Fiber Optic Measurements of Soil Moisture in a Waste Rock Pile

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Conflict of Interest

None.

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Article Impact Statement

High resolution measurements of distributed soil moisture using aFO-DTS.

Abstract

The design and construction of a waste rock pile influences water infiltration and may promote the production of contaminated mine drainage. The objective of this project is to evaluate the use of an active fiber optic distributed temperature sensing (aFO-DTS) protocol to measure infiltration and soil moisture within a flow control layer capping an experimental waste rock pile. Five hundred meters of fiber optic cable were installed in a waste rock pile that is 70 m long, 10 m wide, and was covered with 0.60 m of fine compacted sand and 0.25 m of non-reactive crushed waste rock. Volumetric water content was assessed by heating the fibre optic cable with 15-minute heat pulses at 15 W/m every 30 minutes. To test the aFO-DTS system 14 mm of recharge was applied to the top surface of the waste rock pile over 4 hours, simulating a major rain event. The average volumetric water content in the FCL increased from 0.10 to 0.24 over the duration of the test. The volumetric water content measured with aFO-DTS in the FCL and waste rock was within ± 0.06 and ± 0.03, respectively, compared with values measured using 96 dielectric soil moisture probes over the same time period. Additional results illustrate how water can be confined within the FCL and monitored through an aFO-DTS protocol serving as a practical means to measure soil moisture at an industrial capacity.

Introduction

The occurrence and flow of groundwater through unprocessed mine waste stored in waste rock piles is a potential environmental hazard if not properly managed. Waste rock piles are large structures, with heights sometimes exceeding several hundred meters and with areas covering dozens of hectares (Aubertin et al., 2002). Piles have naturally steep side slopes (>37°) and may contain millions of cubic meters of waste rock (McCarter, 1990; Morin et al., 1991; McLemore et al., 2009; Blight, 2010). They should be designed to remain stable indefinitely (Morin et al., 1991). Each waste rock pile configuration has a unique hydrogeologic system that is a function of numerous factors, including the material and machinery available at a specific mine site, dumping techniques, compacted low-permeability layers due to vehicle traffic, particle segregation along the slope of the pile, and the physical characteristics of the materials (Aubertin et al., 2002; Bussière et al., 2003, 2011; Fala et al., 2005).

Environmental contamination from waste rock piles, such as contaminated mine drainage (contaminated neutral drainage, CND, or acid mine drainage, AMD), depends on several factors including the lithology and mineralogy of the waste rock produced, the movement of fluid (air, water and water vapor), and temperature through the pile (Wilson et al., 2000; Lefebvre et al., 2001; Fala et al., 2005, 2006; Molson et al. 2005, Plante et al. 2010). Environments with high precipitation create favorable conditions for oxygen and water to react with waste rock within the pile (Lefebvre et al., 2001). There is now emphasis for the design of waste rock piles to pivot towards mitigating the formation of contaminants. New waste rock pile design can potentially reduce contamination drainage by controlling the movement of water and vapor through the pile (Aubertin et al. 2002, 2005; Fala et al. 2003, 2005, 2006; Broda et al. 2014) during and after the mining operation.

Controlling water infiltration into waste rock piles could be achieved, in principle, by constructing a soil cover system on the pile at the end of surface deposition (Morin et al., 1991; Zhan et al. 2000; Bussière et al., 2003; MEND 2004; Martin et al. 2006; INAP, 2017). It is also possible to use an alternative construction method for the entire pile, based on the addition of inclined flow control layers (FCL) to prevent fluid percolation into the reactive waste work (Aubertin et al. 2002; Fala et al. 2003). The FCL can be constructed with a sandy soil or with non-reactive waste rock crushed to relatively fine-grained texture and compacted on each raise and bench of the waste rock pile. The compacted surfaces are inclined towards the edge of the pile to help promote runoff and limit surface recharge into the waste rock pile interior. The FCL material must have a specific particle-size distribution to induce a significant hydrogeological property contrast with the coarse waste rock underneath to divert water laterally. Water flows in the finer granular layer under unsaturated conditions due to the capillary barrier effect that develops at the interface with the underlying coarse waste rock (Aubertin et al. 2002, 2005, 2009; Aubertin, 2013; Martin et al. 2005, 2017). In an inclined system, water will move along the interface until suction reaches at the interface the water entry value of the waste rock located below. In the inclined FCL, water will remain in the FCL until the capillary forces (i.e suction) is reduced to the water entry value of the underlying waste rock. Finer grained material has high retention capacity, mitigating against percolation flow into the waste rock layer and maximizing runoff and lateral flow within the moisture retaining layer because of the waste rock low hydraulic conductivity under low VWC and S_r (degree of saturation) values (Aubertin et al. 2009). Water accumulates at the FCL and waste rock interface until surface tension reaches the water entry value of the waste rock. This pressure corresponds to the residual water content of the waste rock. Once water moves across the interface, it progressively increases the VWC and unsaturated hydraulic conductivity of the waste rock. Water will then drain into the waste rock layer beyond the lateral diversion length, at the Down-Dip limit (DDL). This is the capacity of the FCL to control water infiltration before being reduced significantly (Aubertin et al. 2009). This will reduce the effectiveness of the capillary barrier and allow downward flow into the waste rock pile.

