MEASUREMENT OF MOISTURE CONDITIONS FOR MINE WASTE STORAGE FACILITIES USING THE DEEP DIVINER MOISTURE PROBE[1]

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Abstract. There is a need to measure deep *in situ* moisture conditions for all types of waste storage facilities in a safe, cost effective, practical, and efficient manner. This paper describes the Deep Diviner moisture probe, a deep capacitance moisture sensor, which has been developed by the authors with the assistance of the Canada Industrial Research Assistance Program (IRAP). The deep capacitance moisture probe uses the Diviner 2000®, a portable capacitance soil moisture monitoring sensor manufactured by Sentek Sensor Technologies. This portable probe was developed for irrigation management, and is a non-radioactive sensor. Development of the deep capacitance moisture probe involved modifying the Diviner 2000®, which has a limited depth range of 1.6 m, to allow the measurement of volumetric water content to depths of 40 m or 50 m, and possibly deeper. A winch / cable assembly was developed to lower the sensor down within a PVC access tube to allow for fully automated measurement of *in situ* moisture contents at user specified depth intervals, each of which are recorded on a portable datalogger. The prototype of the deep capacitance moisture probe was tested both in the laboratory and in a full-scale field situation to ensure the required hardware modifications were functional. Full scale field testing was also completed on the prototype. The results of this testing show that the deep capacitance moisture sensor is capable of measuring the water content of till and sand materials to depths of 6 m. This paper describes the development and testing of the deep capacitance moisture.

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Introduction

A key component for the development and implementation of a closure plan for all types of waste storage facilities (e.g. mine waste rock dumps, tailings storage facilities, spent heap leach piles, and municipal landfills) is the ability to track moisture movement and establish a water balance for the facility. This requires the measurement of changes in soil moisture storage within the waste and surrounding soils. In some forms of waste (e.g. acid mine waste rock or landfills) the storage and transport of gases are also important to monitor. The transport and storage of gases within the vadose zone are strongly influenced by the *in situ* moisture conditions, which are controlled in part by the internal structure (e.g. textural contrasts) present within the waste itself or created as part of the engineered containment system. It is these preferential flow paths formed by textural contrasts and the subsequent moisture distributions that promote flow for both gas and moisture through the waste material.

The only currently viable technology for measuring soil moisture at depths greater than a few meters is the neutron probe. The use of the neutron moisture probe for measuring *in situ* soil water content was established in the agricultural industry (Gardner and Kirkham, 1952). However, it has been used more recently in other fields such as environmental monitoring. The neutron moisture probe has gained wide acceptance because the method is non-destructive, relatively fast, and can be performed at any time (Silvestri et al., 1991).

The major disadvantage of the neutron probe is that the measurement process cannot be automated. A typical measurement involves manually lowering the probe to a specified depth and taking five readings at each depth interval. The two outliers are discarded and the remaining three measurements are averaged to obtain the final reading. The time to take a single depth reading is dependent on the probe and the settings; however, each reading may take 10 to 15 seconds or longer. When applied to depths of more than 10 m with readings taken 2 to 3 times per meter, this results in hours of monitoring for each access tube installation.

Another disadvantage to using the neutron probe is that the size of the sphere of influence changes in response to changes in the water content of the soil. At high water contents the neutrons collide with many H atoms in a small zone around the sensor. At lower water contents the neutrons must travel further away from the sensor before encountering a H atom which leads to a larger sphere of influence. This can make the interpretation of field data particularly challenging when abrupt changes in water content occur as a result of textural breaks and/or soil layers.

Capacitance sensors have a number of advantages over the neutron probe. Both portable and stationary capacitance sensors are available. The portable sensors are lightweight, quick to use, affordable, and pose no health risks. The stationary sensors are ideal for locations where frequent measurements are required at fixed locations, and can be automated when connected to a data logger.

