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Field Collection of Geotechnical Measurements for Remote or Low-Cost Datalogging Requirements

Reference

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ABSTRACT

Reliable, low-cost datalogging alternatives promote transfer of knowledge and technology to the wider geotechnical and geoscientist community. Alternative systems can ease increased data resolution on large projects, operate in remote locations with restricted site access, or allow developing countries access to reliable and cost-effective datalogging solutions. A low-cost prototype datalogger was developed and tested in the laboratory with the use of open-source materials. Open-source example code is provided at the permanent links included in this paper. The materials for the prototype were 20 % the cost of commercial datalogging units with similar capabilities. With labor, these custom-built units were 35–45 % the cost of a purchased datalogger. Measurements from commercial units and the prototype datalogger were compared to determine the prototype's accuracy. The datalogger was deployed in place of commercially available dataloggers at three sites across western Canada in the past two years. Laboratory and field testing of the low-cost datalogger has shown the prototype to be easily adaptable to various sensor types. The study experimented with negative pore water pressure (matric suction), volumetric water content, and temperatures from SDI-12 sensors as well as positive pore water pressure and temperature from vibrating wire piezometers. Telemetry modules have been attached to remote dataloggers, transmitting occasional data points, and periodically verifying system operation. Assembly, installation, and monitoring with the low-cost datalogging system over the past two years has demonstrated their durability in field applications. The implementation of a low-cost, open-source geotechnical datalogging system can be a challenge in some locations and requires the consideration of limitations, which are addressed.

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Keywords

geotechnical datalogging, prototyping board, vibrating wire piezometer, SDI-12, open-source code

Introduction

Instrumentation monitoring is a key part of nearly every geotechnical investigation. Site accessibility, significant instrumentation costs, and project budget overruns often result in instrumentation cutbacks, which can be detrimental to geotechnical monitoring programs. Cost savings can be key in larger projects, and low-cost instrumentation allows engineers to develop a more detailed instrumentation network, supplementing commercial instrumentation. Geotechnical engineers often rely on dependable monitoring equipment over several years, sometimes in relatively inaccessible locations (Schulz et al. 2009; Uchimura et al. 2010; Klimeš et al. 2012). In developing countries, clients may be unwilling or unable to afford the standard dataloggers used to monitor geotechnical sensors. The design and implementation of a basic low-cost datalogger provides geotechnical engineers with ample opportunity to improve or expand upon their geotechnical monitoring programs.

Although designing sensors can involve precise manufacturing techniques and expensive materials, the collection and analysis of data from these sensors is often straightforward and easily automated. Low-cost versions of commercial dataloggers offer a solution to rising costs of conventional units that have limited storage space and flexibility. Many commercial units contain peripheral equipment and special cables to collect data in the field. The present study documents a low-cost datalogging unit developed using open-source materials and components that are readily available to anyone for the purposes of building their own datalogger.

Focus is placed on the Arduino prototyping board because of its accommodating learning environment and ability to adapt to many instrumentation sensor output signals. Arduino boards have shown significant promise as a low-cost alternative to commercial units in the field of hydrology (Hut 2013). Automation of a double ring infiltrometer (Fatehnia et al. 2016) and the use of commercial sensors for temperature and humidity (Sadler, Ames, and Khattar 2016) have demonstrated their feasibility for simple data collection, storage, and transmission. As the combination of parts and labor for these prototyping board dataloggers are 2–3 times less expensive than commercial units, vast monitoring networks of sensors can be implemented, as shown by previous studies (Wickert 2014; Tauro et al. 2018). Furthermore, they can be installed in remote locations where field accessibility is an issue (Hund, Johnson, and Keddle 2016).

A few common geotechnical sensors were studied as potential suitors for a low-cost datalogger, including the following:

- vibrating wire piezometer (VWP) pressure gauges with thermistors, and
- matric suction and water content sensors (SDI-12).

Permanent links to example code for these sensors used with the Arduino prototyping board may be found at the following addresses:

- Sattler et al. (2020b) (VWP), and
- Sattler et al. (2020a) (SDI-12).

Measurements from each sensor were compared between a commercial datalogging unit and the low-cost datalogging system. Although the list excludes some sensors used in geotechnical engineering, computer microcontrollers have the potential to be used with any sensor with an electrical output signal. One must simply take advantage of the excess of open-source tools, resources, and sharing capabilities made available by the Internet. Numerous web forums exist with the sole purpose of developing and sharing code for worldwide collaboration. These tools are freely available and have the potential to drastically reduce costs and improve efficiency for simple datalogging processes over a wide range of conventional sensors.

Datalogging System

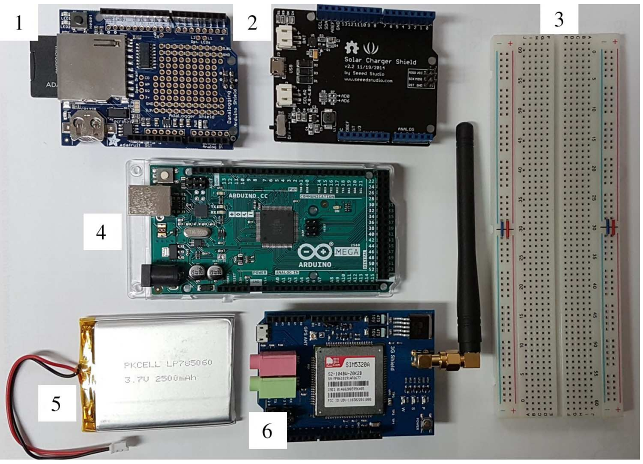
OVERVIEW

The Arduino project began in 2005 and focused on providing a low-cost learning environment for students to interact with various sensors and circuits (Barragán 2004; Cressey 2017). In the past 15 years, the Arduino project has developed several types of open-source hardware, including the Arduino Mega 2560. These prototyping boards have no operating system, are completely programmable using C++ programming language, and have limited power consumption, rendering them useful to field application. Arduino boards have gained a significant following among novice computer programmers and amateur hobbyists for their versatility and widely available hardware, attachments, open-source libraries, and support forums (Banzi and Shiloh 2015).

The Arduino Mega 2560 was chosen over other options (Raspberry Pi and Arduino Uno) because of its low power requirements, flash memory storage (256 KB to the 32 KB Uno), programming simplicity, and reliability. The Arduino Mega is a larger prototyping board with additional digital and analog pins, allowing for more sensors to be connected. Digital pins supply 5-V microcontroller power to sensors (regulated by the on-board voltage regulator), similar to an on/off switch, while analog pins receive variable voltage signals. Variable voltage signals are mapped over a set number of analog-to-digital conversion (ADC) values (1,024 for 10-bit ADC conversion) that determine voltage based on a reference lower and upper bound (Mega has a default of 0 V and 5 V, respectively).