While new waste rock pile with FCL and cover designs open the possibility for mitigating environmental damage, it is important to measure and assess their effectiveness. Monitoring the waste rock, FCL and surface cover through time to understand how fluids move through the material is a challenge. Traditional monitoring methods (e.g. soil moisture probes) provide a low-spatial-density monitoring network (Vereecken et al. 2008). The installation of in-situ probes is difficult because the grain size distribution of waste rock is widely graded and includes particles ranging from clay to boulder fractions, with sand and gravel fractions dominating (Barbour et al., 2001, Nichol, 2002, Aubertin 2013, Martin et al., 2017). The primary challenge is obtaining spatially representative data from spot measurements provided by individual probes. For instance, large pore spaces between the coarser grains may result in loss of contact between the material and the probe, which s can reduce the accuracy or negate the effectiveness of in-situ sensors. Better monitoring methods are required in order to acquire distributed data that is relevant at the site scale, given the coarse and heterogeneous nature of waste rock materials.

Fiber optic distributed temperature sensing (FO-DTS) provides the potential to measure soil moisture spatially at a scale relevant for a waste rock pile (with an FCL) and overcome the limitations of point soil moisture sensors. Fiber optic distributed temperature sensing (FO-DTS) allows for temperature measurements along a fiber optic cable utilizing Raman backscattering (Selker, 2006). A change in intensity occurs when incident light strikes the fiber optic glass wall, which causes Raman backscattering at two frequencies, referred to as Stokes and anti-Stokes. The anti-Stoke intensity is dependent on the ambient temperature where the light is reflected, and thus temperature can be calculated from the ratio of anti-Stokes to Stokes peak intensity (Selker et al., 2006). The error on this technique follows the law of large numbers whereby the noise level of the anti-Stoke intensity is inversely proportional to the sampling interval (Sayde et al., 2010, 2014). The intensity of light follows a Gaussian distribution with its standard deviation inversely proportional to the square root of the intensity (van de Giesen et al., 2012). Temperatures measured using FO-DTS can be used to assess the moisture conditions that exist immediately adjacent to the buried cable (e.g. Briggs et al., 2012).

The active FO-DTS (aFO-DTS) method provides an indirect measure of the soil moisture (volumetric water content, VWC). The approach is based on applying an electrical current across the metal casing of a fiber optic to induce temperature changes in the casing and surrounding medium. By measuring the temperature response, soil moisture can be calculated (see Methods Section). Active FO-DTS methods provide an advantage over point measurement systems for soil moisture, as measurements can be made along the fiber optic cable every 1.0 m or less (depending on the technical capabilities of the system).

The first presentation of the use (with strengths and limitations) of active FO-DTS at an industrial capacity was a field-scale detection of dry, wet, and saturated soil in a landfill liner (Weiss, 2003). This pioneering work suggested that volumetric water content can be inferred from a heated cable using the classical probe method described by Carslaw and Jager (1959). Several publications have since proposed empirically derived calibration curves to infer VWC estimates from the thermal properties of the soil around the cable (e.g. Sayde et al., 2010, Ciocca et al., 2012, Benitez-Buelga et al., 2015). Talon et al. (2013) applied DTS to a mine reclamation soil cover to investigate the spatial and temporal scale of variations within the cover layer and revealed heterogeneity in spatial differences using this technique.

While focused on an applied mine site, results and protocol development have broader applications, particularly for precision and industrial agriculture (e.g. vineyards and crop-fields). The distributed nature of aFO-DTS can allow farmers to observe heterogeneity in precipitation wetting and drying rate patterns in soil at high spatial resolutions, possibly providing them the comprehensive information to adjust crop management at a more localized scale and shorter timescale. To date, there is no peer-reviewed literature detailing the use of aFO-DTS to measure VWC in soils at field scale that we are aware of. We believe the proposed protocol highlighted in this paper has potential to be utilized in other commercial capacities as well as in research focused on recharge, soil science, and other cases with designed and natural surfaces.

The authors previously tested the applicability of active FO-DTS with a lab scale column experiment (see Wu et al., 2020). The lab experiment consisted of a column of screened waste rock (< 10 mm diam.) overlain with a sand layer (< 5 mm diam.) in a 400 litre container. It served as a small-scale experiment for the feasibility of using fiber optic cables to detect changes in VWC in a layered system. The measurement protocol in the experiment inferred VWC at 2 cm vertical resolution through the column and the results correlated closely with point measurements of soil moisture (R^2 of 0.90 and

0.94 for the sand and screened waste rock respectively). Results from this study encouraged the placement of fiber optic cable at field scale capacity.

An experimental waste rock pile was built at the Lac Tio Mine in Eastern Quebec with a cover system that acts as an FCL (Martin et al., 2017). The purpose of the experimental waste rock pile was to evaluate the performance of the FCL in preventing moisture drainage into the waste rock. This paper presents the experimental investigation with key results and discusses the feasibility and accuracy of utilizing active FO-DTS technique to assess the VWC distribution within a constructed waste rock pile. To the knowledge of the authors, it is one of the first attempt to assess in situ water movement into layered waste rock pile.

Study Area and Waste Rock Experimental Pile

The Lac Tio mine is located ~40 km north of Havre-Saint-Pierre, Quebec, Canada. The average local annual air temperature is 1 °C, and the average annual total precipitation is 1007 mm, with 226 cm of snow-water-equivalent (Climate Change Canada, 2019). The open pit mine, which has been operational since the 1950s, extracts a hemo-ilmenite deposit producing iron and titanium. It has generated 72 Mt of low-grade ilmenite and anorthosite waste rock deposited in surface waste rock piles (Martin et al., 2017). Trace sulphides and nickel exist in the ilmenite while the anorthosite is predominantly non-reactive (Plante 2010, 2014, Poaty, 2018). The waste rock effluent pH is near neutral and nickel concentrations are sometimes higher than local regulation criteria indicating the potential for contaminated neutral drainage, CND. Geochemical analyses showed that the oxidation of Lac Tio hemo-ilmenite can result in leaching elemental nickel into the pile effluent (Plante et al., 2014).

