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TECHNICAL ARTICLE

Predicting Water Content and Saturation in Mine Tailings with an Electromagnetic Soil Moisture Sensor

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Abstract

The degree of saturation of mine tailings plays an important role in the geotechnical and geochemical stability of a tailings facility and therefore, reliable measurements of in situ tailings saturation aid in evaluating stability. However, measuring in situ saturation in tailings facilities can be challenging. The objectives of this study were to evaluate the ability of an electromagnetic soil moisture sensor to predict the volumetric water content and degree of saturation of mine tailings and conduct proof-of-concept tests to assess the potential use of electromagnetic sensors as a tool in tailings engineering. Laboratory-scale testing was conducted using an electromagnetic soil moisture sensor embedded in moist-tamped and slurry-deposited specimens of a single hard rock mine tailings prepared at varying volumetric water content, degree of saturation, and dry density. Errors in predicted volumetric water content for proof-of-concept testing were less than 1.5% to 3.8% and the error in predicted saturation was mostly less than 5%. Based on this study, electromagnetic sensor technology offers a viable tool to predict the degree of saturation within tailings facilities and can be incorporated into innovative approaches to address the challenges encountered in different types of tailings facilities.

Keywords Density · Geotechnical · Mining · Soil water

Introduction

Tailings are a fine-grained byproduct of the mining process, consisting of processed rock, soil, and/or residual chemicals that remain following the separation of valuable commodities (Wills and Finch 2016). During the mining process, a considerable amount of tailings are produced and stored in perpetuity in tailings facilities. Characteristics of tailings facilities vary as a function of location, climate, and tailings properties, among many factors (Fourie et al. 2022; Vick 1990). However, nearly all tailings facilities include an impoundment that contains a combination of tailings and water that must be properly designed, constructed, and managed throughout each phase of the facility lifecycle to minimize risk to people and the environment (ICMM 2020; Morrison 2022).

The degree of saturation of mine tailings plays an important role in geotechnical and geochemical stability of a tailings facility. Rodriguez et al. (2021) conducted an in-depth study on flow failures in tailings dams and reported that maintaining saturation below 80% is the most important factor to enhance geotechnical stability. In contrast, Aachib et al. (2004) report that the diffusion of oxygen into unsaturated porous media (e.g. tailings) decreases exponentially at above 85% saturation, which implies that mitigation of acid generation in sulphide-containing tailings requires a high degree of saturation. Regardless of the management strategy adopted for any tailings facility (i.e. slurry deposition or filtered stack), there is a need to reliably determine in situ tailings saturation to assess stability (Zandarín et al. 2009).

Electromagnetic sensors are based on a well-tested principle of operation and have been implemented and researched within the agricultural community for many years (e.g. Bobrov et al. 2019; Noborio et al. 2001; Seyfried and Grant 2007; Topp et al. 1980). Furthermore, electromagnetic sensors can be designed to be durable, corrosion resistant,

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wirelessly capable, and compatible with different data loggers. Certain types of electromagnetic sensors can be manufactured inexpensively. The combination of these qualities allows electromagnetic sensors to be incorporated into an extensive network for monitoring spatial and temporal variations in volumetric water content or degree of saturation across a tailings facility (e.g. Basson et al. 2021; Landim et al. 2023).

Measuring in situ saturation in tailings facilities can be challenging. The objectives of this study were to evaluate the ability of an electromagnetic soil moisture sensor to predict the volumetric water content and degree of saturation of filtered or unsaturated mine tailings and conduct proof-of-concept tests to assess the potential for electromagnetic sensors to be used as a tool in tailings engineering practice.

Literature Review

Previous studies have incorporated electromagnetic sensors in applications relevant to tailings facilities. Several studies have used electromagnetic soil moisture sensors to monitor earthen slopes (Greco et al. 2010; Li et al. 2005; Peranić et al. 2022). Other studies have used electromagnetic soil moisture sensors to monitor variations in volumetric water content within the unsaturated zone of existing tailings impoundments (Basson et al. 2021; Blanco et al. 2013; Cheong et al. 2012). Additionally, electromagnetic soil moisture sensors have been used to monitor the desiccation process of a column of tailings prepared in a laboratory environment (Garino Libardi et al. 2022). Although these studies showed that the sensors were generally able to respond to variations in volumetric water content within earthen slopes and in tailings facilities during precipitation events, they did not specifically address the accuracy of the sensor-predicted water content or the ability to predict degree of saturation.

Woyshner (1992) installed electromagnetic soil moisture sensors at various locations and depths within the unsaturated zone of an existing sulfide ore tailings facility and monitored temporal variations in volumetric water content over a period of about two months. Sensor-predicted volumetric water content was periodically compared to values determined from direct sampling and indicated an average error of + 1.1%, a standard deviation of 2.2%, and a maximum error of 5.5%.

Testing on laboratory-prepared specimens of iron mine tailings has been conducted using the Teros 12 sensor (Landim et al. 2023), which is a more recent variant of the sensor used in this study (i.e. Teros 10). Testing indicated that the manufacturer calibration resulted in a substantial error (≈ 20%) when predicting volumetric water content in the iron mine tailings. Additionally, test results indicated an increase in specimen dry density resulted in an increase in the raw sensor output value reported in millivolts (mV).

Narayanan and Sathian (2021) used a Teros 12 soil moisture sensor to determine the volumetric water content at three different depth intervals within a laterite soil deposit. Sensor predictions of volumetric water content were compared to direct measurements from representative field samples. The manufacturer calibration was used to predict volumetric water content from sensor output and resulted in errors of about − 5%, − 12%, and + 3% at three depth intervals. A material-specific calibration was developed for each depth interval, and calibration specimens were prepared at the respective in situ field dry densities. The material and density-specific calibrations were then used to predict volumetric water content from sensor output, and the error in sensor-predicted volumetric water content reduced to a range from 1.7% to 3.9%. The results of these studies highlight the importance of performing a material-specific calibration and suggest that sensor accuracy is affected by variations in dry density.

Materials and Methods

Experimental Program Overview

The experimental scope of the project is outlined in Table 1. All testing was conducted on a single hard rock mine tailings and included preparation of moist-tamped and slurry-deposited test specimens in either a small or large test mold.

Table 1 Summary of testing programs conducted during this study including the test mold used, specimen preparation method, and number of tests performed for each program

Test program name	Test mold	Specimen preparation	No. of tests performed
Calibration testing	Small	Moist-tamped & Slurry-deposited	48
Accuracy testing	Small	Moist-tamped	6
Characterization of density effects on sensor output	Small	Moist-tamped	36
Sensor response to specimen compression	Large	Moist-tamped	2
Sensor response to specimen infiltration	Large	Moist-tamped	1

Calibration testing was first completed to relate raw electromagnetic sensor output to predicted values of volumetric water content and degree of saturation. Testing was performed on numerous specimens prepared at a wide range of volumetric water contents and degrees of saturation using multiple sensors to create a robust calibration equation. Additional specimens were prepared randomly to evaluate the accuracy of the calibration equations. Several series of moist-tamped specimens were tested to further assess the behavior of sensor output as tailings dry density varied. Following the evaluation and characterization of sensor behavior, proof-of-concept testing was performed, which subjected the sensor to dynamic changes in specimen volumetric water content, saturation, and dry density via compression and infiltration of water. The equations developed during sensor calibration were implemented in the proof-of-concept testing to assess the timeliness and accuracy of sensor response to the induced change in specimen conditions.