Capacitance sensors use the dielectric properties of soil to measure water content, similar to Frequency Domain Reflectometry (FDR) or Time Domain Reflectometry (TDR) sensors (Lane and MacKenzie, 2001). The capacitance sensor is essentially a capacitor that incorporates the soil as the dielectric medium. A high frequency electrical field, created around the sensor, extends into the soil. The magnitude of the frequency is a function of the apparent dielectric constant of the soil, which is dependant on the water content. The more water in the soil, the higher the dielectric constant and the lower the frequency measured by the sensor. The theory behind the capacitance sensor is described further in Dean et al. (1987), Paltineau and Starr (1997), Lane and MacKenzie (2001), and Gaskin and Miller (1996). Currently, the only portable capacitance sensors available on the market are manual. The Troxler Sentry 200 sensor operates in a similar manner to the neutron probe in that the probe must be lowered to a particular depth before a measurement can be taken.

The Diviner 2000® by Sentek has an automated "Swipe and Go™" technology that allows the probe to be lowered and raised rapidly through an access tube without stopping at the individual measurement depths. The logger automatically obtains measurements at 10 cm intervals and logs the entire profile. This process allows the entire access tube (1.6 m) to be measured in less than a minute. The limitation of the Diviner 2000® is that the probe is mounted on a rod and is designed for shallow irrigation applications (< 2 m).

Project Goals

The goal of this project was to develop an automated deep capacitance moisture sensor that could monitor soil moisture in access tubes to depths of up to 60 m. The Sentek capacitance sensors were chosen for modification because the authors have used them and found them to be robust and accurate (Ayres et al., 2005; Williams et al., 2003; and Wels et al., 2001). To automate the collection of measurements, a winch/cable assembly design was chosen that would automatically lower the sensor at a user specified rate, trigger measurements at specified depths, and log the measurements for subsequent downloading from a portable datalogger.

The project involved two phases. The objective of the first phase was to develop a manual prototype that could be tested in the laboratory to ensure that the required hardware modifications were functional. The second phase involved fitting the prototype with the automated winch control system and undertaking full scale testing in the field.

Laboratory Testing

The laboratory testing phase was divided into a series of studies that consisted of two column experiments and an examination of access tube joints.

First Column Study

The primary objective of the first column test was to evaluate the differences in the sensor response when placed in standard 2" schedule 40 PVC access tubes rather than the specially developed Sentek PVC access tubes. The secondary objective was to evaluate modifications made to the sensor head. These modifications were made to facilitate the connection of the sensor to a length of cable. The sensor head was removed from the rod and then the cable was rewired into the Sentek datalogger to allow measurements to be made. A large column, approximately 1 m in diameter and 1 m in height, was filled to a depth of 0.75 m with fine sand. The air-entry value of the sand was approximately 5 kPa. Two access tubes were placed vertically in the column, 30 cm apart, and a minimum of 20 cm from the outside edge of the column. This was to ensure that neither the access tubes nor the edge of the column interfered with the zone of influence of the sensor. One of the access tubes was the Sentek PVC access tube and the other was a standard 2" Schedule 40 PVC tube. The Sentek tube has an inside diameter of 51.5 mm and has low tolerance, uniform wall thickness to minimize the air gap between the sensor head and the PVC and the impact that variations in the air gap along the annulus may have on the measurements. The standard 2” schedule 40 PVC has an inside diameter of 51.8 mm.

The water content of the sand was varied from air-dry to saturation to obtain a full calibration curve for the sensor. The first set of measurements was taken with the sand placed in the column in an air-dry state. Measurements were taken within each tube at three different depths (approximately 10 cm apart) with three replicate sets of readings each time. Once the measurements were completed six small samples of the sand were removed adjacent to the access tubes at the depths of measurement for subsequent determination of gravimetric water content. The access tubes were then removed and water was added to the sand to increase the water content by approximately 10% (volumetric). Following each addition of water, the sand and access tubes were placed back in the column. Another set of measurements was obtained and another set of six samples was taken. This procedure was repeated until the sand began to drain.

The volumetric water content of the sand was calculated using the measured gravimetric water content at each depth and the density of the sand, as calculated from the known mass and volume of sand used in the column.