The automated datalogging system combined several internal components shown in **figure 1**. The datalogging shield included a PCF8523 RTC, as opposed to the DS1307 found on previous versions. In climates with large annual temperature fluctuations, it is important to be aware of the time drift caused by temperature and correct the data accordingly. Field testing with the PCF8523 during this study demonstrated less than 1 hour of drift over a period from November 2019 to May 2020. However, resetting the RTC should be a standard procedure during field visits, as is common with commercial dataloggers. Other open-source dataloggers such as the Mayfly (Hicks

FIG. 1 Internal components of the low-cost datalogger. 1. Datalogging shield (including PCF8523 real time clock (RTC) and Secure Digital (SD) card interface)—stacking headers were installed to promote compact wiring and data transfer interface with the prototyping board; 2. Solar charger shield, a charge controller that regulates current from solar panel to feed the battery or prototyping board; 3. Breadboard, a wiring interface used to connect sensors to prototyping board's digital pins (for long-term installations, it is recommended to use more permanent wiring methods); 4. Arduino Mega 2560, which executes C++ script and sends data to the SD card; 5. Lithium polymer rechargeable battery—we recommend using batteries with at least 6,000 mAh capacity to enable continued operation after extended cloudy or cold temperature periods; 6. 3 G telemetry shield, which uses a SIMCom 5320A modem to transmit data over a cellular network.



et al. n.d.) and ALog (Wickert 2014) have been developed with a temperature-compensated DS3231 RTC and further address power consumption issues due to the inefficient voltage regulator.

EXTERNAL HARDWARE

The internal components of the datalogging system are enclosed in a Pelican 1200 waterproof case with a gasket seal (similar products are available on many online retail outlets). The case has customizable tearaway foam allowing the user to securely hold the internal components in place. Mounting brackets have been attached to the back of the case, allowing the system to be connected to a sturdy close-ended post and oriented in any direction. Holes were drilled in the bottom of the case to allow sensor cables to be fed into the breadboard connections. At minimum, a 9-W solar panel was found to provide enough recharging power to the battery when the datalogger was placed in exposed locations that receive adequate sunlight (no shadows) throughout the year. The solar panel was hinge-mounted on the lid of the waterproof case, creating a 45° angle with the ground. Grommets have been placed in all holes to maintain a watertight seal against the cables as they enter the waterproof case (screw-in glands could also be used).

The cost of components for the low-cost datalogger was up to five times less when compared with standard prices for conventional units with similar capabilities. When labor is factored into the cost, the custom-built unit is 2–3 times less expensive. A complete datalogging unit, ready for field installation, was constructed from parts worth approximately 260 USD. Labor costs would account for an additional 35–45 % on top of the parts. Practiced users and construction styled after a small assembly-line can greatly reduce the time required to build these units. Basic commercial units with similar capabilities for SDI-12 cost at least 520 USD (limited to 5 sensors). For VWP application, comparable commercial units cost between 930 and 1,200 USD. The primary expense in the low-cost datalogger was allocated to the solar panel and the hard-shell case that housed the electrical components. All the connected sensors are wired to the prototyping board through the breadboard. Long-term installations should utilize more permanent wiring methods such as hard-wired solder connections or screw terminals. These methods do not add much cost and improve durability. A summary of the primary expenses for the low-cost datalogger is shown in **Table 1**.

After mounting the case to a close-ended post, the sensor cables were securely wrapped around the post and armored, leaving some cable slack at ground level for potential settlement. Protective cable wrapping is recommended, especially in areas that have a large wildlife presence. Finally, the loggers are oriented due south for a northern hemisphere installation to take advantage of the solar radiation throughout the year. Where human vandalism is a concern, these cases can be locked with a padlock to minimize disturbance.

TABLE 1

Cost breakdown for the low-cost datalogger components

Components	Potential Supplier	Unit Cost, USD
Arduino Mega (R3)	Canada Robotix	15.86
Full size breadboard	Canada Robotix	3.96
Set of stacking headers (R3 compatible)	Canada Robotix	1.26
3.7-V Li-po battery (6,000 mAh)	Canada Robotix	26.00
Datalogging shield	Adafruit	13.95
8-GB SD card	Adafruit	9.95
3-V CR1220 lithium coin cell battery	Adafruit	0.95
9-W 6-V solar panel (9.5 in. by 8.125 in.)	Adafruit	78.95
Solar charging shield	Seeed Studio	13.50
5.5-mm DC barrel jack to Japan solderless terminal (JST) molex connector	SparkFun	2.95
3.5-mm tip ring ring sleeve (TRRS) jack breakout	SparkFun	3.95
Pelican 1200 case	Amazon	54.95
Hardware	Any supplier	35.00
Total cost		261.23

VWP PRESSURE

The programmable datalogger was connected to a VWP and successfully used to measure pore water pressure and temperature in the subsurface. Development and manufacture of vibrating wire sensors requires specialized knowledge, equipment, and techniques (Choquet et al. n.d.). However, the data collection from these instruments can be reproduced with limited technical background and inexpensive materials.

The working principle for VWPs centers around a tensioned steel wire attached to an internal diaphragm. External pore water pressure acts on the diaphragm through a porous stone, altering the tension in the attached steel wire. The vibrating steel wire induces alternating voltage current (AC) in a set of pickup coils positioned around the wire. Signal processing of the induced current is used to determine the pressure on the diaphragm. Calibration factors are specific to individual sensors, and the user must determine the associated calibrated pore water pressure in the postprocessing stage after measurements are downloaded from the datalogger.