Mine Tailings

Hard rock mine tailings from a precious metal mine was used in this study. X-ray diffraction of the tailings yielded the following mineralogical composition: 34% quartz; 20% calcite; 9% feldspar; 19% illite / mica; 11% mixed-layered illite / smectite; 3% chlorite; 2% kaolinite; and 2% pyrite. Particle size analysis yielded 14% fine sand and 86% fine-grained particles (i.e. silt and clay that pass the no. 200 sieve), by mass. The tailings had low plasticity with a liquid limit of 30 and a plasticity index of 9. The particle size and plasticity testing indicated lean clay classification, with the symbol CL per the unified soil classification system (USCS). The specific gravity of the tailings was 2.72. Standard Proctor compaction testing (ASTM D698) yielded a maximum dry density of 1.69 Mg/m3 and an optimum gravimetric water content of 15.8%. Particle size, plasticity, and compaction test results were extracted from Aghazamani (2022) and the specific gravity was determined as part of this study.

Teros 10 Soil Moisture Sensor

The Teros 10 sensor is a commercially available soil moisture sensor manufactured by the METER Group, Inc. (Pullman, WA, USA). The Teros 10 is an electromagnetic sensor, which is sensitive to the dielectric permittivity of the surrounding medium and can be used to predict apparent dielectric permittivity, volumetric water content, and/or degree of saturation. The sensor operates by supplying a 70-MHz oscillating electromagnetic wave to charge a pair of stainless-steel waveguides (needles). The charge time is proportional to the dielectric permittivity of the surrounding medium (METER Group, 2021). A microprocessor within the sensor body measures the charge time and produces an output in the form of an analog signal based on the dielectric permittivity. The raw output signal, reported by the sensor in mV, can be calibrated to volumetric water content and/or degree of saturation. Additional information regarding dielectric permittivity and soil moisture sensor principals of operation are discussed in previous studies (Bobrov et al. 2019; Peddinti et al. 2020; Seyfried & Grant 2007; Topp et al. 1980).

An ESP32 Adafruit Feather micro-controller was used to operate up to three Teros 10 sensors and record output values. The ESP32 was programmed using the Arduino IDE software platform. When more than one sensor was used, testing for each sensor was conducted simultaneously. During testing, raw sensor output in mV was recorded for post-test processing. The micro-controller was programmed to report the average of a specified number of measurements as a single output value to smooth noise in the raw sensor output.

Examples of raw sensor output for different tests conducted in this study are shown in Fig. 1. Calibration, accuracy, and characterization of density effects testing (Table 1) was performed on tailings specimens prepared to a target water content and dry density that did not change during the test. Figures 1a and 1b include representative data produced during calibration, accuracy, and characterization of density effects testing. In these tests, a single sensor output value for each test was determined based on an arithmetic average and was coupled with a physical measurement of volumetric water content, degree of saturation, and dry density from the prepared specimens. The sensor output with respect to elapsed time trends in Figs. 1c and 1d are representative of proof-of-concept testing intended to assess the sensor response to compression and infiltration (Table 1). Proof-of-concept testing incorporated an evaluation of all reported output values individually. Additional details on the sensor, operation, and data processing are in Martin (2023).

Test Molds

Customized test molds were fabricated to facilitate the laboratory tests performed in this study and needed to accommodate the volume of influence of the sensor. The volume of influence delineates the three-dimensional space of the sensor measurement. Pictures of the molds as well as schematics depicting the approximate sensor volume of influence within the molds are shown in supplemental Figs. S-1 and S-2. Two test molds were used in this study, a 100-mm-diameter "small mold" and a 300-mm-diameter "large-mold," both of which were larger than the sensor volume of influence to ensure negligible impact on sensor output. Both molds were fabricated from PVC pipe cut to lengths of 150 mm and 360 mm for the small mold and large mold,

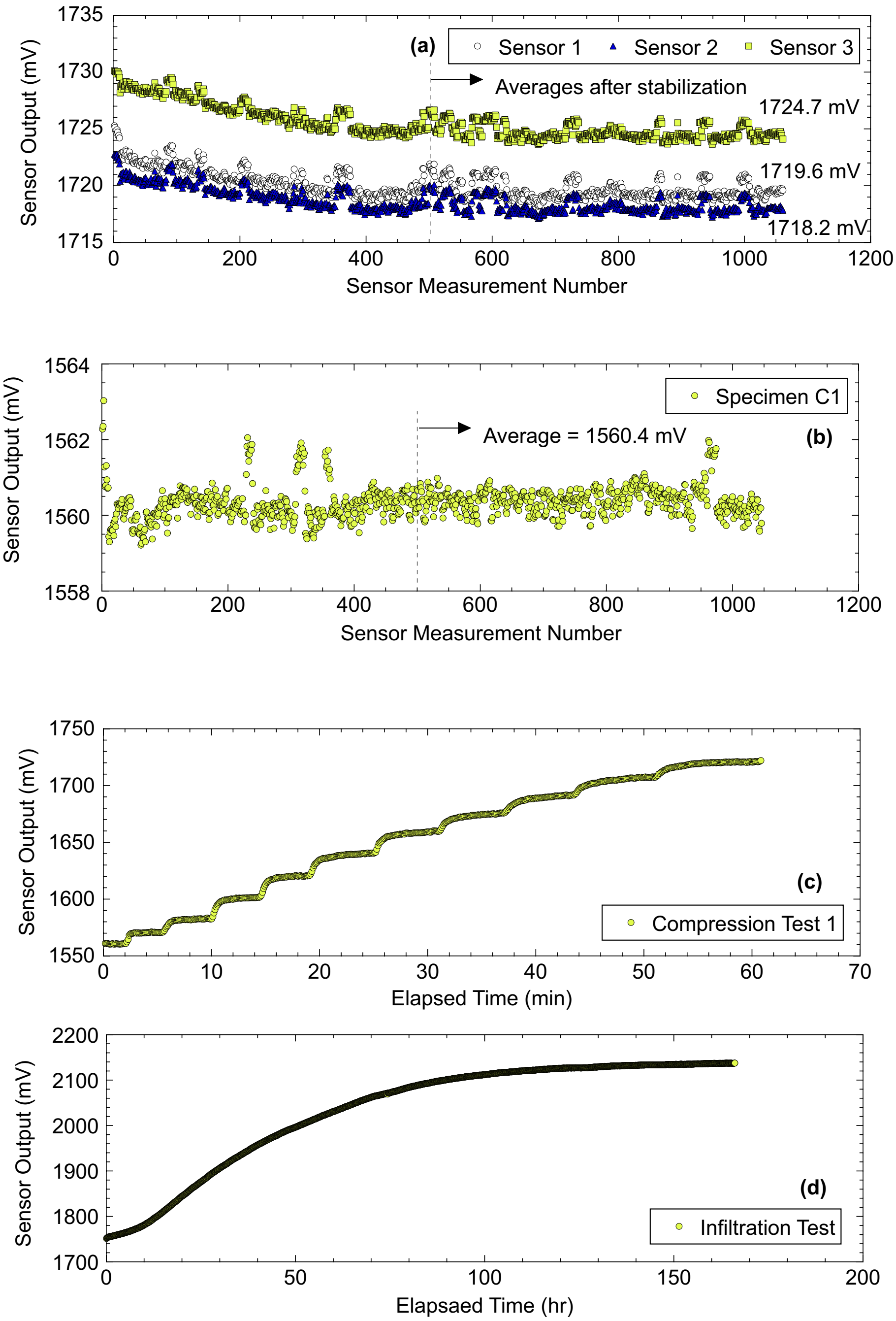


Fig. 1 Examples of sensor data from **a** calibration test specimen M-05, **b** characterization of density effects Specimen C-1, **c** Compression Test 1, and **d** Infiltration Test

respectively. Mold end caps were sealed using PVC primer and cement or silicone caulk.