The results of the first column experiment are presented in Fig. 1. Calibration curves were fitted to the measured data using the equation supplied by Sentek ($SF = A\theta^B$) where SF is the scaled frequency reading from the probe, θ is the volumetric water content, and A and B are curve fitting parameters. The measured and estimated water contents were strongly correlated for both the Sentek tube ($R^2 = 0.93$) and for the schedule 40 PVC ($R^2 = 0.95$) calibration curves. The scaled frequency reading from the probe is a calibrated reading obtained by taking measurements when the access tube is surrounded by air and then by water. This allows a direct comparison of the impact of the access tube on the measured results.

It was observed that the schedule 40 PVC reduced the variation in the SF over the same variation in water content; as compared to the Sentek access tube, albeit with a somewhat lower sensitivity. The sensitivity of the schedule 40 PVC access tubes, however, was still sufficient for accurate readings of water content. The schedule 40 PVC provides significant benefits over the Sentek access tubes in terms of cost, availability, robustness, and the opportunity to extend the access tubes to a greater length.

Second Column Study

It is necessary to increase the mass of the sensor head to help the sensor to overcome friction and other obstructions that may be encountered as it is lowered in deep access tubes. The weight also increases tension in the cable, which helps to keep the cable taut and to increase the accuracy of the depth measurement. The objective of the second column experiment was to determine the impact, if any, of a weight attached to the sensor.

The second column experiment involved a single access tube installed vertically in the center of a column approximately 1.5 m in height and 0.4 m in diameter. The sand used in the first column experiment was also used in this experiment. The sand was placed in the column at a water content of approximately 10% (volumetric).

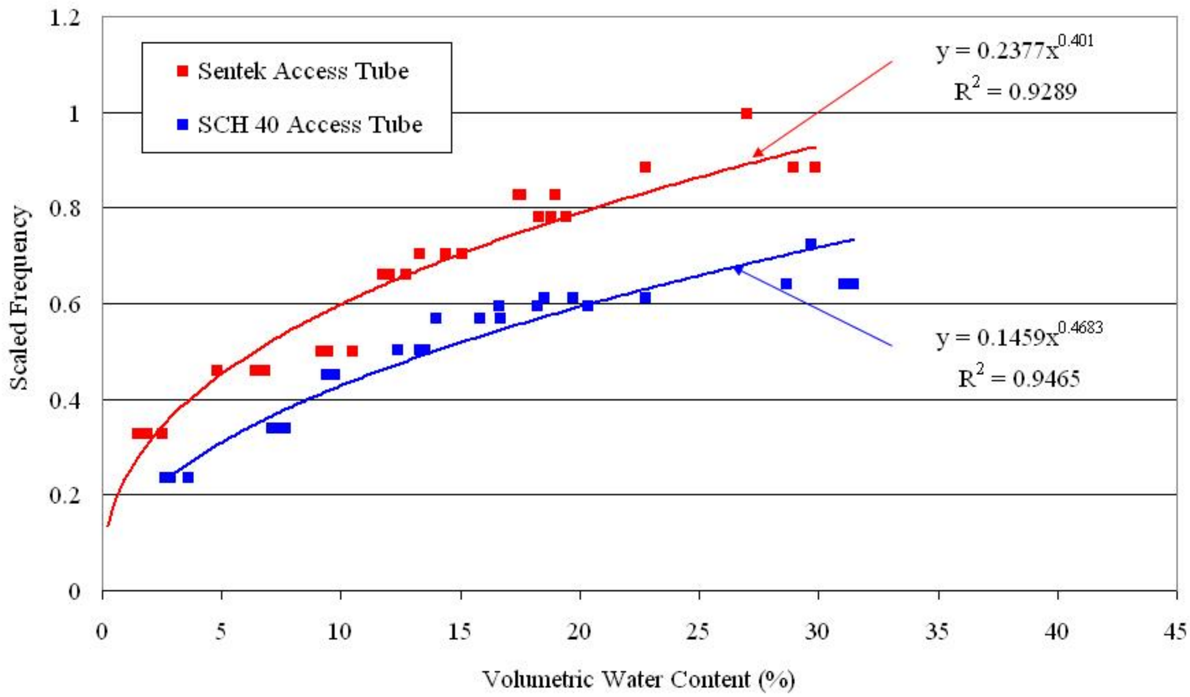

Figure 1. Calibration of prototype sensor in fine sand comparing Sentek PVC access tube to 2" schedule 40 PVC access tube.