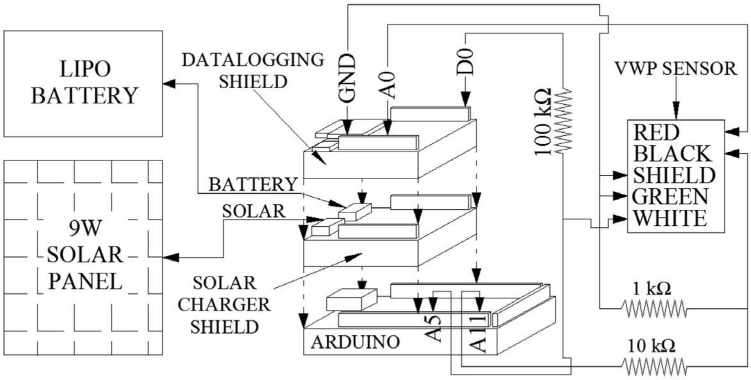
There are several methods of inducing current that may be used to conduct a pore water pressure measurement using a VWP (Viman et al. 2004; Pop et al. n.d.; Porfirio et al. 2016). A common method is to "pluck" the tensioned steel wire in square wave pulse trains that are relayed at rapidly increasing frequency over a set period. The designated range encompasses the expected natural frequency of the steel wire. After a short period of time, all frequencies die out except the natural or resonant frequency (Kovacs et al. n.d.). To measure the AC output from the sensor, it is necessary to shift the voltage to a positive frame of reference and change the reference lower and upper bound for ADC conversion. AC signals have both positive and negative voltage (negative voltage cannot be measured by the analog pin). The voltage can be shifted to the positive domain by sending the signal through a voltage divider that contains two resistors of different value in series (1 kΩ and 10 kΩ, shown in **fig. 2**). The resistor with a lower resistance (1 kΩ) is connected to a ground while the signal passing through the resistor with a higher value of resistance (10 kΩ) travels to the analog pin used to measure the sensor output. Shifting the bounds allows the set number of ADC values to be used to measure the output signal over of smaller voltage range (0 to 1.1 V), leading to 5 times higher resolution in the data record when compared with unshifted voltage. By shifting the AC signal and changing the analog pin reference, it was possible to determine the natural frequency from the maximum and minimum voltage peaks using Fast Fourier transform (FFT) analysis. The natural frequency (f_r, Hz) is used to calculate "B_{units}" via equation (1). The resultant "B_{units}" are used in the calibrated equations supplied by the sensor manufacturer to determine the equivalent pressure at the sensor.

$$B_{units} = (f_r)^2 \times 10^{-3} \tag{1}$$

Initially, testing was conducted in MATLAB's integrated development environment (IDE) using data output from an oscilloscope that sampled at 200 MHz. The methods were extended to the Arduino datalogger using an open-source library known as "arduinoFFT" available through GitHub (Condes 2020). After determining the

FIG. 2

Sample wiring diagram for VWP sensor connected to the Arduino datalogger.



most suitable analysis parameters through the initial testing, the code was programmed for VWP signal processing. The accuracy of the measurement is greatly improved with higher rates of sampling and the relatively large random-access memory (RAM) of the microcontroller enabled it to store the required temporary working data for the FFT calculation. The data were improved by rapidly testing for the natural frequency multiple times and averaging the results. Further verification of the data validity was conducted by comparing the results to measurements taken by commercial dataloggers. A sample wiring diagram for a single VWP sensor is shown in **figure 2**. The results of the study are shown in the section on VWP pressure data verification.

VWP THERMISTOR

VWPs contain an internal thermistor that provides indication of the soil temperature at the sensor depth. Thermistors have variable resistance based on temperature. By measuring the voltage drop across the thermistor with one of the analog pins on the prototyping board, the equivalent resistance of the thermistor is determined. One end of the thermistor must be grounded while the other end is connected to a resistor of known value in series. A jumper wire is inserted between the thermistor and the known resistor. The jumper wire is connected to an analog pin which measures the ADC value and subsequently the voltage. The other end of the known resistor is connected to a digital pin that cycles power through the circuit. All other parts of the circuit are known (such as voltage supplied to the circuit and the resistance of the known resistor). A standard wiring setup for measuring the thermistor from the Arduino is included in **figure 2**. The thermistor's resistance is converted to temperature based on the Steinhart and Hart (1968) relationship shown in equation (2):

$$T^{-1} = A + B \times \log(R) + C[\log(R)]^3 \tag{2}$$

where:

T = the temperature, K,
A, B, and C are constants, and
R = thermistor resistance, units based on constants.

WATER CONTENT AND SOIL SUCTION

Many types of soil water content and soil suction sensors transmit measurements to the datalogger using the serial-digital interface standard at 1,200 baud (SDI-12). A primary advantage of this form of data transmission is that data from multiple sensors can be sent over a single cable with minimal current drain, which reduces system cost (SDI-12 Support Group 2019). Furthermore, sensors do not need to be connected to the datalogger in any predetermined order, as each sensor is programmed with an individual identification number during setup.

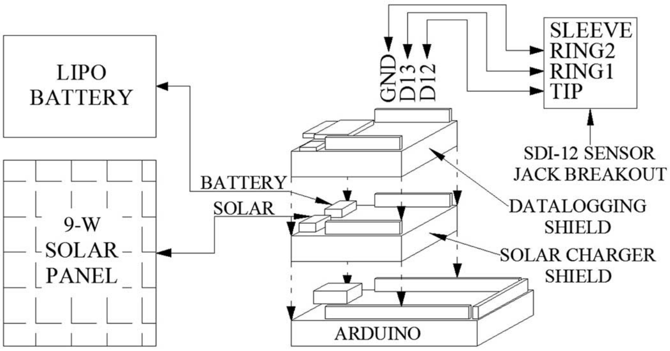
Sensors with SDI-12 compatibility are readily available from several environmental instrumentation suppliers. Open-source libraries have been specifically developed to interface SDI-12 sensors to an Arduino prototyping board and are accessible on GitHub, such as "EnviroDIY/Arduino-SDI-12" (Smith et al. 2020). These repositories provide example code and forums to discuss issues with the source code and proper methods for implementation. As part of this study, the example code was modified to permit the use of multiple sensors with separate identification numbers. Measured data were written to an SD card, allowing for universally accessible data collection. A potential wiring setup for an SDI-12 sensor connected to the Arduino datalogger is shown in **figure 3**.

OPTIONAL TELEMETRY

Telemetry attachments have been added to the datalogging system where a cellular network signal is present. Telemetry enables data to be collected remotely and limit expenditures on travel to the field. The current setup used a telemetry shield set up on a 3 G cellular network from Seeed Studio to transmit data via instant messaging. One of the current drawbacks is the additional power consumption required when operating a cellular modem. The modem typically remains off, consuming minimal power, and only turns on when a particular sequence (or time interval) is achieved in the coding. At present, the primary use of the telemetry module is focused on

FIG. 3

Sample wiring diagram for SDI-12 sensor connected to the Arduino datalogger.



occasional transmission of datapoints to verify ongoing datalogger operation and identify potential issues in the data collection process.

However, newer telemetry shields and development boards contain modems with the added capability of transmitting data to cloud storage and private servers (Woo 2021; Particle Industries, Inc. 2021). More advanced development kits are being produced every year with added functionality and better data transmission rates. As cloud storage becomes more accessible and cellular coverage becomes more reliable, it may become more common for users to set up their own servers to store collected measurements transmitted from the field. Although many current servers are heavily proprietary and costly, future competition on the Internet of Things (IoT) marketplace has already started (Craft 2021) and enables low-cost private access to set up higher capacity collection servers. Open-source initiatives for IoT cloud storage are also available.