Specimen Preparation and Testing Methodology

Specimen preparation methods were generally similar across the various tests performed. Pre-test processing consisted of oven-drying tailings for ≥ 24 h, lightly breaking dried clods, and passing the tailings through a no. 40 sieve (0.425 mm). Pre-test processing rendered the tailings workable for mixing with water and subsequent hydration to target water contents for testing. Pictures of moist-tamped and slurry deposited specimens prepared in the small mold and large mold are included in supplemental Figs. S-3, S-4, and S-5.

Small mold specimen preparation and testing

The small mold was used to conduct calibration, accuracy, and characterization of density effects testing (Table 1). A cross-sectional schematic of a typical test specimen prepared in the small mold is shown in Fig. 2. Each test specimen prepared in the small mold can be divided into two zones

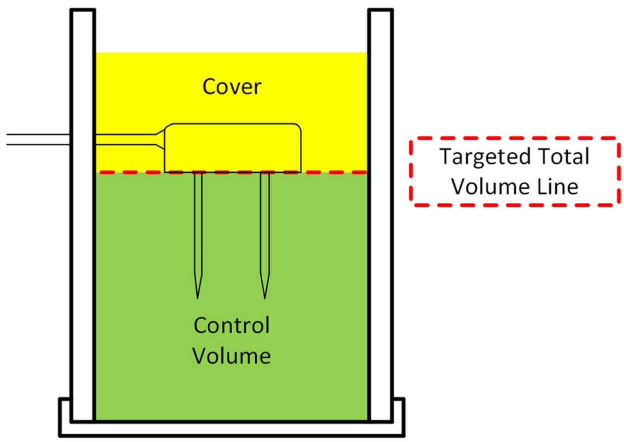


Fig. 2 Cross-section of small mold with control volume and cover zones identified

referred to as the control volume and the cover. Creating a specimen with the desired volumetric water content and dry density was achieved by calculating the mass of dry tailings and deionized water needed to occupy the control volume.

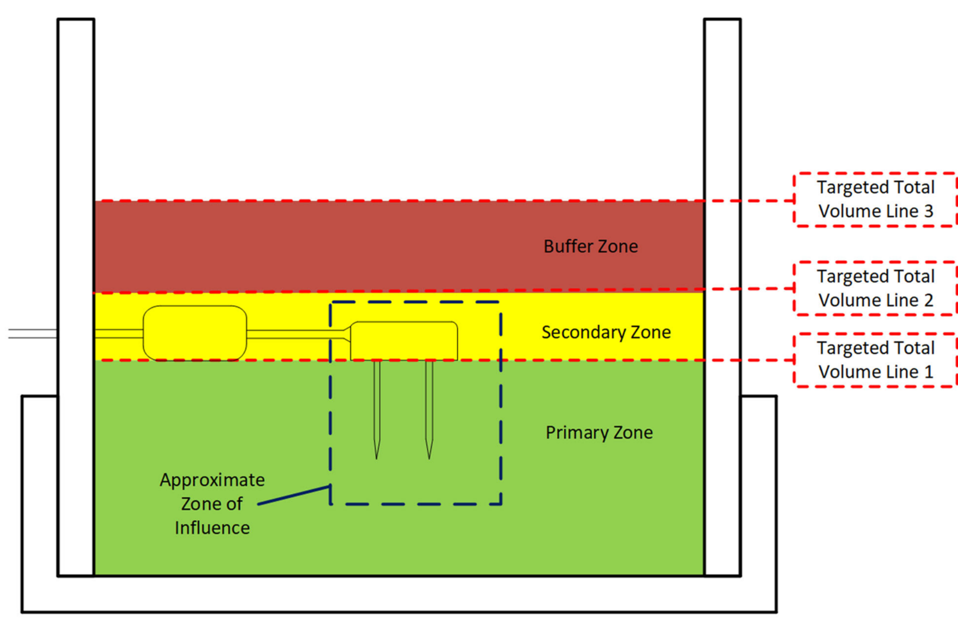
Moisture-conditioned tailings in the control volume were placed and compacted in uniform lifts or tailings slurry was poured into the mold until the target total volume line was reached. Prior to inserting the sensor, measurements were taken to determine the total mass and volume of the prepared specimen. After careful sensor insertion, the cover was constructed by placing and compacting moisture-conditioned tailings in uniform lifts or by pouring additional tailings slurry, and the mold was sealed with flexible plastic wrap and tape. Sensor output was recorded for a desired period of time, after which, the cover material and sensor were removed from the mold. A representative sample of the control volume was collected within the zone of influence of the sensor to determine gravimetric water content.

The mass-volume measurements and gravimetric water content taken from the control volume were used to compute the actual volumetric water content, degree of saturation, and dry density of the control volume to the nearest 0.1% or 0.01 g/cm^3, as appropriate. The control volume occupied most of the sensor volume of influence and was expected to have a dominating effect on sensor output. Therefore, the representative sensor output for each test was related only to the mass-volume properties determined for the control volume when using the small mold.

Large Mold Specimen Preparation and Testing

The large mold was used to conduct proof-of-concept testing to assess sensor response to specimen compression and infiltration (Table 1). A cross-sectional schematic of a test specimen prepared in the large mold is shown in Fig. 3. Specimens prepared in the large mold can be divided into three general zones referred to as the primary, secondary, and buffer zones. A calculated mass of dry tailings and deionized water needed to occupy each zone was determined based on a desired volumetric water content and dry density. The pre-determined quantity of moisture-conditioned tailings was compacted in uniform lifts to the targeted total volume line for each zone to achieve the desired initial volumetric water content and dry density throughout the specimen. Measurements were taken from the constructed specimen to determine the actual mass-volume properties of the specimen prior to compression.

Fig. 3 Cross-section of large mold with primary, secondary, and buffer zones identified



After specimen construction in the large mold, a sheet of 4-mil plastic was placed on top of the specimen to prevent loss of water within the specimen during compression. Vertical load was applied to the surface of the test specimen incrementally via an air-cylinder connected to a vertical load rod. A load cell positioned at the top of the load rod provided continuous measurement of the applied load throughout a given test. A linear potentiometer continuously measured vertical deformation to aid computing changes in specimen volumetric water content and saturation. Output from the embedded Teros 10 sensor was continuously recorded to compare associated changes in sensor-predicted values. Following compression testing, the specimen was deconstructed, and five samples were taken to determine a representative gravimetric water content.

There were two compression tests conducted in the large mold. Both tests were conducted on similarly prepared specimens with a target dry density of 1.36 g/cm^3 and target volumetric moisture content of 15%. After completing compression Test 2, water was added incrementally to the top of the specimen to observe the sensor response as the wetting front infiltrated through the specimen. A thin, heat-bonded, non-woven geotextile was placed on top of the specimen for compression Test 2 in-place of the 4-mil plastic to allow water to infiltrate into the specimen. Water was added to the specimen surface while under the final applied load to simulate a layer within a filtered tailings stack that is compressed from stack raising and then subjected to downward migration of water via gravity flow. Specimen deformation was recorded throughout the water infiltration period to correct volumetric water content and saturation calculations for comparison with predictions made via the Teros 10 sensor. At the conclusion of testing, excess water was removed from the specimen surface, total mass of the specimen and mold was measured, and samples were collected to determine the gravimetric water content.

Results and Discussion

Calibration and Accuracy Testing

Calibration testing of the Teros 10 sensor for the mine tailings was conducted by relating raw sensor output to physical measurements of volumetric water content and degree of saturation. Moist-tamped and slurry-deposited specimens were prepared in the small mold to capture the tailings continuum. Moist-tamped specimens were prepared with volumetric water content ranging from 0 to 40% and dry density ranging from 1.44 g/cm^3 to 1.76 g/cm^3; slurry-deposited specimens were prepared at volumetric water contents of 50% and 60%. Volumetric water content, degree of saturation, and dry density for each test specimen were determined from direct measurements obtained during specimen preparation and at the end of the tests. Three unique Teros 10 sensors were used during each calibration test to account for potential variations between sensors. Thus, three separate test specimens were prepared at each target volumetric water content and associated dry density.