Construction of the experimental waste rock pile to investigate the effectiveness of a surface FCL began in 2014 on the Lac Tio mine site (Martin et al., 2017). The experimental waste rock pile is 70 m long, the top of the pile is 10 m wide, and the base of the pile is 35 m wide (**Figure 1**). The top surface of the pile is covered with a 0.85 m thick flow control cover layer (FCL) inclined at 5% to promote lateral drainage. Broda et al. (2014) estimated using unsaturated numerical modelling that a fine-grained FCL layer inclined at 5% could decrease infiltration into the waste rock by up to 90% and divert most of the surface recharge to the edge of the pile. The waste pile is separated into a reactive core containing predominantly hemo-ilmenite and a non-reactive exterior of predominately anorthosite. The 0.85 m FCL is constructed with sand layer overlain by crushed anorthosite. The sand, brought from a nearby quarry in Havre-Saint-Pierre, is a well-graded sand classified as SW-SP according to the Unified Soil Classification System (Bréard Lanoix et al., 2017, 2020). The anorthosite was crushed onsite and has a clean sand (SP-SW) classification (Martin et al., 2017). The porosity, measured with a Troxler 3440 nuclear density probe, is 0.30 in the FCL sand and 0.26 in the crushed anorthosite (Bréard Lanoix et al., 2020). The porosity of the ilmenite and anorthosite waste rock is assumed to be 0.25 (Peregoedova et al., 2013). The saturated hydraulic conductivity measured using double ring infiltrometers is between 2×10^{-6} m/s and 2×10^{-5} m/s for the sand and assumed to be similar for the crushed anorthosite (Bréard Lanoix et al., 2020). More information on the design, construction, and monitoring results of the Tio experimental waste rock pile can be found in Martin et al. (2017), Dimech et al. (2017), Dubuc (2018) and Bréard Lanoix et al. (2020).

Materials & Methods

Active FO-DTS

A total of 1300 m of fiber optic cable was deployed in the FCL (sand and upper crushed waste rock layers) and within the waste rock. The cable, placed 0.5 m above and below the FCL/waste rock interface, is 0.7 cm in thickness. This cable consists of optical fibers encased in a galvanized steel tube surrounded with steel braids and bounded with a polyurethane sheath. It spanned the 70 m length of the pile 8 times (**Figure 2**). The cable was laid 40 cm from the top and bottom of the waste rock and FCL sand layers respectively. The material was compacted around the cable using a vibratory plate compactor. The cable passes through containers with temperature sensors to correct for temperature drifts and to improve precision in the FO-DTS data. The containers are filled with insultation foam and ice water for the warm and cold baths respectively. The containers are repurposed commercial chest freezers, chosen for their large size and insulation. An AP Sensing N4388A GeoDTS was utilized for the active FO-DTS protocol in this experiment. The spatial resolution is 1.0 m, with a sampling interval of 0.5 m, and a minimum dual-ended measurement interval time of 20 s. Raw DTS data was transferred and parsed through a MATLAB function. The function performs a transit correction of the temperature value to the bath temperatures.

Heating of the fiber optic cable was performed with a Control Concepts Fusion SCR power controller which delivered 5.6 kW of power across 537 m of the 1300 m cable buried in the FCL sand cover and waste rock layer. This power supply was chosen for its ability to maintain constant power in response to changing resistance in the cable caused by the heating protocol. A 15 kW Kubota SQ1210 generator supplied power to the controller. This generator has a current rating of 85 A and 45 continuous hour fuel consumption. The protocol applied 7.8 kW - 65 A, 120 V at ambient air temperature to maximize joule heating for power efficiency (see Discussion). This power combination is needed to heat the cable at least 10 °C under saturated conditions for the given length and resistance of the cable. A Raspberry Pi 3 micro-computer controlled an OMRON Electronics G9EA-1-CA-DC12 solid-state relay to cycle the heating protocol of the power controller. The protocol involved a 15-minute heating every hour, with 136 cycles over 6 days. The water infiltration test (see below) started several hours after the first heating cycle.

Soil Moisture Probe

Decagon GS3 VWC dielectric probes (Meter, 2016) collected data concurrently in the FCL and upper waste rock layer (**Figure 1**). The GS3 measures the polarity of the medium induced by a weak charge and measures the dielectric permittivity of the medium (Topp et al., 1980). The volumetric water content (VWC) can then be obtained from the calibration on specific samples (Ullrich and Bechtold, 2018). The probes were placed every 10 m along the length of the pile within the FCL and waste rock. The probes measured volumetric water content in the experimental pile every 15 minutes with Decagon EM50 dataloggers. Precision of the GS3 probes is ± 0,03 (Meter, 2016) and the soil specific calibration was the measured value less 0.16 and 0 for the sand and waste rock respectively (Dubuc, 2018).

Infiltration Test

To better understand water flows in to the FCL and the underlying waste rock pile under heavy precipitation, a water truck with a horizontal spray system was used to apply water onto the surface of the experimental waste rock pile (**Figure 3**). An estimated 17 m^3 of water was applied on the pile over a period of 4 hours to simulate a large precipitation event. Due to the mine site shift schedule, the spraying truck ran for 2 hours and 17 minutes followed by a 48 minute break, before a second run of 57 minutes. Each pass of the truck was driven at 3 to 5-minute intervals to minimize surface runoff. The amount of water applied on the FCL was estimated to 38 mm of total recharge during the course of the 4 hour infiltration test (i.e. 9.5mm/hour). This amount of water is quite typical for a heavy rain event in the Havre-Saint-Pierre region of Quebec.