Results and Discussion

ANALYSIS OF VWP SIGNAL

Testing was conducted in the laboratory to determine the most effective input pulse frequency pattern for excitation voltage on the tensioned steel wire in a 0.35-MPa VWP sensor that produced a consistent value of natural frequency while the sensor pressure was held constant. Signal processing of the return wave required knowledge of the wait time necessary to analyze the natural frequency. A digital storage oscilloscope manufactured by Agilent Technologies was used to sample the output voltage signal. Data points were exported to MATLAB's IDE and used to determine the ideal pulse wave and delay for repeatable estimation of the natural frequency.

A square wave pulse train of 0 to 5 V incrementing by 50 Hz at 4-ms intervals was found to be effective in producing repeatable natural frequency measurements. The frequency increased from 1,400 Hz to 3,500 Hz over a period of approximately 172 ms. Following a 20-ms delay, the induced voltage was analyzed over a 40-ms period (fig. 4*A*). The voltage data points were sampled and binned using an FFT algorithm to determine the frequency at which the maximum amplitude occurs (fig. 4*B*). This frequency is the natural frequency for the tensioned steel wire.

VWP PRESSURE DATA VERIFICATION

A side-by-side comparison of the VWP signal processing from the low-cost datalogging system and a commercial datalogger (Slope Indicator VW data recorder) was conducted to verify measurements. A polyvinyl chloride (PVC) pressure chamber rated to 2 MPa was built in the laboratory to pressurize a VWP sensor and compare readings from the two datalogging systems (fig. 5). A standard VW2100 model piezometer was sealed inside the pressure chamber, and the entire chamber was filled with water. The apparatus was pressurized up to 150 kPa

FIG. 4 FFT analysis of induced sensor signal at zero pressure: (*A*) square wave pulse train followed by 20-ms delay and 40-ms sampling period along with (*B*) the observed amplitude during sampling period demonstrating the prevalent natural frequency.

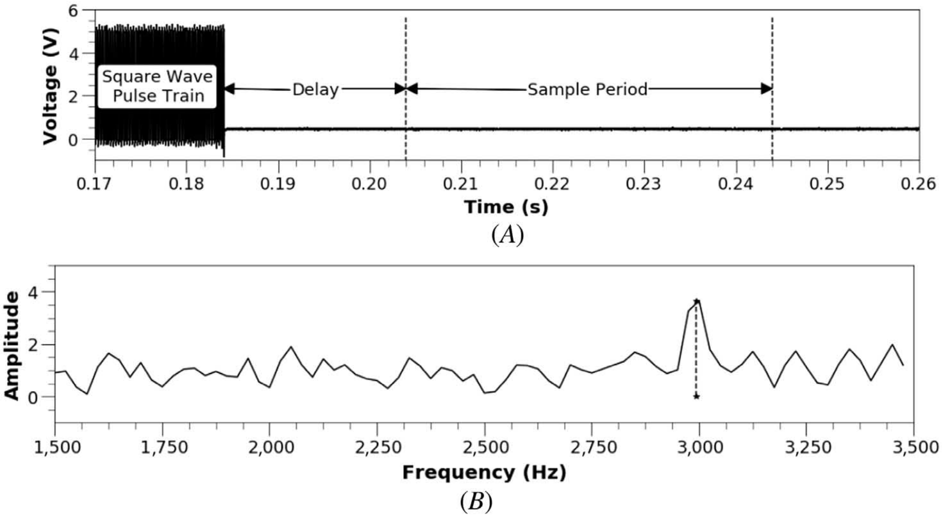


FIG. 5

Pressure chamber with commercial readout unit and low-cost datalogger.

using a pressure-volume (PV) controller that enabled constant pressure in the chamber (fig. 6). At approximately 10-kPa increments, both the low-cost datalogger and conventional datalogger were connected to the VWP sensor cables to conduct a pressure reading. The two dataloggers demonstrated a high degree of correlation, validating the low-cost datalogger measurements (fig. 7).

FIG. 6

PV controller used to pressurize the VWP pressure chamber.

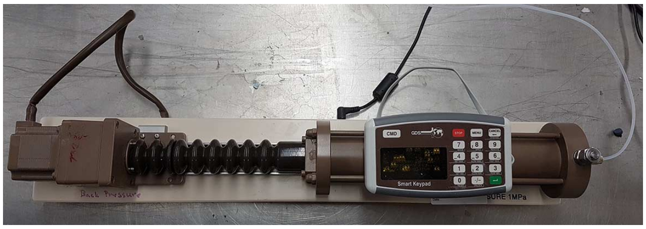
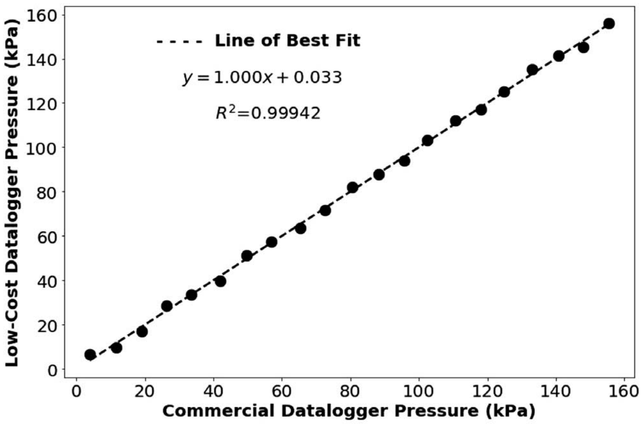


FIG. 7

VWP pressure comparison between two datalogging systems.



VWP TEMPERATURE DATA VERIFICATION

After determining the validity of pressure measurements by the low-cost datalogger, a side-by-side comparison of temperature measurements was completed. The same VW data recorder from the previous section was employed as the commercial datalogger comparison for the purposes of this test. As ground temperatures do not fluctuate to the same extent as surface temperature, a smaller range of testing would be required. However, accuracy and durability of the datalogger was tested by conducting a series of temperature changes to both the sensor and the datalogger. Testing was conducted with a dry VWP sensor that did not have water between the porous stone and diaphragm. Frozen water in VWP sensors can cause irreparable damage to sensors.

A simple test was carried out by exposing the VWP sensor and low-cost datalogger to a series of temperatures while taking measurements with the low-cost datalogger and the commercial readout unit at 2-min intervals. Initially, the VWP was placed in a refrigerator with a mercury thermometer, allowing time for the temperature to equilibrate around 2.5°C. The sensor was then removed from the refrigerator and allowed to equilibrate around 25°C. Once acclimatized at 25°C, the sensor was placed into a deep freezer along with the low-cost datalogger. The commercial readout unit was left outside the deep freezer for comparison. The temperature in the deep freezer began to stabilize around −6°C after an hour. Finally, the sensor and datalogger were removed from the deep freezer and allowed to equilibrate at room temperature (fig. 8). Comparison of

FIG. 8

Time series of VWP thermistor temperature from both dataloggers.