Relationships between volumetric water content and degree of saturation versus sensor output in millivolts for each specimen tested during the calibration process of the Teros 10 sensor are shown in Fig. 4. The calibration equations developed for volumetric water content and degree of saturation are included in the figures. Calibration equations for volumetric water content and degree of saturation were fit to each data set using the curve-fitting app in MatLab. A third-order polynomial was used for the volumetric water content calibration curve, which is consistent with the calibration curve developed by METER Group (i.e. Teros 10 manufacturer) as well as other studies on electromagnetic sensors (Bhuyan et al. 2020; Kanso et al. 2020; Narayanan

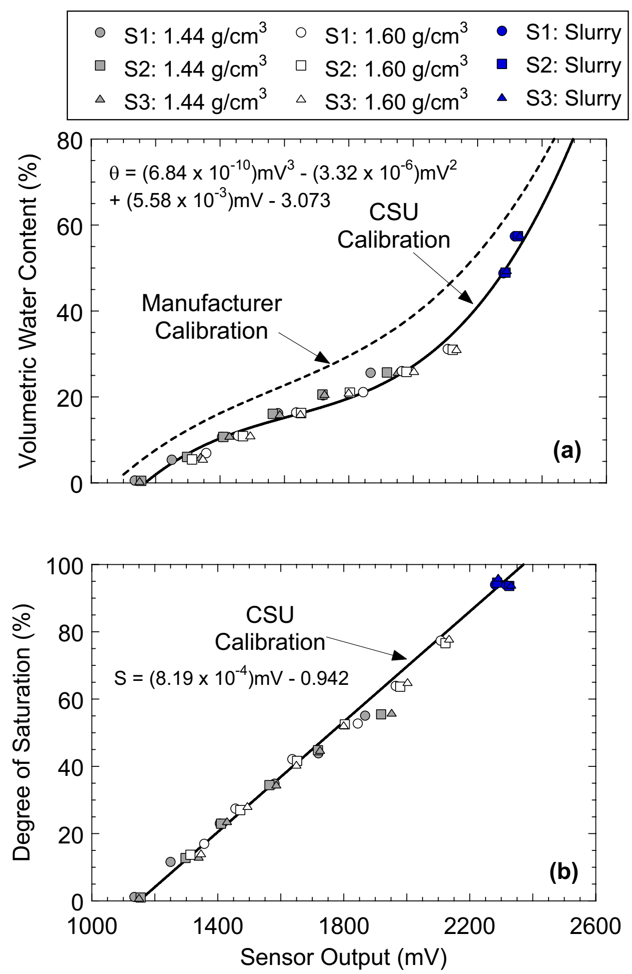


Fig. 4 Results from calibration testing that show **a** volumetric water content and **b** degree of saturation vs. sensor output in millivolts (mV)

& Sathian 2021; Topp et al. 1980). The degree of saturation calibration curve is a linear relationship.

The METER Group calibration curve (Fig. 4a) was developed to convert millivolt sensor output to volumetric water content in mineral soils via calibration testing on a wide variety of soil types. Therefore, the calibration is considered general and may not provide the desired level of accuracy for site specific applications (e.g. mine tailings applications). In the case of the mine tailings evaluated herein, the mineral soils calibration curve overpredicted volumetric water content by ≈ 6% to 12% when compared to the material-specific calibration. A similar error range was reported by Narayanan and Sathian (2021) when using the manufacturer calibration on laterite soils and Landim et al. (2023) reported an overprediction of ≈ 20% when using the manufacturer calibration on iron ore tailings. The METER Group does not provide a general calibration to degree of saturation for the Teros 10 sensor.

Results of the calibration testing indicated that two distinctly different sensor outputs can be measured for a given volumetric water content depending on the dry density of a prepared specimen. Relationships between volumetric water content and degree of saturation vs. sensor output in millivolts for test specimens prepared to a volumetric water content of ≈ 16% are shown in Fig. 5. The two sets of specimens at different dry densities (1.44 and 1.60 g/cm^3) have equivalent volumetric water contents; however, the sensor reports a higher millivolt output for specimens prepared at a higher dry density. In contrast, the degree of saturation calibration appears unaffected by variations in dry density, particularly at low degrees of saturation. The change in sensor output resulting from varying dry density was attributed to a change in the volumetric proportions of the air, water, and solid particles surrounding the sensor, which in turn changes the average dielectric permittivity of the specimen. The effects of variations in dry density on sensor behavior are discussed subsequently.

After developing calibration equations, additional moist-tamped specimens were prepared in the small mold to evaluate sensor accuracy. Results of the accuracy testing performed using the Teros 10 sensor are presented in Fig. 6. Measured volumetric water content and degree of saturation of each specimen were compared to sensor-predicted values based on the developed calibration equations. Residual values (i.e. predicted minus measured) of volumetric water content and degree of saturation are presented on the second y-axis of each plot. Predicted volumetric water contents had an average error of + 0.2% and a standard deviation of 1.5%, which is consistent with electromagnetic sensor performances achieved in previous studies (Narayanan & Sathian 2021; Wyoshner 1992). Predicted degrees of saturation had an average error of − 1.8% and a standard deviation of 4.7%. There was no bias observed in the volumetric water content predictions (Fig. 6a); however, the two highest degrees of saturation were underpredicted by ≈ 8% (Fig. 6b). Additional data points at the high range of saturation would help to further evaluate bias and accuracy of the calibration equations.

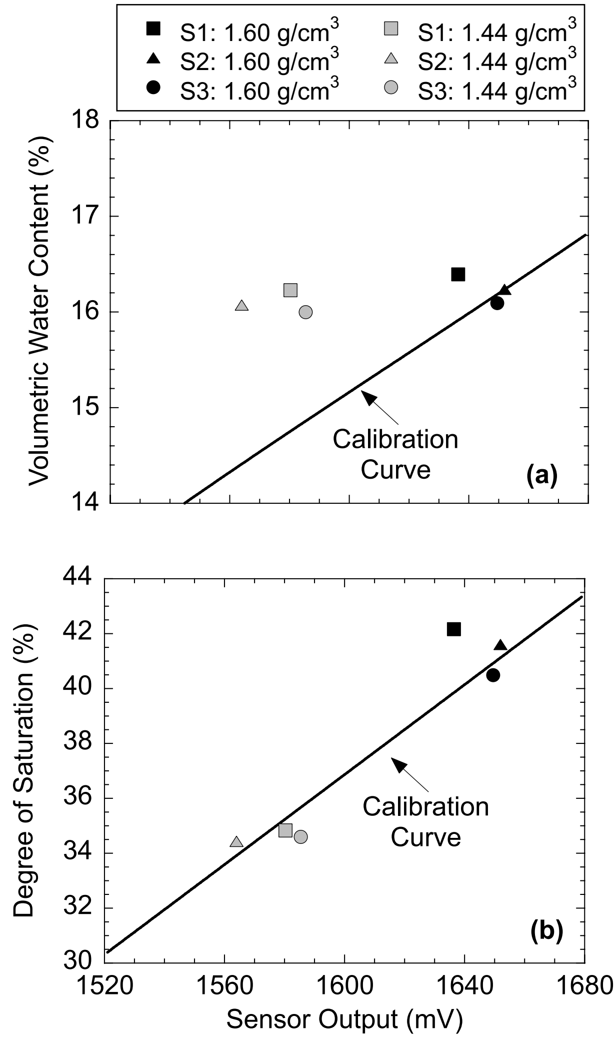


Fig. 5 Calibration test results of specimens prepared at the same volumetric water content but two different dry densities: **a** relationship between sensor output and volumetric water content, and **b** relationship between sensor output and degree of saturation for the same specimens