The weight system included a standoff rod attached to the sensor cable at one end and the sensor head at the other. The mass could be varied in order that the optimum mass could be determined. The purpose of the standoff rod was to keep the weight out of the zone of influence of the sensor. The results of the second column experiment are presented in Fig. 2.

The presence of the weighting system did not influence the SF measurements taken by the capacitance moisture sensor. It was determined that a mass of 350 g would have no impact on the measurement results but would provide sufficient cable tension for accurate metering and minimizing cable stretch.

Access Tube Joint Study

The third study undertaken in the laboratory testing phase was to determine the influence of the access tube joints on the ability of the sensor to move freely within the access tube. Short sections (0.3 m) of schedule 40 PVC were cut and joined using couplers and PVC glue. The joints were visually inspected for potential obstructions. A gap was left on the inside between the tube edge and the central rib of the coupler. Glue had been forced into this gap but no glue was present inside the tube. The sensor was raised and lowered inside each of these test tubes. The weight was observed to catch on the gap left between the tube edge and the central rib of the coupler. The sensor also caught when being raised in the tube due to the square edge of the top of the sensor. Based on these observations, the final design of the weight system utilized a round-edge weight rigidly attached to the sensor head so that the sensor was forced to travel smoothly through the access tube. Installation specifications would also have to be developed to minimize obstructions developed as a result of tube joints.

Based on the results of the laboratory phase of the sensor development, it was determined that the design of a winch / cable assembly to raise and lower the sensor was feasible and the results justified proceeding to a field prototype with field testing.

