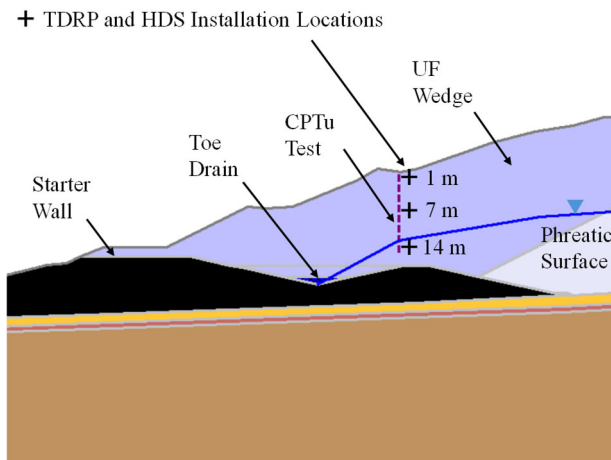


Figure 6. Cross section through monitoring line.

## 6 DISCUSSION

### 6.1 Atmospheric Effects

It is speculated that, temperature and/or barometric pressures influence both VWC and matric pressure data, causing diurnal fluctuations in sensor output. These effects should be filtered out during data post-processing to avoid attribution of short-term variation to hydrological events. This will be addressed in future time series, by including meteorological observations.

### 6.2 Saturation Profile and Phreatic Surface

Interpretation of sensor data, supported by CPTu dynamic pore pressure and dissipation measurements, indicates that the sensors installed at 14 m depth are located below the phreatic surface. VWC readings at this depth indicate saturation, despite having a lower VWC than what is indicated by the laboratory developed SWCC at full saturation. This illustrated in Figure 7, in which in-situ VWC and matric pressure measurement pairs are overlaid on the laboratory-derived SWCC for the tailings.

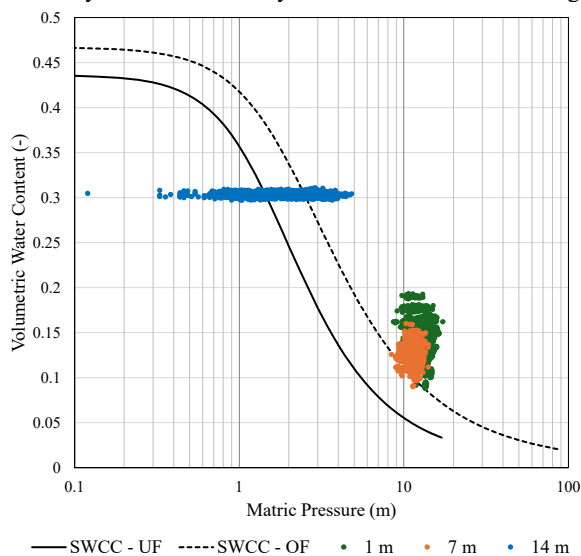


Figure 7. VWC versus matric pressure, superimposed on the SWCC.

This is expected as it is more difficult to achieve full saturation in-situ due to the presence of entrapped (occluded) air bubbles. The difference can also be attributed to different void ratios in the field compared to the calibration samples, insensitivity of the TDR probes at the dry end of the SWCC, diurnal temperature effects or hysteresis between wetting and drying cycles. Saturation also aligns with low matric pressures recorded by the HDMP sensors. It is important to note that HDMP sensors are not designed to measure positive pore pressures, so low readings merely indicate prevalence of the saturated regime rather than providing positive head values.

In contrast, data recorded in TDR and HDMP sensors at 1 m and 7 m reflect that these sensors were installed above the inferred phreatic surface. At these shallower depths, VWC values and matric pressures indicate an unsaturated state, with the presence of higher suctions. There is little to no long-term fluctuation in pore pressure at these sensor elevations, consistent with their position above the saturated zone. Cone resistance, friction ratio, and dynamic pore pressure measurements confirm that all sensors were embedded in cycloned underflow tailings, ensuring measurement reliability, considering calibrations were done in underflow tailings, and relevance to the intended structural zone.

The observation of continuous flow in the toe drains within the starter wall further supports the interpretation that the phreatic surface extends downstream of the instrumented section, consistent with saturation at greater depth (14 m) but partial saturation at shallower levels.

### 6.3 Response to Rainfall and Deposition

Rainfall events, particularly those of high intensity (e.g., early March and April 2025), produced a marked reduction in matric pressure at the 1 m depth, indicating short-term wetting of the upper prism. This shows the sensitivity of the near-surface layer to direct rainfall infiltration. However, aside from these event-driven decreases, a general increasing (more negative) trend in matric pressure was observed throughout the monitoring period, corresponding to seasonal drying during the transition to winter and sustained evaporative demand.

Little or no measurable impact of rainfall events was detected at 7 m depth, highlighting the buffering capacity of the tailings body or the absence of fast downward percolation of surface saturation. There is a delayed and dampened decrease in matric pressure at 14 m which alludes to the arrival of a wetting front or a slight shift in the phreatic surface; however, it is unclear what the cause of the shift is. This lagged response indicates that if there is an impact from surface rainfall infiltration on the 14 m sensor, it requires considerable time to propagate downward, and moisture changes at depth are likely to be delayed and attenuated.