Characterization of Density Effects

Mine tailings in a tailings facility, whether in the embankment or impoundment, can have spatial and temporal variation in dry density. As shown in Fig. 5, variation in specimen dry density can produce distinctly different sensor output for a given volumetric water content. Landim et al. (2023) noted an increase in raw sensor output for specimens prepared at higher dry densities and Narayanan and Sathian

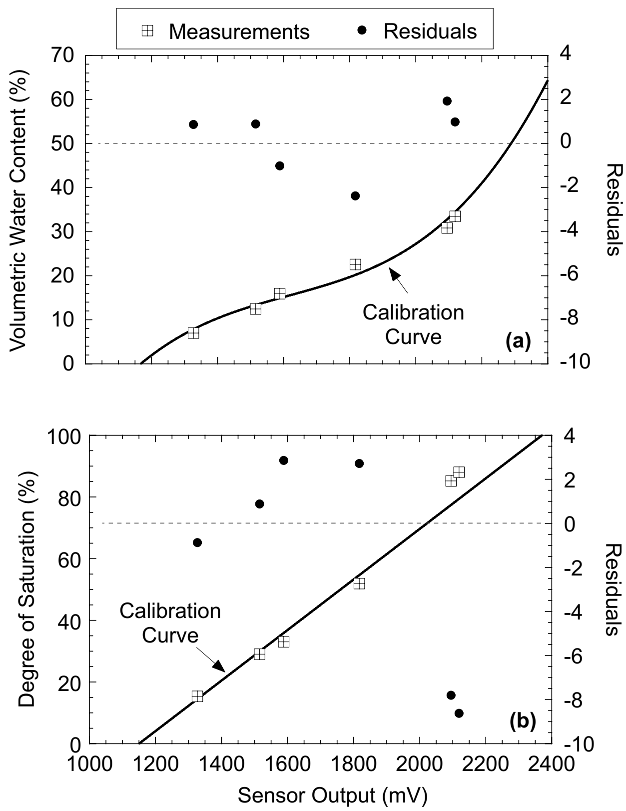


Fig. 6 Accuracy test results for **a** volumetric water content calibration and **b** degree of saturation calibration

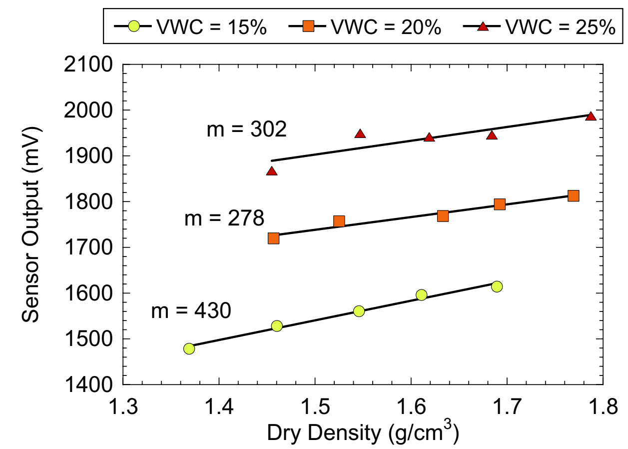


Fig. 7 Relationship between sensor output and specimen dry density for constant values of volumetric water content (VWC). The parameter m is the slope of the linear regression

(2021) concluded that sensor accuracy is affected by the dry density of the surrounding medium when predicting volumetric water content. A general understanding of the dielectric permittivity of porous media and sensor function can help explain the sensor behavior.

Porous media, such as tailings, can be separated into air, water, and solid phases, whereby each has a unique dielectric permittivity. The Teros 10 sensor output is representative of the weighted average dielectric permittivity of the three phases occupying the total volume of influence of the sensor. Therefore, the sensor output is unique to a specific combination of air, water, and solid particles present within the volume of influence. If the volumetric proportions of the three phases change within the sensor volume of influence, the weighted average dielectric permittivity will also change and yield a different sensor output. The dielectric permittivity of granite, for example, ranges from about 7 to 9, and the dielectric permittivity of air is 1 (Noborio 2001). Thus, an increase in dry density with a constant volumetric moisture content increases the weighted average dielectric permittivity and yields a unique sensor output.

The effect of varying dry density on sensor output was evaluated using moist-tamped specimens prepared in the small mold to a range of volumetric water contents for six dry densities. All testing was conducted using a single Teros 10 sensor. Relationships between sensor output and specimen dry density for target volumetric water contents of 15%, 20%, and 25% are shown in Fig. 7. For a given volumetric water content, a linear increase in sensor output was observed with increasing dry density. Furthermore, the slope between sensor output and dry density was generally consistent for the three volumetric water contents evaluated. This behavior suggests that the change in sensor output resulting from a change in dry density is constant and independent of volumetric water content. Therefore, the sensor-predicted volumetric water content should exhibit consistent sensitivity to dry density regardless of actual volumetric water content.

The relationship between sensor output and dry density for tailings specimens prepared to target degrees of saturation of 30%, 45%, and 60% are shown in Fig. 8. For a given degree of saturation, the relationship between sensor output and dry density was linear. Specimens prepared at a degree of saturation of 30% exhibited negligible change in sensor output for the range of dry density. As the degree of saturation increased, the slope of the linear relationship between sensor output and dry density became increasingly negative (shown as m in Fig. 8).

The results in Fig. 8 suggest that changes in dry density have a more pronounced effect on sensor output for a given degree of saturation as saturation increases. At a lower degree of saturation (e.g. 30%), variations in dry density had little effect on sensor output. Therefore, sensor prediction of saturation would be unaffected by changes in dry density at low degrees of saturation. However, at higher degrees of saturation, variations in dry density had a more pronounced effect on sensor output, thus making sensor

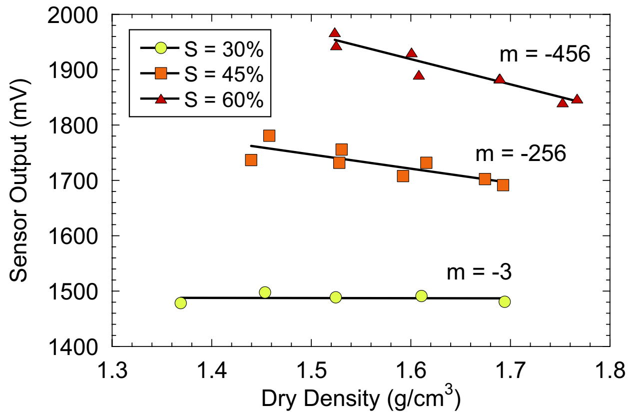


Fig. 8 Relationship between sensor output and specimen dry density for constant values of degree of saturation. The parameter m is the slope of the linear regression