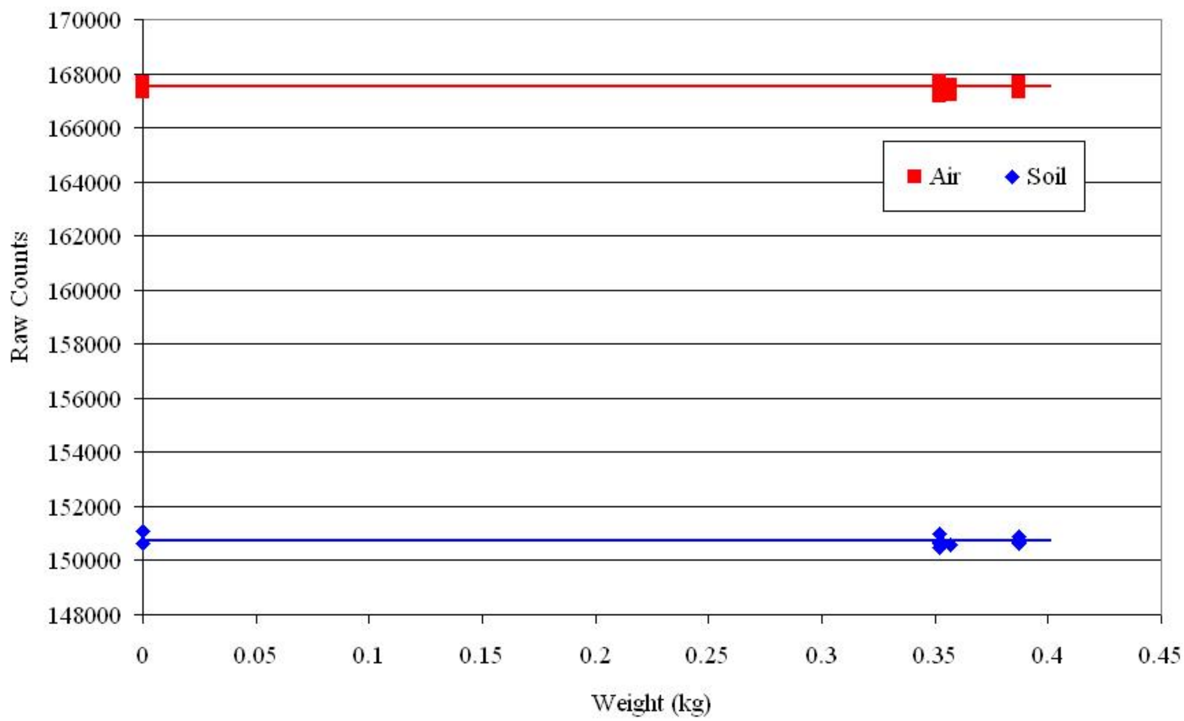

Figure 2. Impact of sensor weighting system on capacitance measurements in second column experiment.

Field Testing

The field testing phase of the sensor development involved two major tasks: (1) construction of a field prototype and (2) testing of this prototype deep access tubes in the field. There were four major components in the development of the prototype. The first was the design and evaluation of the sensor head and the associated cable used during laboratory testing. The second was the development of a metering head attached to a tripod to orient the cable as it is raised or lowered and to encode the length of cable downhole. The third component was the motorized winch system that spooled the cable. The fourth was the motor controller and datalogger unit. All components were custom designed and fabricated for this application. Completion of the design, manufacture, and laboratory testing of the apparatus concluded the first task of the field testing phase. A schematic of the field prototype is illustrated in Fig. 3.

The second task in this phase was to field test the prototype in deep access tubes. This task highlighted a challenging aspect of the project. The Diviner 2000® capacitance sensor has a small sphere of influence. The "sphere" (actually a toroid) extends into the soil a radius of approximately 15 cm from the centre of the access tube. This small sphere of influence allows a high frequency of depth measurements but poses potential problems for standard installation methods involving backfill of the annulus around the tube since the sphere of influence may not reach beyond the annulus backfill.

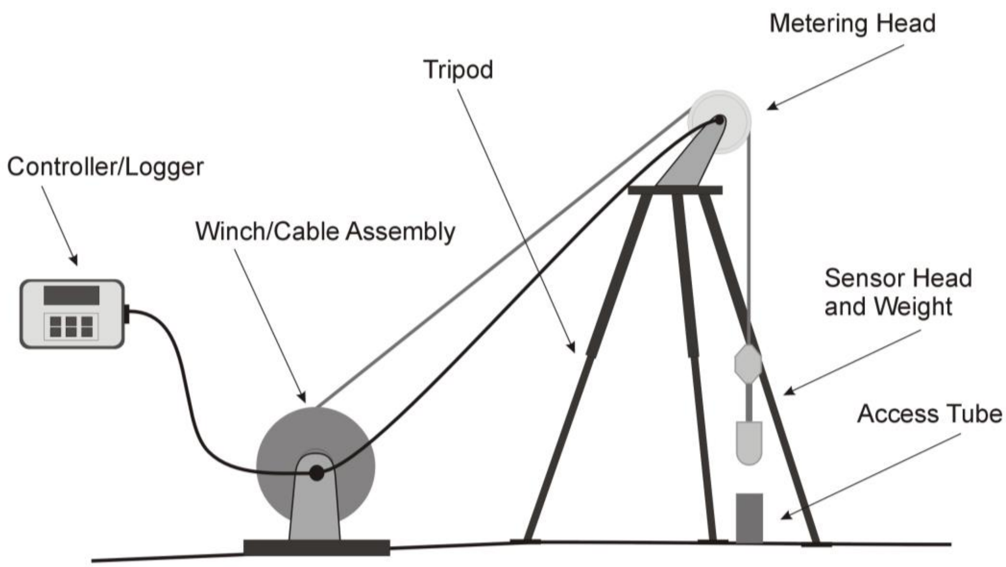

Figure 3. Schematic of the field prototype of the deep capacitance moisture sensor.

Installation of the shallow Sentek access tubes uses a direct placement method where a cutting ring is placed on the end of the tube and the tube itself is hammered into the soil. This method provides close contact between the access tube and the soil. This method is not practical for deep access tubes.