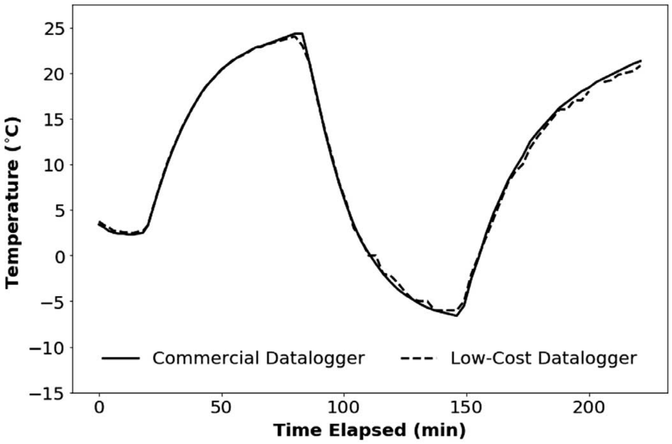
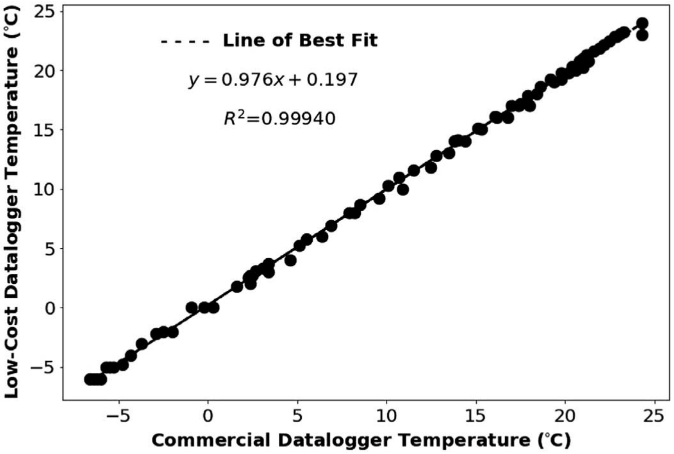


FIG. 9

VWP thermistor temperature comparison between two datalogging systems.



the measurements from the low-cost datalogger and the commercial readout unit over this period indicated that there was a high degree of correlation between the two datalogging systems (fig. 9).

SDI-12 SENSOR OPERATION AND DATA VERIFICATION

Preassembled open-source libraries (such as "EnviroDIY/Arduino-SDI-12") compile a set of unique self-calibration algorithms for SDI-12 data conversion to recognizable measurements. The process is readily conducted by microprocessor-based dataloggers developed using the Arduino prototyping board. New sensors can be added by simply setting a new sensor address to each new sensor. Because of the low power requirements for many SDI-12 sensors, the low voltages supplied by microcontroller interfaces are often enough to power the sensors for data transmission. Communication between the sensors and the datalogger takes the form of ASCII character commands and responses that are relayed to individual sensors by using a unique sensor address at the start of each command (SDI-12 Support Group 2019). The remaining sensors remain idle in low-power mode during data transmission of other sensors.

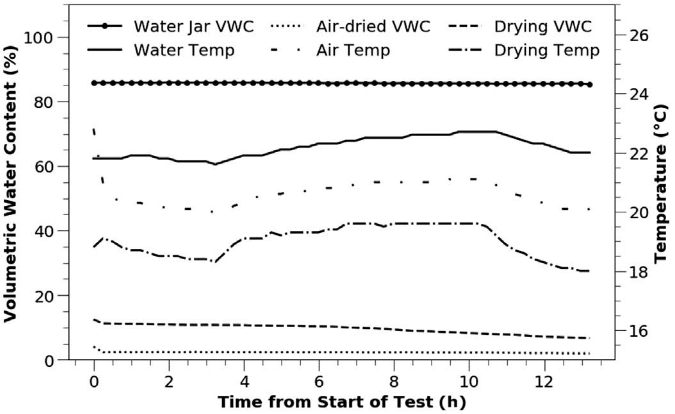
Data collection from individual sensors is based on unique identifiers in the data transmission. Therefore, sensor measurements do not differ when collected by two different types of dataloggers, assuming the conversion is done properly. If the sensor has been calibrated properly by the manufacturer, the actual data recording should also be accurate. More detail on factory calibration of sensors can be found in the manufacturer's individual sensor documentation. A series of testing and comparisons were performed to evaluate the sensor operation and compare measurements to existing sensors connected to commercial dataloggers. Testing was conducted with both water content and matric suction SDI-12 sensors.

The upper bound, lower bound, and a transitional water content for a set of water content sensors were studied using a simple experiment. Based on manufacturer specifications, the sensor has an accuracy of ±3 % with generic calibration over a range of 0–50 % volumetric water content (Meter Group 2019). Accuracy is not guaranteed outside of this range. The upper bound test sensor was completely submerged in a jar of tap water. The lower bound test sensor was air dried at room temperature in the laboratory. A transitional water content sensor was wrapped in a wet paper towel and allowed to dry alongside the dry sensor at room temperature over a 13-h period (fig. 10).

The measurements suggest that the wet sensor recorded approximately 85 % volumetric water content throughout the test. The sensors are not designed to record water content above 50 % so water submersion measurements should not be expected to be accurate. The manufacturer states that apparent dielectric permittivity (ε_a) measurement for the soil range (1–40) is ±1 ε_a and 15 % of the measurement for an ε_a of 40–80 (ε_a of air

FIG. 10

Drying experiment with three sensors: wet, drying, and air dried.



and water are 1 and 80, respectively) (Meter Group 2019). At the drier water contents, the data appears to follow the expected trends. The air-dried sensor remains constant around 0 % volumetric water content for the duration of the test. The sensor wrapped in wet paper towel experiences a gradual decline in volumetric water content over the 13-h period due to evaporative loss of water from the wet paper towel.

Measurements from water content sensors were verified by thoroughly mixing a batch of Battleford Formation till and compacting the sample at a specific water content (12 %). Battleford Formation till is comprised of approximately 55 % silt and clay with a plasticity index around 11 (Christiansen 1992). It is highly sensitive to changes in water content, making it a prime candidate for water content monitoring. Plastic covering was used to retain water content and limit evaporation during the test. Four sensors were then inserted into various locations across the sample (fig. 11). These water content sensors verified the targeted water content (12 %) based on the manufacturer specified error tolerances (±3 %).

Comparison of matric suction measurements from a commercial datalogger and those collected by the low-cost datalogger was possible from sensors installed at the Ripley Landslide in British Columbia, Canada. Measurements of matric suction (fig. 12) and soil temperature (fig. 13) from each datalogger were plotted over the same time frame to compare SDI-12 data transmission via both datalogger types. Although the sensors were not installed side by side (approximately 50 m of separation), they are all installed within the landslide head scarp with the depth of each sensor noted in the following figures.