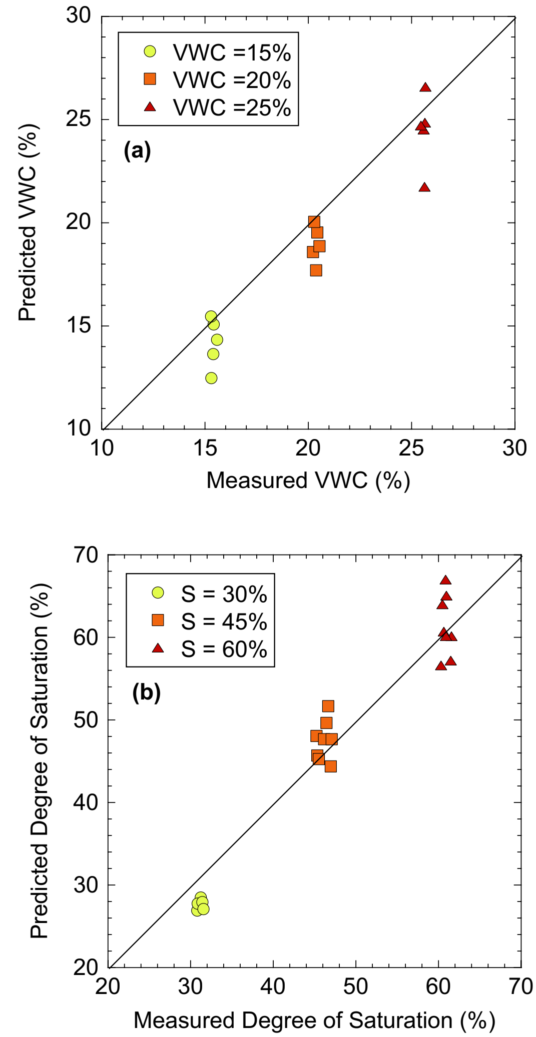


Fig. 9 One-to-one plots of predicted vs. measured **a** volumetric water content (VWC) and **b** degree of saturation (S) from specimens evaluated in the characterization of density effects testing

prediction of saturation more sensitive to changes in dry density at elevated saturation levels.

One-to-one plots of predicted (via equations in Fig. 4) vs. measured volumetric water content and degree of saturation are shown in Fig. 9. Understanding the effect of variations in dry density on sensor output provides insight into potential errors in predicted volumetric water content and degree of saturation. When using the sensor in a field application to estimate volumetric water content or degree of saturation, the potential error due to variations in dry density depends, in part, on the range of anticipated dry densities throughout the duration of the project. A wider variation in dry density would yield greater potential error in predicted values of volumetric water content and degree of saturation. For all three volumetric water contents tested, the dry density of the specimens varied by ≈ 0.32 g/cm^3, resulting in ≈ 3% to 5% variation in predicted volumetric water content. Specimens prepared at 30% saturation varied in dry density by ≈ 0.32 g/cm^3, and the predicted degree of saturation varied by less than 1%. Specimens prepared at 60% saturation had a smaller variation in dry density of ≈ 0.24 g/cm^3 and the predicted degree of saturation varied by ≈ 10%.

Sensor Response to Specimen Compression

Tailings deposited in an impoundment increase the vertical stress on the underlying tailings, which produces compression and/or consolidation over time. Filtered tailings are initially placed and compacted in an unsaturated state typically at densities and water contents that yield degrees of saturation below 80% (Cacciuttolo and Pérez 2022; Mckenna 2023). However, filtered tailings will likely compress under load that would change the degree of saturation. The sensor response to specimen compression was evaluated to simulate the behavior of stacked filtered tailings and observe the ability of the sensor to predict volumetric water content and degree of saturation under such conditions. Two experiments were conducted on moist-tamped specimens prepared in the large mold to a target dry density of 1.36 g/cm^3, which is ≈ 80% Standard Proctor maximum dry density. The specimens were prepared at a target volumetric water content of 15%.

Incremental vertical loading in the filtered tailings compression test was intended to simulate placement of ≈ 4 m of filtered tailings compacted at optimum water content and 80% of maximum dry density (Standard effort). A total of 10 load increments were applied and the final vertical stress was 668 kPa. Each applied load was maintained ≈ 5 to 7 min to allow for immediate deformation to reach apparent completion before the subsequent load was applied. Temporal trends of volumetric water content and degree of saturation for the two compression experiments (Test 1 and Test 2) are shown in Fig. 10. Sensor output and vertical deformation of the specimen were recorded continuously during load application. The sequential stepped increase in volumetric water content and degree of saturation observed in Fig. 10 was identical to the temporal compression behavior (data not shown).

The volumetric water content and degree of saturation predicted by the Teros 10 sensor (i.e. predicted in Fig. 10) were compared to actual values determined from direct measurements of specimen volume based on continuously recorded deformation. Calculations of actual volumetric water content and degree of saturation (i.e. measured in Fig. 10) assumed specimens experienced no loss of solid particles or water during compression. The standard deviation shown in Fig. 10 was determined via the accuracy testing discussed previously. Throughout the compression process, the volumetric water content and degree of saturation predicted by the sensor remained within one standard deviation of the measured value, except for the predicted saturation for Test 2 during the first four load applications. The greater error in predicted saturation during Test 2 was believed to be due to density heterogeneity within

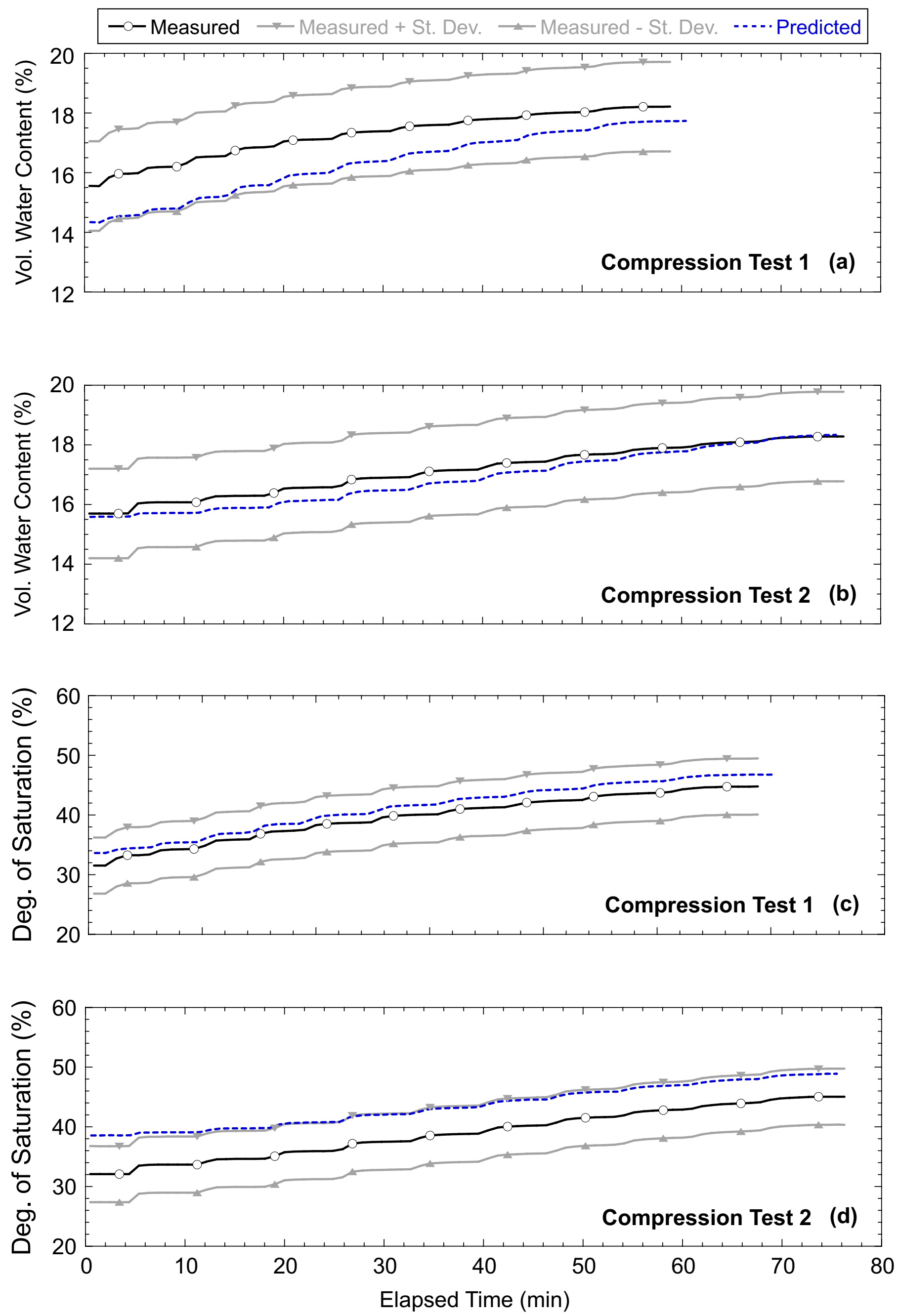


Fig. 10 Temporal trends of volumetric water content (**a** & **b**) and degree of saturation (**c** & **d**) for compression tests 1 and 2. The measured response was based on weight-volume relationships, predicted response from calibration equation in Fig. 4, and standard deviation based on results from accuracy testing

the specimen created during specimen preparation, which resulted in a higher degree of saturation within the sensor volume of influence compared to the overall average saturation determined from mass-volume measurements of the entire specimen.