Inferring VWC from FO-DTS Measurements

Our calculation of soil moisture follows the methodology presented by Wu et al. (2020) in determining VWC from active FO-DTS measurements. By applying electrical current to the cable during a specified period, the VWC of the cable can be inferred from the resulting change in temperature. When a current is applied across the metal casing surrounding the fiber optic cable, the cable heats up during this time period (Sayde et al., 2010) due to the inherent electrical resistance of the cable:

$$T_{cum} = \int_0^{t_0} \Delta T dt \tag{1}$$

where T is the temperature at time t (s), and T_{cum} (°C s) is the cumulative heat up cycle from period 0 to t_0 (s).

Benitez-Buelga et al. (2016) presents a similar method to relate thermal conductivity to change in temperature over time. This approach integrates the natural log time during the heat up period as an algebraic relationship to the thermal conductivity of the medium. The rise in temperature, and therefore, T_{cum} can be expressed as a function of thermal conductivity, which is in part a function of soil moisture (Wu et al., 2020):

$$T_{cum} = \frac{Qt}{4\pi\lambda_k}[ln(t) - 1] + Bt \tag{2}$$

where Q is the source heating strength (W/m), t is the heating pulse duration (s), and λ (W/(m °C)) is the thermal conductivity of the medium, and constant B is the bulk parameter of the soil texture (°C). The thermal conductivity is influenced by the VWC of the material. For example, a dry soil would cause the cable to rise to a higher temperature (compared to a saturated soil) since water has a higher thermal conductivity compared to dry media (800 J/kg °C and 1632 J/kg °C for dry and saturated sand respectively).

Parameter λ_k is the Kersten number (Kersten, 1949; Johansen, 1975; Halloran et al., 2016) normalized to the thermal conductivity of the medium when it is dry λ_{dry} and saturated λ_{sat}:

$$\lambda_k = \frac{\lambda - \lambda_{dry}}{\lambda_{sat} - \lambda_{dry}} \tag{3}$$

It is assumed here that the change in moisture content in the medium is the only cause for the variation in the rate of temperature rise during a heating cycle. If the heat up values are known for the medium under dry and saturated conditions, a numerical or analytical model can be applied to infer the degree of saturation. The Lu et al. (2017) equation was used in this project:

$$S_r = [1 - \frac{ln(\lambda_k)}{\gamma}]^{\frac{1}{\gamma - 1.33}} \tag{4}$$

where γ is a soil texture dependent parameter. The volumetric water content (θ or VWC) can then be calculated from the porosity, n (0.30 and 0.26 for the FCL and waste rock respectively. This equation is applied to each measurement point along the cable.

$$\theta = S_r \times n \tag{5}$$

Results

The four adjacent FO-DTS cables detected similar VWC values along the width of the pile in the FCL sand and waste rock layers during the infiltration period. The measured VWC difference between the four cables in the FCL were small: i.e. maximum difference of the VWC of 0.06, average difference of 0.02. The average VWC of the four cables combined in each layer is represented in **Figure 4**. Each color plot in the figure represents the average VWC each hour since the start of the infiltration test (i.e. the first pass of the watering truck). Distance from the head to the toe of the pile is represented by the y-axis.

Similar values between the four cables in the FCL were expected as the saturated hydraulic conductivity of the crushed anorthosite and sand is close to 10^{-6} m/s (Bréard Lanoix et al., 2020). The estimated time for water to reach the bottom of the FCL is at about 10 hours considering this same value of the saturated vertical hydraulic conductivity for both materials (i.e. 10^{-6} m/s for anorthosite and sand).

The FO-DTS reading indicated that the majority of water appeared in the FCL sand layer approximately 8 hours after the start of the infiltration test (**Figure 4**). Highest VWC values along the cables appears at location between 20 m and 35 m, 8 hours into the test, at variably saturated levels. Drainage into the waste rock during the same period indicated that the vast majority of water flowed sideways, towards the edge of the pile. The average FCL VWC was 0.07 ± 0.01 at the start of the infiltration test, and 0.12 ± 0.06 12 hours after the start of the infiltration test.

The statistical distribution of VWC in the FCL is represented in **Figure 5**. The distribution appears gaussian before the start of the infiltration test (**Figure 5a**). Homogenous VWC was also measured widthwise across the pile (with $P < 0.05$, where P is the calculated probability). This normal distribution indicates that there are minimal differences between VWC across the four cables during pre-infiltration period. The distribution of VWC became negatively skewed twelve hours after infiltration started at t_i (**Figure 5b**). The skewness is also represented in **Figure 6c** where higher VWC exist in the second, third, and fifth quintans at t_i+12h. However, the widthwise distribution of water remains uniform.

Distribution of VWC at select times is shown in **Figure 6**. The average downslope VWC is represented for each FCL and waste rock sublayer. At the start of the infiltration test, t_i, the DTS measures VWC of 0.10 and 0.05 averaged across the length of the pile in the FCL and waste rock layers respectively. Following four hours of artificial infiltration, the VWC in the FCL and waste rock layers increased to 0.11-0.18 and near 0.08 in the waste rock beneath. Eight hours following the beginning of infiltration, the FCL reached near saturation between 20-35 m and 55m downslope. Other areas in the FCL are above 0.20 for the VWC. Volumetric water content in the waste rock peaks at a location near 55 m downslope with increases in VWC also observed between 20-35 m to a lower degree.