It was determined that the most practical solution for preliminary testing was to utilize an existing deep access tube installed as part of a standard 2" schedule 40 PVC standpipe piezometer. Although the annulus of these installations are backfilled with a bentonite/cement slurry, it was felt that the objectives of the field testing phase of the project would still be met provided a direct comparison between the deep capacitance moisture sensor and the Diviner 2000® was completed. This was undertaken in a short (2.5m) schedule 40 PVC tube installed in the field. Measurements in the standpipe were used simply to evaluate the functionality of the field prototype and the repeatability of the readings.

<u>St. Denis Test</u>

A 2" schedule 40 PVC access tube was installed to a depth of 2.5 m at a field location near Saskatoon, Saskatchewan. The tube was cut close to the ground to accommodate the Diviner 2000®. Measurements were obtained using both the deep capacitance moisture probe and the Diviner 2000® and the results of this comparison are shown in Fig. 4. The deep capacitance moisture probe was set to take a measurement at 4 cm intervals as compared to the 10 cm intervals of the Diviner 2000®. Figure 4 shows that the measurements with the deep capacitance moisture probe and the Diviner 2000® are in good agreement.

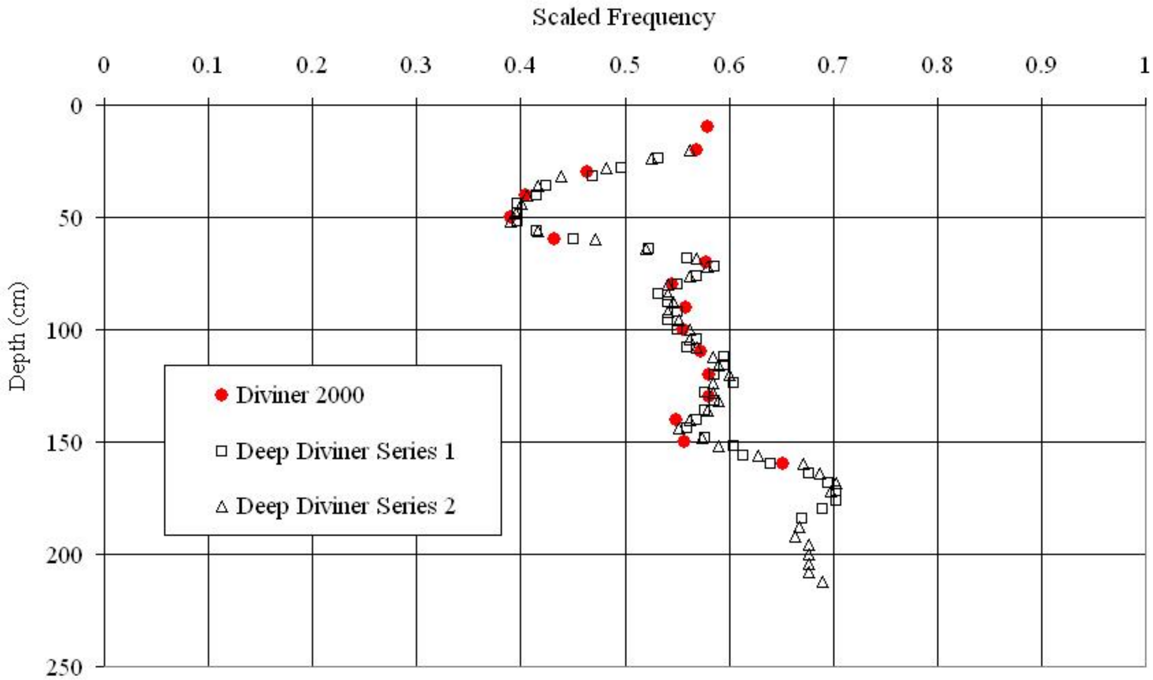

Figure 4. Comparison of field measurements taken using the Diviner 2000® and the prototype of the deep capacitance moisture sensor.

The site chosen for the piezometer testing was at the Environment Canada research site at St. Denis, Saskatchewan. This site was chosen because it had a number of 2" schedule 40 piezometers with deep monitored water tables and it was close to Saskatoon.