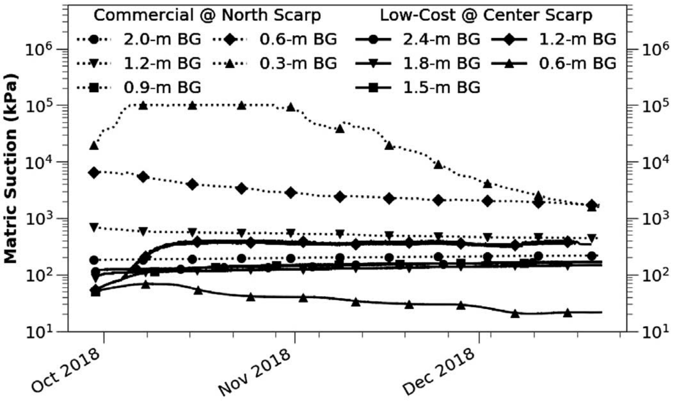
The low-cost datalogging sensors were installed in October 2018 and show a period of equilibration during the first two weeks. Sensors were initially hand-packed with wet soil to ensure intimate contact between the sensor and the surrounding soil, which is required for proper sensor operation. If the hand-packed soil around the sensor is wetter than the surrounding soil, there will be an increase in matric suction as the sensor reaches pore pressure equilibrium. The measurements from October 2018 through December 2018 at 0.6 m BG indicate that general trends between sensors located at the same depth were consistent between the commercial and low-cost datalogging units, following pressure equilibration (fig. 12). Soil temperature trends downward over the study period due to the oncoming winter (fig. 13). Short-term fluctuations in the trend due to infiltration and changes in air temperature are most evident in the shallow sensors from both locations, indicating that the sensors are responding to these external boundary conditions as expected. These results provide further verification that measurements do not vary based on the datalogger type. Both suction and soil temperature trends exhibited strong correlation, considering the distance between the commercial and low-cost dataloggers. Changes in the material type and soil properties between the two locations cause differing values of soil suction and temperature. However, soil suction and temperature trends may be expected to follow similar patterns at the same depth over short periods of time.

FIG. 11

Verification of volumetric water content sensor accuracy.

FIG. 12

Comparison of commercial and low-cost datalogger collection of head scarp matric suction at two locations on the Ripley Landslide. BG, below ground.

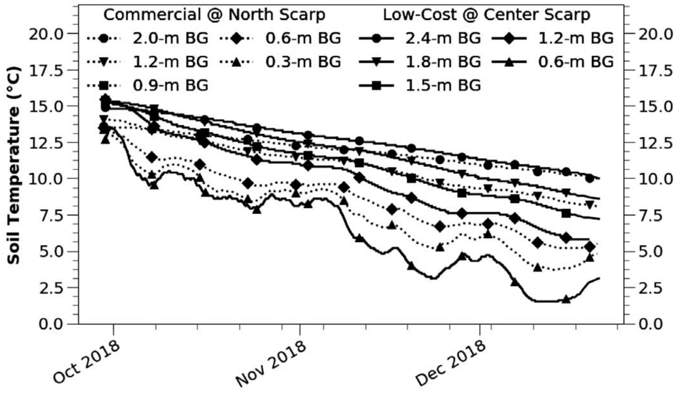


LOW-COST DATALOGGER FIELD APPLICATION

The low-cost datalogging unit was installed in field sites at three locations across western Canada. Initial deployment logged VWP measurements near the Borden Bridge northwest of Saskatoon on Highway 16. A second deployment included matric suction (TEROS 21 obtained from Meter Group) and volumetric water content

FIG. 13

Comparison of commercial and low-cost datalogger collection of soil temperature at two locations on the Ripley Landslide.



(5TE from Meter Group) sensors at the Ripley Landslide near Ashcroft, British Columbia in November 2018 (fig. 14). A subsequent installation of water content sensors was conducted in the summer of 2019 at Mile 153.8 on the Canadian Pacific Scotford Subdivision northeast of Edmonton, Alberta. In November 2019, matric suction sensors and water content sensors were installed and connected to the low-cost datalogging system at the Borden Bridge site.

The low-cost datalogging system has been exposed to a wide array of atmospheric events, solar radiation challenges, drastic temperature fluctuations, and wildlife disturbance. Damage to the dataloggers over the past two years has been limited to weakened brittle wires in cold temperatures and one instance of severed cables due to a curious deer and a lack of cable armoring. The occurrence indicates that cable armoring is a necessity for loose cables in high traffic wildlife locations. Temperature fluctuations have been found to impact the low-cost datalogger no more than commercial dataloggers installed on the same site. Further discussion on datalogger operation during extreme cold can be found in the next section.

Solar radiation seems to be the biggest concern when operating the low-cost datalogging system. The system relies on solar radiation, which minimizes the need to change expensive batteries. However, the system is then restricted to where it can be placed. In the northern hemisphere, raised ground south of dataloggers cast shadows during the winter months, which can present challenges when logging through the winter. Where the dataloggers are not shadowed during the winter, operation persists with no issues. As a result, datalogger location is an important factor in terms of winter solar radiation. If the installation is to be placed in hilly terrain, one must consider the solar elevation as the days approach winter equinox. It is also important to remember that increasing

FIG. 14

Low-cost datalogger installation at Ripley Landslide near Ashcroft, British Columbia.

the number of sensors will increase the required power consumption, and the datalogging location should be planned accordingly.

Standard data collection (without telemetry) is very straightforward. The low-cost datalogging system case forms a sort of platform when opened allowing the user to pull the SD card, copy the. txt file to a laptop computer, and re-insert the SD card (**fig. 15**). Data collection by the datalogger is automatically skipped while the SD card is not inserted and resumed when the SD card is replaced. There is no additional software required to access the data. No programs need to be downloaded before traveling to the field. The only requirement is an SD card reader, which comes standard on many laptops.

EXTREME COLD TEMPERATURE TESTING

Extremely cold temperatures below −30°C can cause incredible strain on commercial datalogging units on the Canadian prairies and in the arctic. Cold temperatures result in limited charging efficiency due to slower chemical reactions and restricted charge-transfer kinetics due to temperature limitations (Jaguemont, Boulon, and Dubé 2016). Limited charging efficiency during long stretches of cold weather can destroy lithium-ion datalogger batteries. Therefore, lithium thionyl chloride batteries are commonplace for dataloggers in climates with extreme annual temperature fluctuations. It is common to check on dataloggers in the spring to ensure continuous operation and replace commercial datalogger's nonrechargeable lithium thionyl chloride batteries. This can add considerable expense to already expensive datalogging programs. The rechargeable batteries on the low-cost datalogging system are approximately the same cost as the commercial unit's nonrechargeable batteries. However, they can be expected to maintain their charge for 2–3 years.