The results of the active FO-DTS moisture measurements follow similar temporal patterns and trends as the GS3 moisture probes, but the two systems do not give the same absolute values (**Figure 7**). The grey bar around the GS3 measurement represents the manufacturer calibration precision of ±0.03. The fiber optic measurements overestimate the GS3 probe data in the majority of cases. Exceptions are seen at 25 m downslope and 5 m downslope locations in the FCL and waste rock respectively.

The DTS protocol has longer integration time than the GS3. For example, the rise the VWC is seen earlier in the GS3 than the DTS at 25 m downslope in the FCL (**Figure 7)** due to the higher measurement interval of the GS3 probe. The measurement interval of the GS3 is 5 minutes and it is 15 minutes with the active FO-DTS protocol. The distributed nature of the FO-DTS protocol identifies VWC changes undetectable by the GS3 as shown at 55 m downslope in the waste rock below the FCL. One of the main advantages of the DTS protocol is the continuous representation of the entire measurement area. However, the local precision may not be as accurate as spot measurements such as those with the GS3 probes.

Analysis and Discussion

Assessment of the FCL

The main objective of the experimental pile design with the FCL was to favor horizontal flow towards the toe of the pile. The lateral flow within the FCL is related to the capillary barrier effect at the interface with the coarse waste rock, which induces a retention force wherefore water tends to remain in the overlying sand layer and flow laterally towards the toe of the pile. The degree of saturation in the FCL would naturally be higher downslope, when approaching the toe, with minimal vertical drainage to the waste rock underneath (Fala et al. 2005; Aubertin et al. 2009).

Pre-infiltration test, the FCL was not saturated and had a maximum average VWC of 0.10. The effective of the FCL is dictated by the contrast in grain size and hydraulic properties of the FCL and waste rock (MEND 2004). A dry FCL could also exhibit hydrophobic properties, aiding the diversion capacity of the cover. Infiltration rates may be reduced on order of magnitudes in water repellent soils (Brandt 1969a; Wallis and Horne 1992). Wallis et al. (1991) demonstrated that the hydrologic balance is affected by water repellency of dry soils under heavy rainfall in irrigation systems. The effect of an increased degree of saturation in the FCL would hinder the effectiveness of the cover, however, it could provide a more natural initial condition for the experiment. The initial VWC at the start of the experiment was not controlled as part the experiment design, rather as a result of precipitation event weeks prior to the test.

The VWC was measured using active FO-DTS in the FCL and waste rock prior to, during, and after the 4-hour water infiltration test. Temperature was measured every 0.5 m across the four cable lanes along the pile in the sand layer and waste rock below, for a total of 968 spatial-distributed measurement points. The point density is thus one measurement per 1.25 m^2 along the surface of the experimental pile.

A gradual increase of VWC from the head downslope towards the toe of the pile was expected based on numerical simulations (e.g. Fala et al. 2005; Broda et al. 2014). The highest VWC in the FCL was measured near the middle (second and third quintans of the pile (**Figure 6c**). The water retained in this area of the FCL does not appear to drain into the waste rock below, with a VWC remaining near 0.11 in the waste rock, with exception of the fifth quintan where the VWC exceeds 0.15. Water thus appears to be held in FCL by capillary forces with some moving laterally towards the toe of the pile where it accumulates and drains into the waste rock (as indicated by the low VWC in the first 4 quintans below the FCL)

The limited downslope variability of moisture content in the FCL sand uphill of the fifth quintan appears to be related, at least in part, to its higher than anticipated density (due to heavy compaction), which reduced hydraulic conductivity and increased the VWC by capillary retention (before and during the infiltration test). The FCL allowed some lateral drainage during the infiltration test but held water strongly, as shown by the relatively large VWC, which did not flow laterally as quickly as expected towards the toe of the pile despite the inclined angle of the layer (compared with the preliminary simulation results of Broda et al. 2014, conducted before the pile construction). A more rapid and efficient drainage in the sand layer would have resulted in the upper and core sections of the FCL to be at lower VWC than near the toe. Both the active FO-DTS protocol and GS3 soil moisture probes results confirm that this did not occur as well as initially planned (**Figure 4**). The post-infiltration field measurements shown in **Figure 6c** indicates that a higher quantity of water moved and was stored downslope, near the longitudinal center of the pile. Thus, the FCL had a shorter diversion length than expected for this artificial precipitation event, due to the in-situ material properties that differed somewhat from the original design.

Strong crosswind during the infiltration test may also have played a role by angling some of the sprayed water towards a side of the pile, as shown in the darker coloration of the sand ramp (**Figure 3**). Despite the crosswind and some localized surface ponding near the side of the pile, the similarity of the data between the four cables over the entire pile surface suggest that this factor didn't influence significantly the horizontal spread of water which appears evenly distributed across the FCL width when it reaches the FO-DTS cables at the bottom of the FCL.

Assessment of Active FO-DTS Data

Active FO-DTS measurements gave higher VWC values compared with the moisture probes at the field site. The difference in the VWC values obtained from active FO-DTS was more pronounced in the FCL than in the waste rock of the pile. Both types of VWC values generally follow the same trend in the FCL, but the GS3 moisture probes did not detect VWC changes in the waste rock (see **Figure 7**, 55 m downslope). This is likely caused by the finer sampling interval of the FO-DTS at every 0.5 m against the very small scale (local) measurements used to represent the VWC at 10 m sampling interval with the GS3 layout. In addition, the GS3 probes are influenced by many factors, such as mineralogy, electric conductivity of the water, and contact between the soil and the probe (Son et al. 2017). As the volume of measurement of this probe is small, large particles (and pores) near the probe could affect significantly the output.