The sensor behavior observed during testing suggests the sensor responds timely to changes in volumetric water content and degree of saturation induced by compression of the surrounding tailings, and a reasonable degree of accuracy was observed throughout specimen compression. The behavior observed in the predicted saturation for Test 2 highlights an important consideration for the use of sensor networks in a tailings facility. The sensor's volume of influence is relatively small, and when compared to the scale of a tailings impoundment, each sensor in a network would provide an isolated point value of predicted saturation at any given time. Potential heterogeneity in volumetric water content or saturation that exists between sensor volumes of influence will not be detected. Consequently, the stratified nature of conventional tailings facilities and the presence of thin layers of tailings with unique particle size distributions (e.g. layered slimes in sandy tailings) present a potential shortcoming for a sensor network. Reducing the spacing of sensors and/or staggering sensor elevations within a sensor network could reduce the likelihood of undetected and/or uncertain zones of saturation within a tailings impoundment.

Sensor Response to Specimen Infiltration

During the lifetime of any tailings facility, impounded tailings will be subject to some degree of variation in moisture due to drain down, desiccation, and/or infiltration. Filtered tailings, placed in an unsaturated condition, may experience an increase in saturation, which is important to geotechnical and geochemical stability throughout the life of a facility. Data collected during previous studies have shown that electromagnetic sensors embedded in existing tailings facilities or in columns of tailings can capture variations in volumetric water content and respond accordingly to desiccation or surface water infiltration from precipitation (Basson et al. 2021; Cheong et al. 2012; Garino Libardi et al. 2022). However, these studies did not focus on the accuracy of electromagnetic sensors to respond to such conditions.

An infiltration test was conducted in the large mold on the specimen from Compression Test 2 at the end of compression to simulate a potential wetting event of a filtered tailings stack to observe the accuracy of sensor response to surface water infiltration. Water was poured on the surface of the compressed specimen in four daily 600-mL increments, and the specimen remained under the final applied stress during infiltration. Sensor output was recorded throughout the wetting process and the test concluded when the signal showed negligible change for 24 h, which occurred about 4 d after the final water application.

Temporal trends of predicted volumetric water content and degree of saturation (Fig. 4) during the infiltration test are shown in Fig. 11. The initial volumetric water content and degree of saturation computed based on mass and volume at the end of compression, and final volumetric water content and degree of saturation based on end-of-test measurements on exhumed samples are also shown in Fig. 11. Due to uncertainty in the amount of water that infiltrated into the specimen, continuous direct calculation of volumetric water content and degree of saturation during testing was not possible. Therefore, the accuracy of the sensor response to specimen infiltration was only evaluated by comparing sensor predictions to the measurements at the beginning and conclusion of the infiltration test.

Results from infiltration testing indicate that the calibration for degree of saturation performed well, and that the saturation predicted by the sensor was generally within about one standard deviation of the direct measurement. However, the calibration for volumetric water content produced an over-prediction of ≈ 8% at the completion of infiltration. This discrepancy in volumetric water content could be due, in part, to the higher dry density of the specimen at the end of infiltration when compared to the dry density of specimens prepared for sensor calibration. The average dry density of moist-tamped specimens prepared during calibration testing was 1.55 g/cm^3, and at completion of infiltration testing, the dry density of the specimen was 1.75 g/cm^3. As discussed previously, an increase in dry density increases sensor output for a given volumetric water content.

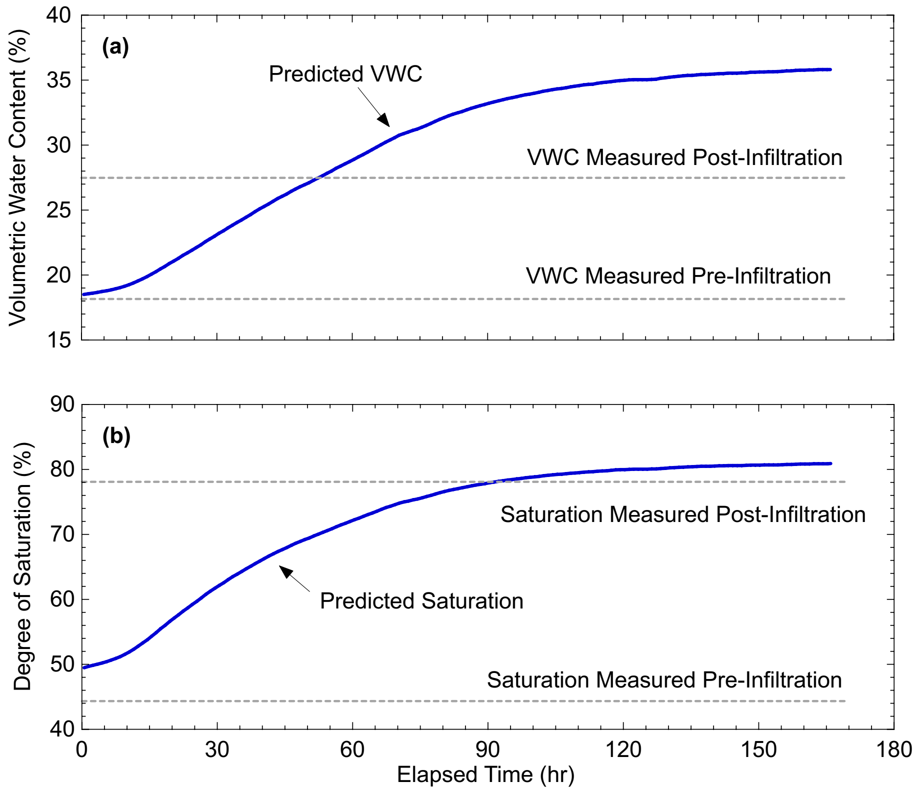
A correction for density effects was applied to reduce the error in predicted volumetric water content. The following equation was developed based on results of the characterization of density effects to correct the raw sensor output:

$$mV_{corrected} = mV_{raw} - m_{avg.}\left(\rho_i - \rho_{ref.}\right) \quad (1)$$

where $mV_{corrected}$ = sensor output corrected for dry density, mV_{raw} = raw (uncorrected) sensor output, $m_{avg.}$ = average slope of line relating dry density to sensor output for a given volumetric water content (see Fig. 7), ρ_i = specimen dry density during testing, and $\rho_{ref.}$ = reference density deemed representative of specimens prepared during sensor calibration. The corrected sensor output was then used to predict the volumetric water content based on the calibration equation developed during this study (Fig. 4).