Testing in the deep standpipes was carried out during two site visits. The preliminary site visit was used to ensure that the sensor and weight attachment would move freely up and down the tube, and to check the function of the winch and the electronics. A number of refinements were made prior to the second site visit. During the second site visit, measurements were taken in a standpipe to a depth of 6.5 m.

Figure 5 presents the predicted volumetric water content profile with depth. Samples of the soil (a glacial till) from St. Denis were not available for sensor calibration, so the default calibration curve provided by Sentek for the Diviner 2000® was used to determine *in situ* volumetric water content values. Three sets of measurements were obtained during the field test and the three sets were averaged to obtain a representative data set, as shown in Figure 5.

After the field tests at St. Denis, a number of refinements were made to the field prototype. Most refinements were to improve the portability, durability, and cosmetics of the sensor. It was also determined that the depth measurement method used by the metering sheave did not give sufficient accuracy. Therefore, a different metering sheave was designed for the final field prototype.

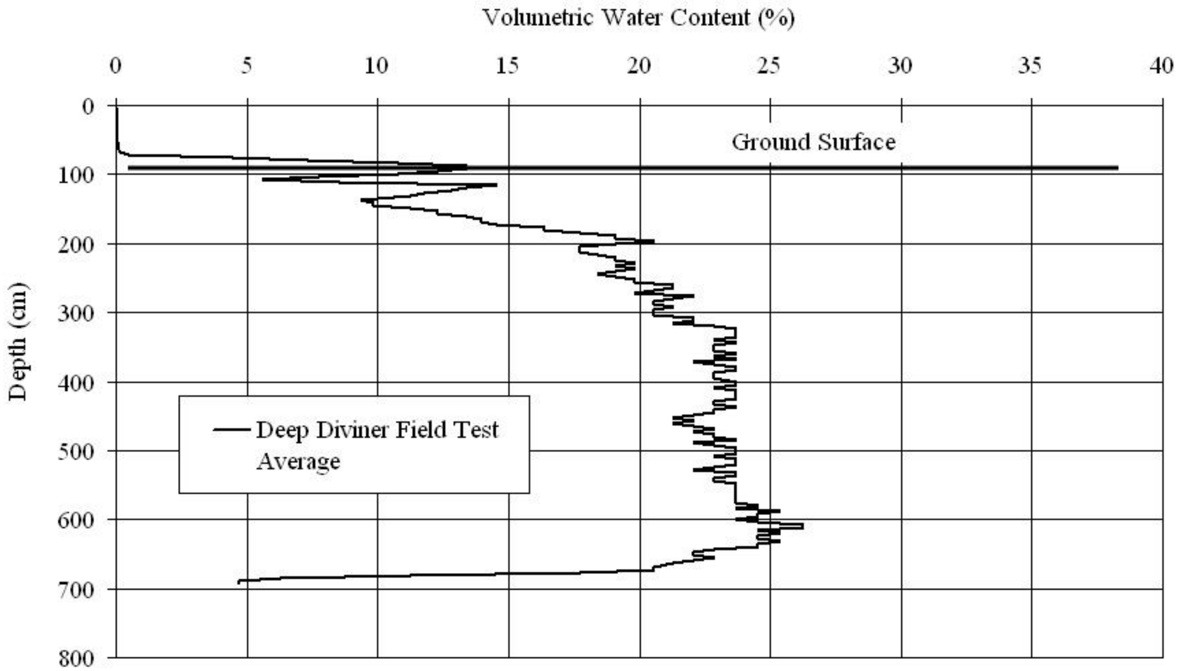

Figure 5. Measurements using the prototype deep capacitance moisture sensor in a piezometer at St. Denis, Saskatchewan—volumetric water content calculated using default Sentek calibration.

Fort McMurray Test

The prototype system with the refinements made after the initial field trial was then tested in deep access tubes installed in a sand tailings facility at an oil-sands mine near Fort McMurray, Alberta, Canada. Samples of the tailings were sent to Saskatoon, Saskatchewan for detailed material-specific calibration. Calibration requires preparing the material at a wide range of water contents and taking measurements at each water content interval. Figure 6 presents the calibrated results for the final prototype for a 5 m access tube in oil-sand tailings.