The active FO-DTS results have lower temporal resolution than the GS3 probe measurements (1 hour versus 10 minutes respectively). However, the active FO-DTS measurements can resolve finer spatial changes in VWC than the GS3 moisture sensors at a distributed scale, but at the expense of noisier results. For example, at the field experimental site, there were 30 GS3 probes installed in the FCL compared to 480 measurement locations for the active FO-DTS in the same unit. Nonetheless, the active FO-DTS protocol can detect drainage into the waste rock pile at the toe of the pile, at the resolution applied in the experiment.

The GS3 probe values in the FCL used in this experiment were corrected to values obtained with a nucleodensimeter (Bréard Lanoix, 2017, Dubuc, 2018). The nucleodensimeter is an industry standard device that uses gamma rays for precise in-situ VWC measurement in field settings (Susha Lekshmi et al., 2014). The nucleodensimeter was used adjacent to one GS3 probe, and the difference in values between the two probes, a soil moisture of 0.16, was then applied to all the GS3 values from the FCL (Dubuc, 2018). Nucleodensimeter tests could not be completed in the buried waste rock layer.

In-situ moisture probes are prone to measurement challenges. Due to the heterogeneity and range of pore sizes in a waste rock pile, the accuracy of moisture measurements must be interpreted with care. The FO-DTS measurements resolve VWC from the degree of saturation (see Equation 5), as a function of porosity. For both the FO-DTS and GS3 moisture probe results, porosity becomes a constraint for accurate measurements. The comparison of water content between the FO-DTS and the GS3 moisture probes is thus dependent on the accuracy of the (average) porosity determination. The sand layer (FCL) is well compacted along the fiber optic cable, although the presence of flowing water and the active heating protocol may disrupt soil pore structure and contact resistance to the cable (Sourbeer and Loheide, 2015). This loss of compaction may grow over several freeze and thaw cycles, thus could disrupt the average porosity along the cable. Compactness to the cable may interfere with accurate calculations of VWC during the heating protocol as well.

The waste rock below the FCL is more heterogeneous than the sand layer due to the coarse particles and cobles. Such coarse-grained material has a lower water retention capacity (i.e lower moisture contents), and the accuracy of the FO-DTS measurement can be comparable to the GS3 in the waste rock (**Figure 7)** with an advantage to the former with a highly distributed sensing network. This accuracy decreases at higher moisture contents (Wu et al., 2020), but the waste rock with its relatively large pore spaces allow VWC to remain low during the infiltration test.

Protocol improvements

Future work should be conducted to revise power inputs to improve the signal to noise ratio in active FO-DTS results, improve data interpretation, and allow the implementation to be more economical. The active FO-DTS measurements required line or generated power to the cable to perform measurements. A 15kW generator was used to apply 15 W/m to 537 m of cable. The generator needed to be refueled every two to three days. The cost associated with line electric power or generator fuel may be a limiting for some operations. Therefore, the electrical resistance of the fiber optic cable metal must be taken into account to minimize the energy required to run the FO-DTS protocol. Although a

15kW generator was needed, only 7.8 kW of power was used in the protocol. This discrepancy is explained by the need for nearly 65 A to achieve adequate heating due to the length and resistance of the cable.

An efficient FO-DTS protocol maximizes joule heating for the given resistance and length of cable in a project. Heat is produced in a metal conductor proportional to the square of the current multiplied by the resistance Joule (1843). Therefore, amperage and cable resistance may be a more comprehensive indicator of active FO-DTS protocol. A higher gauge cable can joule heat more efficiently than a thicker gauge cable with the same voltage rating. The length of the cable must be taken into account as resistance it is proportional to length.

The GS3 sensors provided difficult readings in the waste rock because the capacitance of crushed ilmenite was similar to water (~80 at 20 °C) (Topp et al., 1980). This similarity in values requires more work to interpret the GS3 results (Martin et al., 2019). In normal operations, the GS3 assumes there is a large contrast between the dielectric permittivity of the soil (~10) and the water (~80).

Assuming the corrected GS3 values accurately replicate the actual VWC values in the FCL, the active FO-DTS results have a higher volumetric VWC at all locations. The average active FO-DTS value at all FCL locations is ± 0.06 greater than the average GS3 values, averaged over all time steps in the FCL (Figure 7). The VWC given by the FO-DTS cables in the waste rock layer are all within the accuracy margins of the GS3 measurements (± 0.03).

A higher resolution FO-DTS can improve the ratio and can be more cost effective for large scale operations. Installing fiber optical cables to better match the heating strategy for the given environment and cable length would also improve the signal to noise ratio and reduce costs. We suggest a 10-15°C change in temperature in near saturated conditions to be optimal for modern DTS units. A lower wattage and cheaper power supply can produce similar heating requirements if an adequately resistive fiber optic cable is installed to maximize joule heating. If these systems are concurrently optimized, FO-DTS can serve as a useful standalone tool to monitor VWC in waste rock material in full scale waste rock pile.