The calibration equation for volumetric water content was assumed to be representative of the average dry density of the moist-tamped specimens prepared during the calibration process. Therefore, the average dry density of moist-tamped calibration specimens was used as the reference density. If the specimen dry density at a given point

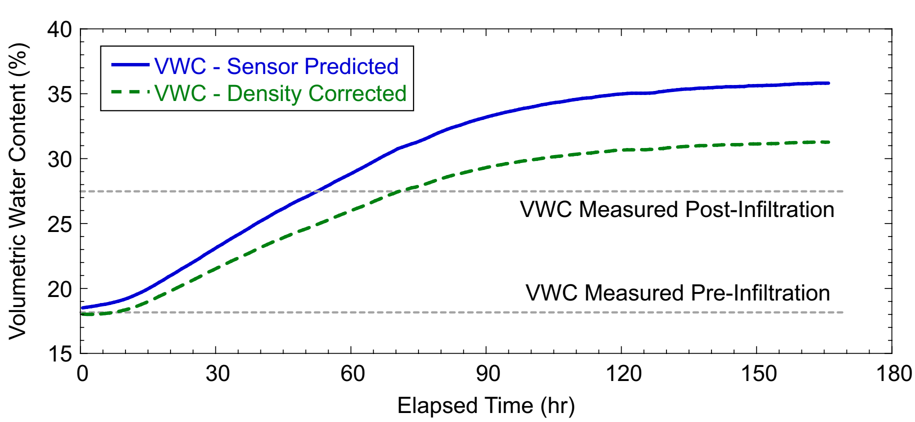
Fig. 11 Temporal trends of volumetric water content **a** and degree of saturation **b** for the Infiltration Test. The pre- and post-infiltration bounds were based on weight-volume relationships at the start and end of infiltration and the measured response was based on weight-volume relationships, predicted response from calibration equation in Fig. 4, and standard deviation based on results from accuracy testing



in time during infiltration is known, the specimen density relative to the reference density can be determined. The relationship between the change in specimen dry density and resulting change in sensor output for a given volumetric water content (represented by the variable m in Fig. 7) can be used in conjunction with the density of the specimen to approximate an increase or decrease in sensor millivolt output due to variations in dry density at a given volumetric water content. The test results presented in Fig. 7 suggest m is consistent, regardless of the volumetric water content, as long as the specimen remains unsaturated. Therefore, the average value of m for the three volumetric water contents tested during the characterization of density effects was used along with the specimen density to correct the sensor output.

The temporal trend of the predicted volumetric water content during the infiltration test is reproduced in Fig. 12 along with the prediction that incorporates the density-corrected sensor output. The applied correction reduced the error by 4.5%, which corresponded to a final error of 3.8% between predicted and measured volumetric water content at the completion of infiltration. The remaining error in the sensor prediction of volumetric water content could be due partly to heterogeneity within the specimen. Additionally, preparing all moist-tamped specimens at the same target dry density during calibration testing could help to further improve the

Fig. 12 Temporal trend of volumetric water content for the Infiltration Test that includes the direct sensor prediction via the calibration equation in Fig. 4, and the prediction coupled with a density correction. The pre- and post-infiltration bounds were based on weight-volume relationships at the start and end of infiltration



correction to sensor output because this would reduce uncertainty in specimen density relative to the average specimen dry density during calibration.

The gradual and steady change in predicted volumetric water content and degree of saturation during infiltration suggest that the sensor response was likely similar to the rate of moisture infiltration. However, the accuracy of the sensor predictions at intermediate points during specimen infiltration was unknown, and more sophistication and control in the approach and equipment used during testing would be required to more appropriately assess temporal accuracy of the sensor to infiltration. The advantage of knowing the accuracy of the sensor at intermediate points during specimen infiltration would depend on the intended application of the sensor in the field.

Practical Implications and Future Work

Calibrating an electromagnetic sensor to predict the degree of saturation in tailings can offer benefits when assessing the geotechnical and geochemical stability of a tailings facility. The potential error in predicted volumetric water content and degree of saturation due to variations in tailings dry density will depend, in part, on the range of dry density the sensor will be subjected to during a field application. The potential range of tailings dry density at a given facility should be considered when developing sensor calibrations. During calibration, preparing specimens at a dry density near the middle of the expected range of dry densities should help reduce potential error in predicted values. When calibrating a sensor in the laboratory, efforts should be made to mimic field conditions to the extent possible to reduce potential error in predicted values of volumetric water content and degree of saturation.

The compression and infiltration proof-of-concept testing performed in this study evaluated sensor performance when embedded in unsaturated tailings, as would be the case in a filtered tailings stack. Rodriguez et al. (2021) indicate that the risk of flow failure in tailings facilities increases when the degree of saturation within the facility > 80%. Filtered tailings stacks are often designed with tailings compacted to densities and water contents that yield degrees of saturation < 80% to enhance geotechnical stability and reduce the risk of liquefaction (Cacciuttolo and Pérez 2022; McKenna 2023). Furthermore, filtered tailings may dry during transport and desiccate after placement, which can result in lower degrees of saturation. Thus, there is a need to monitor the degree of saturation in filtered tailings stacks < 80% as well as identify when the degree of saturation reaches and surpasses 80% to assess liquefaction potential. Measured degrees of saturation in the compression and infiltration testing performed during this study ranged from ≈ 32% to 78%, and sensor accuracy was ± 5%. Therefore, the testing demonstrates a useful application of the electromagnetic sensor to monitor changes in the degree of saturation in a filtered tailings stack to assess stability.

In contrast to filtered tailings stacks, conventional slurry-deposited tailings are deposited saturated and can remain saturated throughout the life of the tailings facility (e.g. Fourie et al. 2022; Morrison 2022). The electromagnetic sensors evaluated in this study could be used in the embankment of a conventional tailings facility but would not typically be placed in slurry tailings that have very high degrees of saturation (e.g. > 90%). Once the degree of saturation within tailings exceeds 85–90%, tailings are conservatively considered saturated. This high range of saturation was not the focus of this study and additional testing would be needed to evaluate sensor performance at high degrees of saturation.

Future studies involving a more focused and robust characterization of the effects of dry density on sensor output to develop a density correction process that can be implemented in tailings engineering practice would be very beneficial in advancing the successful application of sensor technology in tailings facilities. Evaluating sensor performance on a variety of tailings materials would also be beneficial to further understand the effects of material properties on sensor performance and the importance of developing material-specific calibrations for different types of tailings.

Conclusions

The scope of work in this study suggests that an electromagnetic soil moisture sensor can be used to predict the volumetric water content and degree of saturation in filtered or unsaturated mine tailings with a useful degree of accuracy, depending on the application and precision required. The following conclusions were drawn from this study.

- A material-specific calibration is important for accurately predicting volumetric water content and degree of saturation relative to using a generalized manufacturer calibration. The manufacturer's calibration overpredicted volumetric water content by 5.7% to 12.3% for the tailings tested.
- Sensor output is affected by variations in dry density of the surrounding medium. The effect of dry density on sensor output was generally consistent for different volumetric water contents but was more pronounced as the degree of saturation increased.
- Sensor output reflected the average dielectric permittivity of the materials within the sensor volume of influence weighted by the volume of each material. The volumetric fractions of air, water, and solid phases explained the observed change in sensor output for a given volumetric

water content and degree of saturation but differing dry densities.

- During specimen compression, error in predicted volumetric water content was less than 1.5%, and error in predicted saturation was predominantly less than 5%. After specimen infiltration, the error in predicted saturation was also less than 5% and the error in predicted volumetric water content was 3.8% when corrected for dry density effects.
- Understanding the effects of variations in dry density on sensor output can be utilized to correct sensor output for density effects and reduce potential error in sensor predicted values. Correcting sensor output for the effects of dry density resulted in a 4.5% decrease in the error of predicted volumetric water content at the end of infiltration testing.

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Data Availability All data relevant to this study are included herein. Additional data can be provided by the authors if desired.

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