Deposition cycles, as inferred from facility records, did not produce immediate changes in either VWC or matric pressure at the monitored locations. This was expected, as the impact of deposition on the phreatic surface and deep saturation profiles would change only gradually over extended periods, with new water requiring weeks or months to migrate to depth. It should be noted that the probes were installed in the outer slope of the TSF and would not experience direct deposition over their installation location.

### 6.4 SWCC Interpretation and Instrument Comparison

Overlaying in-situ VWC and matric pressure data on the laboratory-derived SWCC provides further context. The 1 m and 7 m probes typically plot within the transition zone of the SWCC, indicating an unsaturated state, while the 14 m probes cluster within the saturated zone. However, measured data do not fall precisely on the laboratory SWCC. The variation could

be attributed to void ratio differences between calibrated samples and in-situ tailings, insensitivity of the TDR probes at the dry end of the SWCC, diurnal temperature effects or hysteresis between wetting and drying curves. The findings highlight an important limitation: while SWCCs offer useful general guidance, inferring soil suction solely from measured water content (or vice versa) is prone to error, especially under field conditions with incomplete or non-representative drying/wetting histories. Thus, direct measurement of suction (by HDMP sensors) as well as volumetric water content is demonstrated to be the most reliable indicator of field saturation status.

Furthermore, if the SWCC alone had been used to translate VWC measurements to matric pressure, particularly above the phreatic surface, it would have underestimated the actual suctions observed at 1 m and 7 m, reinforcing the need for dual-variable monitoring. However, developing a SWCC in a controlled environment is key to understanding the in-situ nature of the soil being tested and the variations between in-situ and laboratory measurements.

## 7 CONCLUSIONS AND RECOMMENDATIONS

### 7.1 Conclusions

This study demonstrates the successful application of TDR probes and HDMP sensors for the monitoring of saturation and suction states in the outer prism of an upstream-constructed platinum tailings storage facility (TSF). Through multi-depth, automated monitoring over several months, the following key conclusions were drawn:

- The instrumented cluster of TDR probes and HDMP sensors allowed for clear distinction between saturated and unsaturated zones within the TSF embankment. Sensors at 14 m depth were confirmed to be below the phreatic surface and consistently indicated saturation, while those at 7 m and 1 m depths measured higher suctions and partial saturation.
- The VWC of the 14 m probe did not reflect a laboratory saturated material. This indicates how an in-situ porous material, indicating a lower saturated VWC than measured under laboratory saturated conditions, should be considered fully saturated as trapped air can be prevalent in the in-situ material. The variation could be attributed to void ratio differences between calibrated samples and in-situ tailings, insensitivity of the TDR probes at the dry end of the SWCC, diurnal temperature effects or hysteresis between wetting and drying curves.
- Rainfall produced observable wetting near the surface (1 m depth), whereas deeper sensors were largely unaffected in the short term, underscoring the slow downward migration of moisture through the tailings.
- Overlaying field measurements on laboratory-derived SWCCs revealed that direct in-situ suction measurements provide a more reliable representation of saturation conditions in the field than inferences made from laboratory defined SWCCs and in-situ VWC measurements alone.
- The monitoring approach, including sensor installation at depth in coarse tailings, was practically achievable and generated robust, high-frequency data suitable for performance assessment and operational decision-making.

### 7.2 Practical Implications and Recommendations

- The results validate the use of clustered in-situ sensors as an effective early-warning system for tracking changes in

saturation, which is critical for TSF operational safety and liquefaction risk management.

- Monitoring the VWC in real time and at multiple depths enables continuous assessment of facility performance relative to design criteria and regulatory requirements. While matric pressure provides valuable information, it alone is insufficient for evaluating slope stability. The effective stress within slope materials is fundamentally dependent on pore water pressure, which is directly influenced by the VWC. Soils with suctions close to saturation can rapidly develop positive pore water pressures during certain loading events. This sudden increase in pore pressure reduces effective stress in the soil, increasing the risk of slope failure.
- The current approach proves that both TDR probes and HDMP sensors can be reliably installed at depth within tailings, supporting wider adoption for similar facilities.
- While the achieved monitoring outcomes were in line with expectations, there is potential to further improve observation accuracy by refining calibration procedures and by incorporating additional environmental corrections (e.g., temperature filtering).

For future work, it is recommended to:

- Expand monitoring networks to include a higher spatial density of instrument clusters and to monitor additional operational and climatic cycles.
- Refine calibration through undisturbed in-situ sampling.
- Integrate direct positive pore pressure measurement below the phreatic surface, at the same location as the TDR probes and HDMP sensors, to complement the current suction-focused approach.
- Continue long-term observation to better capture cycles of wetting/drying and deposition and strengthen early warning capabilities for adverse hydrological trends.
- VWC and matric pressure data can be used in finite element porous media simulation models to verify observed drain fluxes, predict future responses to extreme events and to build confidence in the design of stable facilities.

Overall, this methodology provides a robust foundation for improving TSF monitoring, supporting proactive management of saturation-related risks, and enhancing the resilience of tailings infrastructure.

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