The computer microcontroller used in the low-cost datalogger has an industrial temperature operation range of −40°C to 85°C (Microchip Technology Inc. 2020). However, other components may fail near the extremities of

FIG. 15

Accessing data from low-cost datalogger installation at Borden Bridge.

this temperature range. Microcontroller component strain increases with higher temperature operation. Dataloggers placed in temperatures near the upper reaches of this range are not standard for in situ geotechnical instrumentation, although due care and attention by users (avoid leaving units in a vehicle on a hot summer's day) is important to extend microcontroller life cycle. On the other hand, temperatures dropping to −40°C are often experienced at many field sites in the arctic as well as on the Canadian prairies and can cause concern for continuous data collection. Other components, such as the battery, may pose more serious challenges to consistent datalogger operation.

During the initial testing phase of the low-cost datalogger, a stretch of cold temperatures experienced in Saskatoon, Canada, was used to identify possible issues related to data loss. A VWP was connected to the datalogger to measure the temperature-controlled interior temperature of a house while the low-cost datalogger was positioned outside and exposed to winter temperatures over a span of two days in January 2019 (**fig. 16**).

Data collection of the interior temperature compared to an exterior temperature from a local meteorological station situated 1.5 km from the datalogger (Environment Canada 2020) demonstrated consistent data collection during the cold stretch. The temperature measurement did not appear to drift or lose accuracy due to the fluctuating and extreme cold temperatures that the low-cost datalogger was exposed to for the duration of the test.

Two of the three study sites experience especially harsh winter weather with temperatures regularly dipping down to −40°C. Field testing of the low-cost datalogger at the Scotford site (in Alberta, Canada) and the Borden Bridge site (in Saskatchewan, Canada) during winter demonstrated the datalogger functionality through temperatures below −30°C during the winter months of 2020. Power loss in the low-cost dataloggers during periods of extreme cold is often synchronous with commercial units on the same site. For example, in February 2019, the Borden Bridge site experienced extremely cold temperatures, consistently dropping to −40°C, which caused several lithium thionyl chloride batteries in the commercial dataloggers to die. The lithium polymer battery in low-cost datalogger measuring the VWP sensors also died around the same time as the commercial dataloggers. However, although the Arduino stopped executing the code, the solar panel recharged the battery. The batteries in the commercial units had to be replaced with new batteries, whereas the lithium polymer batteries in the low-cost datalogger were fully charged by the next site visit, and the Arduino simply had to be reset to continue datalogging.

The low-cost dataloggers at the Scotford site measure volumetric water content from SDI-12 sensors at various depths in two subsequent track sections. Measurements collected by two dataloggers between November 2019 and May 2020 indicate consistent datalogging with minimal data gaps during the coldest days of the winter, when compared with the Elk Island National Park weather station (Environment Canada 2020) (**figs. 17** and **18**). Temperatures are shown to drop below −40°C during a stretch in January 2020. The low-cost dataloggers at each track section continued to operate during and after these extreme temperatures, as solar

FIG. 16

Low-cost datalogger cold temperature test in Saskatoon, Saskatchewan, Canada, during January 2019.

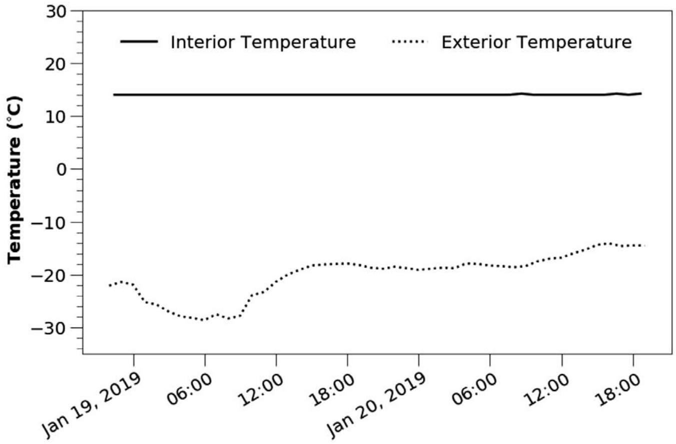


FIG. 17

Low-cost datalogging of soil water content in track geotextile (TG)-section at the Scotford site northeast of Edmonton, Alberta, Canada during winter 2020. BBS, below ballast surface.

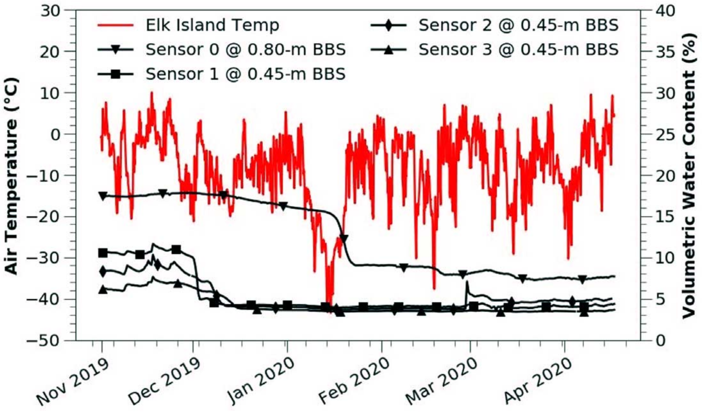
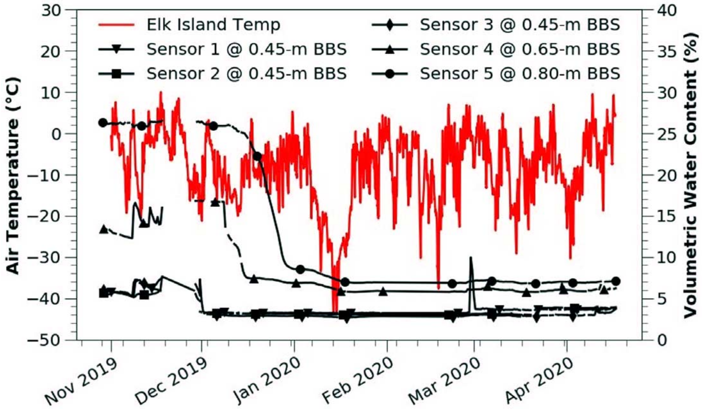


FIG. 18

Low-cost datalogging of soil water content in T-section at the Scotford site northeast of Edmonton, Alberta, Canada during winter 2020.



radiation is entirely unobstructed at this site. During data retrieval, one of the wires broke that had become brittle in the colder weather. With replacement of the wire, the unit was returned to full functionality. The problem could be avoided by hard-wiring connections, which would enhance the datalogger's internal durability.