Conclusion

The application of active FO-DTS to monitor an experimental waste rock pile shows that an FCL can limit infiltration by storing water and diverting part of this moisture along the FCL and towards the toe of the waste rock pile. The layered cover system induced a capillary barrier effect along the inclined 5% interface and prevented the vertical drainage of water into the waste rock layer. A portion of the water retained in the inclined FCL flowed laterally towards the end of the pile, as expected, and drained down the toe of the waste rock pile. The active FO-DTS protocol measured VWC in a large volume of the waste rock pile and was able to show the diversion capacity of the FCL after an artificial wetting event. VWC assessed during 15-minute heat cycles at 15 W/m every half hour show that water remained confined to the FCL. These results indicated that FO-DTS is practical to monitor moisture changes in waste rock and in a cover layer.

Active FO-DTS is a new potential tool for measuring distributed moisture at the scale of field sites. This study in a constructed environment demonstrates that the technique can be used to measure VWC and unsaturated water movement in mine waste rock and in a sandy soil. The active FO-DTS system can infer VWC comparable to that of GS3 moisture probe values, but heating profiles (along with fiber optic cable properties) could be further optimized to reduce the signal to noise ratio.

The field experiment presented here demonstrates the potential utility in using distributed soil moisture measurements to evaluate the effectiveness of an engineered geotechnical system, such as a waste rock cover system. The results also indicate that careful selection of material (e.g. hydrological properties) is essential for an effective cover layer. By using a system such as active FO-DTS, that is built into the design and installed during construction, we were able to monitor how the system worked post-construction. The field data is now being used to assess if the FCL had the optimum inclination, was made with appropriate materials, and created the required hydrologic contrast between the FCL and waste rock below. This type of monitoring system can be particularly useful for large scale events that may lead to localized processes within the cover system, which might not be identified by a few discrete soil moisture probes.

This paper has thus shown that single source active FO-DTS measurements can capture changes in soil moisture in a field setting. A fiber optic cable can be cost effective and efficient in making distributed VWC measurements in coarse and low thermally conductive soils over a large spatial context. Active FO-DTS has the potential to be utilized in additional industrial applications.

Areas of high-water content in landfills and precision agriculture sites where infiltration is a potential concern are other potential subsurface applications of the technique. Particularly for precision agriculture, good agricultural yields, especially in irrigated areas, is limited by soil moisture and its availability for crops. VWC measurements for irrigation management are commonly obtained from point sensors. Although work in literature has tried proper sensor placement techniques (Dabach et al., 2015), progress for VWC spatial variability and its associated impact on VWC distribution has been minimal. Fiber optic cables provide large amounts of data with high spatial and temporal resolution and can fill the gap of point moisture sensors by monitoring vadose zone hydrology for agricultural yield frameworks. The low temperature rise in aFO-DTS monitoring provides minimal disruption to the medium and allows VWC capture several times per hour, at high spatial resolution which is beneficial to both short- and long-term monitoring.

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Figure 1: a) Photograph of the experimental wasterock pile at the Tio Mine. b) Longitudinal cross-section of the experimental waste rock pile showing the design of the flow control layer, the location of the fiber optic cable used to measure moisture content, and the waste rock below the FCL.

Figure 2: Transverse map sectional view of the fiber optic cable distribution within the experimental setup. The sand (Flow Control) layer lies directly above the waste rock.

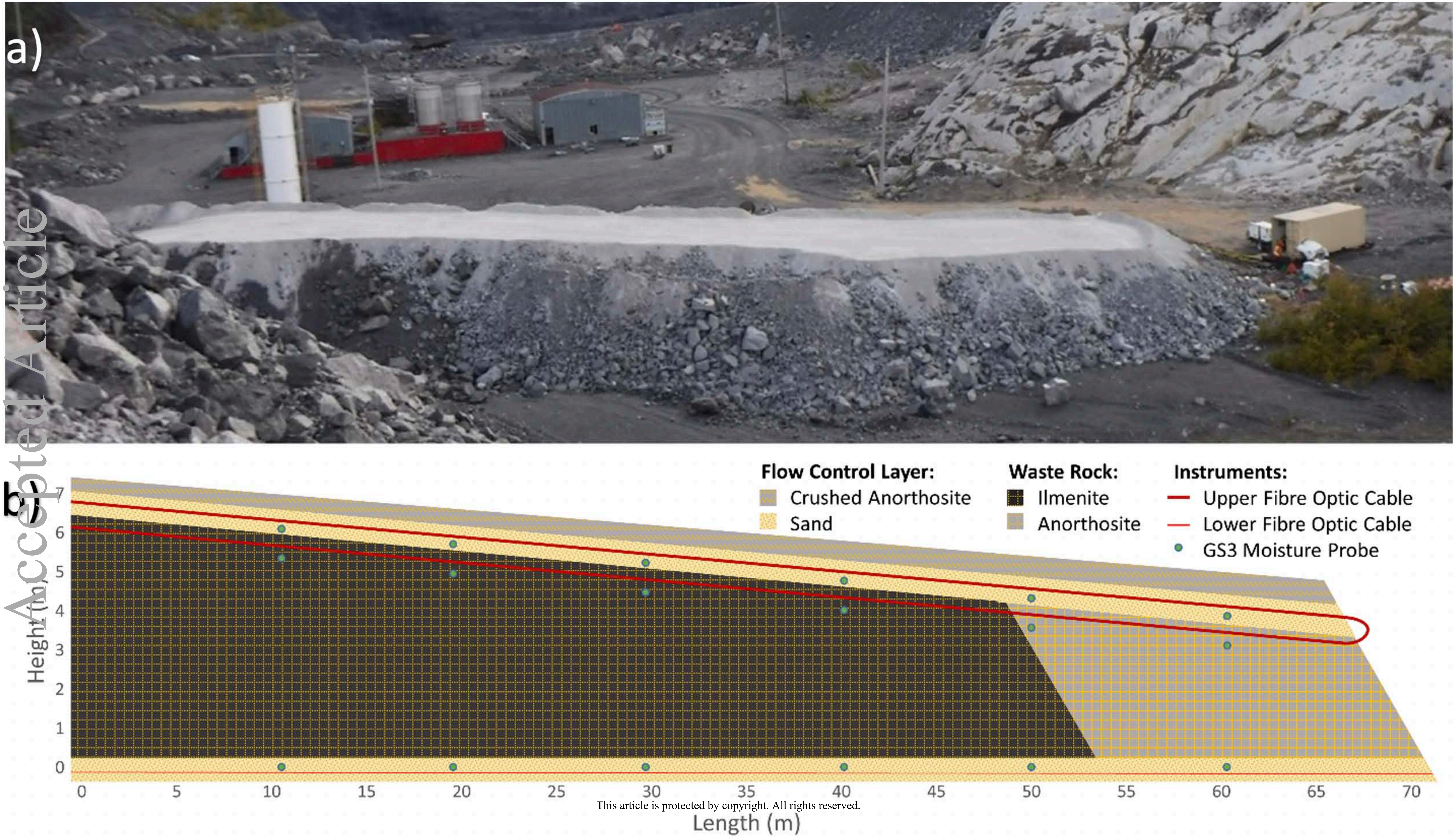
Figure 3: Artificial precipitation was applied with a water truck to simulate short duration, large volume precipitation events.