Based on the results of the field and laboratory testing, it was concluded that the deep capacitance moisture sensor has the potential to provide accurate, safe, and efficient measurements of soil moisture content in deep 2” schedule 40 PVC access tubes.

Current and Future Work

The deep capacitance moisture probe is undergoing field testing at a number of sites in Canada, the US, and Australia. This includes several sites in which the access tubes have been installed laterally along a soil cover or above textural break layers that are horizontal or sloping. The ability to obtain measurements of moisture conditions in the unsaturated zone within mine waste material has provided valuable data for understanding current and long-term behaviour of mine waste storage facilities at these sites.

Following this preliminary laboratory and field testing, the authors plan to develop a commercial version of the moisture sensor for general use. A second project is currently underway with the assistance of Canada's Industrial Research Assistance Program (IRAP), to develop and test a new sensor that will monitor both water content and electrical conductivity. A number of improvements will be made to the design based on the results of the work presented herein, as well as that being conducted at numerous field sites.

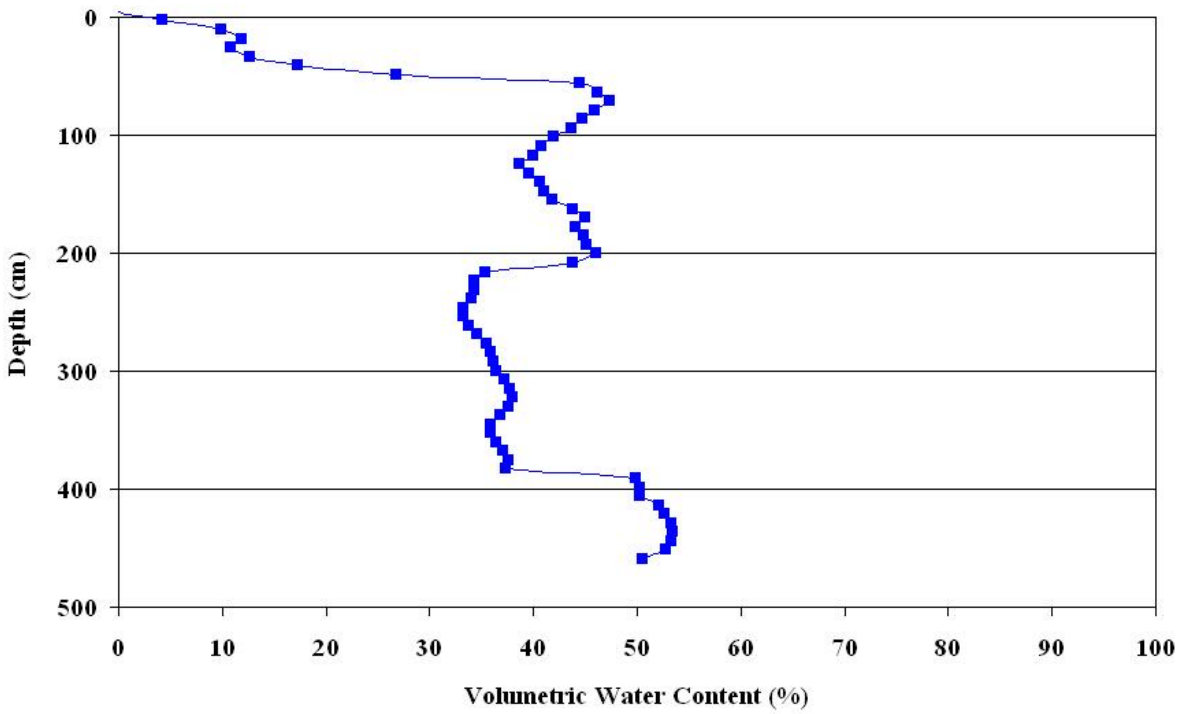

Figure 6. Measurements using the final prototype deep capacitance moisture sensor in a deep access tube installed in a tailings facility.

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