Another example of cold weather durability was demonstrated by the second round of low-cost datalogger installations at the Borden Bridge site. These two dataloggers measure matric suction from SDI-12 sensors at depths up to 2.7 m at two locations along Highway 16 near the Borden Bridge. The low-cost dataloggers and SDI-12 sensors were installed in November 2019 and show the initial period of pressure equilibration, followed by equilibrated soil suction measurements. A self-logging barometer was installed inside one of the dataloggers and provides a temperature trend that is compared with the datalogger measurements between November 2019 and May 2020 (figs. 19 and 20). Once again, solar radiation remains mainly unobstructed at these two borehole locations throughout the winter months, and the dataloggers continued to operate when temperatures fell to −40°C, as measured by the barometer thermistor.

CHALLENGES AND LIMITATIONS

The development and testing of any new datalogging system always involve challenges that need to be addressed and revised in future installations. Over the past two years, significant improvements have been achieved in the

FIG. 19

Low-cost datalogging of soil suction in BH-1 at the Borden Bridge site north of Saskatoon, Saskatchewan, Canada, during winter 2020.

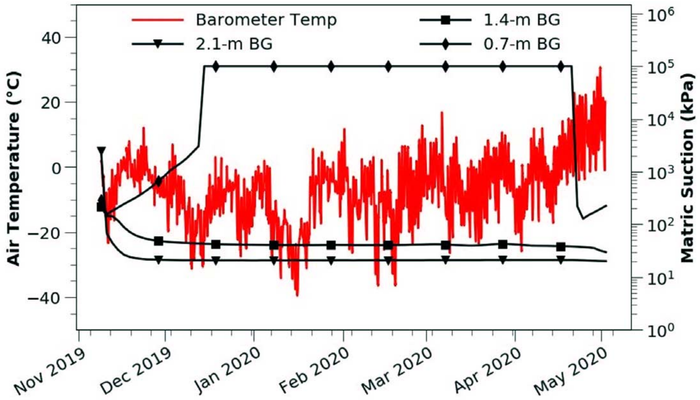
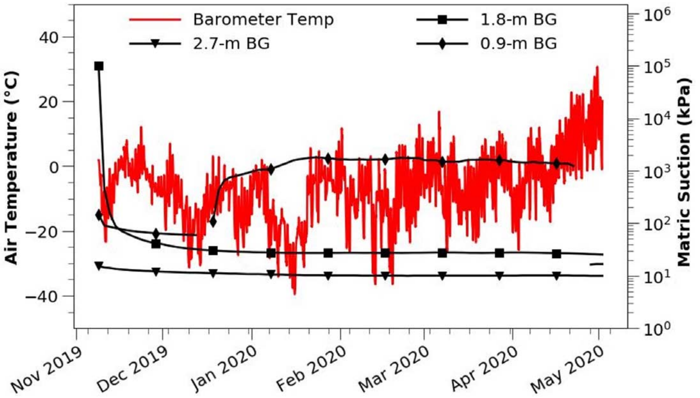


FIG. 20

Low-cost datalogging of soil suction in BH-2 at the Borden Bridge site north of Saskatoon, Saskatchewan, Canada, during winter 2020.



low-cost datalogging system. However, power requirements can remain a challenge in some installation scenarios. Improvement to coding efficiency, temperature compensation from the RTC, and limitation of unnecessary power usage due to the inefficient voltage regulator in the Arduino Mega would reduce power usage, making the system more reliable in the winter months. Furthermore, future revisions of the low-cost datalogging system can be combined with conventional power sources to enhance reliability. Other open-source dataloggers, such as the Mayfly and ALog, demonstrate general-purpose solutions to solar datalogging needs, such as a low power draw, powerful processors with enhanced memory, and large quantities of input pins.

Telemetry attachments for the Arduino setup are becoming more popular and are constantly being updated. Additional development and expansion to 4 G and 5 G networks in the future will increase data transmission rates and reduce our reliance on third parties. Some telemetry attachments, such as Particle, have their own servers, which enables seamless transfer of data when a network connection is established. The introduction of cloud storage servers allows for more efficient data collection and transmission (Stoica et al. 2001). Personal ownership of data with more secure data transmission and privacy may be important to some users and can be addressed through encryption and or modifications of the peer-to-peer network system (Lu 2018). The cloud storage industry, including telemetry capabilities, have been advancing rapidly in recent years as remote data collection has gained popularity and importance (Atzori, Iera, and Morabito 2017).

Additional sensor types may be connected to the datalogging system in the future. Adjustment of sampling rates in relation to battery drainage and incorporating a temperature-compensated RTC will help to determine the interval required between site visits. Continued testing and installation at additional field sites will further the development of the low-cost datalogger solution.

Conclusions

Site accessibility and financial constraints often plague geotechnical monitoring programs. Consequently, instrumentation might be scaled back, causing data gaps that limit our ability to gauge and understand site conditions. Commercial datalogging systems can be cost-prohibitive, especially in developing countries. However, open-source resources and materials are readily available that can help ease the financial burden for basic datalogging needs on some projects. Alternatively, a low-cost datalogging system can be deployed in geotechnical investigations to increase the size of monitoring networks for minimal cost.

The present study developed a low-cost programmable datalogger with open-source example code using several open-source libraries and online forums. The present datalogging system has been installed at three sites across western Canada, collecting data over the past two years. The datalogging system has been programmed to operate with VWP pressure gauges, thermistors, and water content and matric suction sensors, although any type of sensor with electrical output could be measured using a similar datalogging system. Furthermore, the number of sensors attached to the datalogging unit is only limited by the number of ports on the prototyping board. For SDI-12 sensors, data are sent through a single cable, and the number of sensors can be increased by programming additional identifiers for new sensors. Datalogging limitations to the number of sensors is primarily related to the power required to operate additional sensors.

The low-cost datalogger is compact (case dimensions are 27 by 25 by 12 cm) and lightweight (total mass around 1.5 kg). The assembled datalogger can fit in a backpack, allowing one to travel with the datalogger, spare parts, and tools as airplane carry-on luggage. A lightweight datalogger makes it easier for the user to transport the system over rough and difficult terrain when accessing remote walk-in only sites. All the delicate datalogging components, excluding the solar panel, are housed inside the rugged carrying case, which limits damage during transport. Provided the solar panel is protected properly, the low-cost datalogging system can be the lightest and most durable component of the equipment and sensors transported to site.

Lab and field testing confirmed the durability and accuracy of the low-cost datalogging system. The system is highly adaptable, which makes it particularly advantageous to the field of geotechnical engineering. These dataloggers are customizable, require no proprietary peripherals, and have standardized data storage. The development of a low-cost datalogging system offers consultants and researchers the ability to expand their monitoring networks when greater data resolution is preferred, but project budgets are limited. Remote sites can be difficult to access, and a lightweight datalogger allows for easier transport of materials. Furthermore, application to geotechnical practice in developing countries offers an accurate datalogging solution to economies that cannot afford expensive conventional monitoring systems.

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