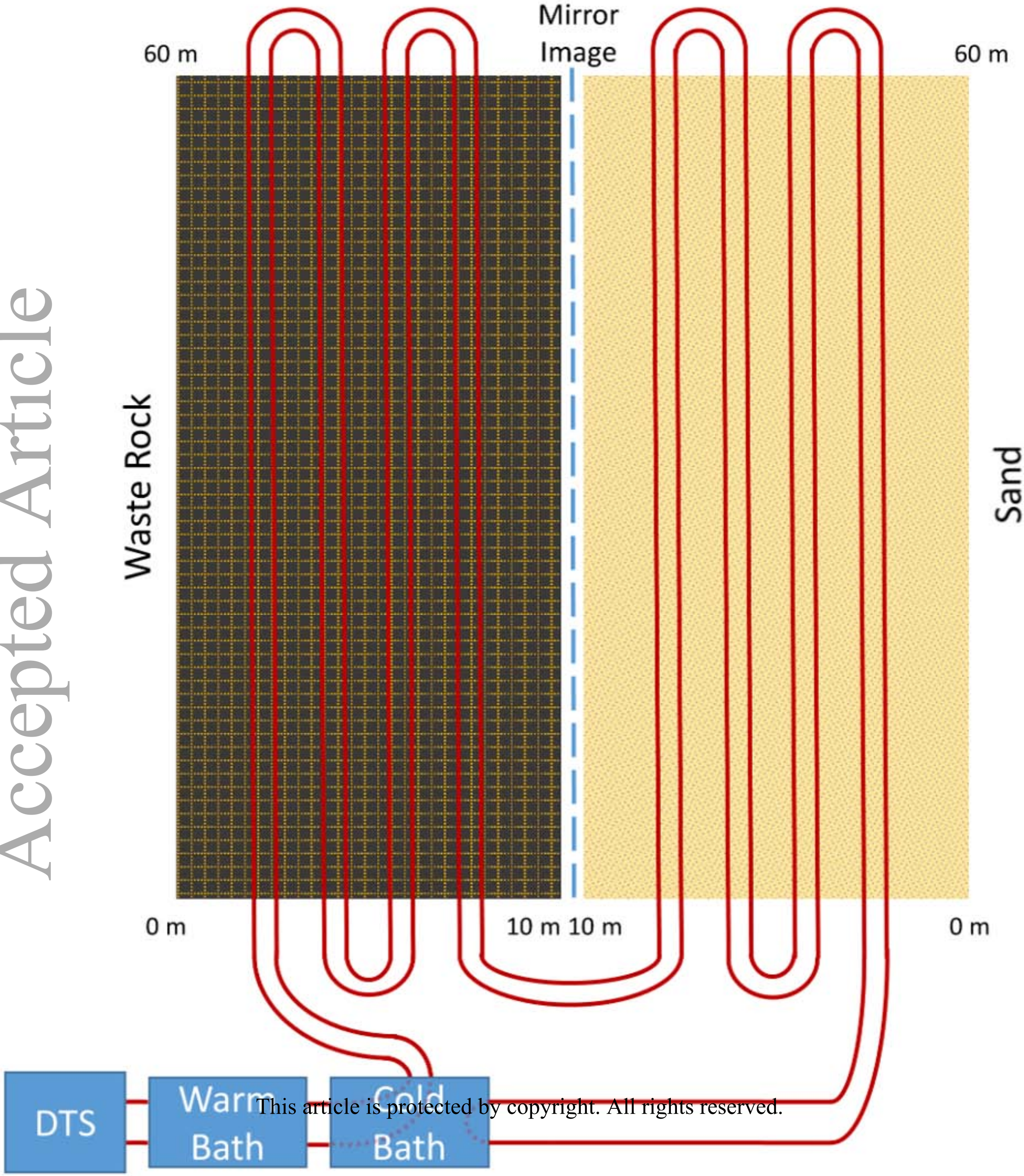
Figure 4: Volumetric water content in the Flow Control (sand) Layer and waste rock underneath after the start of the infiltration test; the values are averaged from the four adjacent pairs of cable. The longitudinal dimension of the experimental waste rock pile is represented on the y-axis.

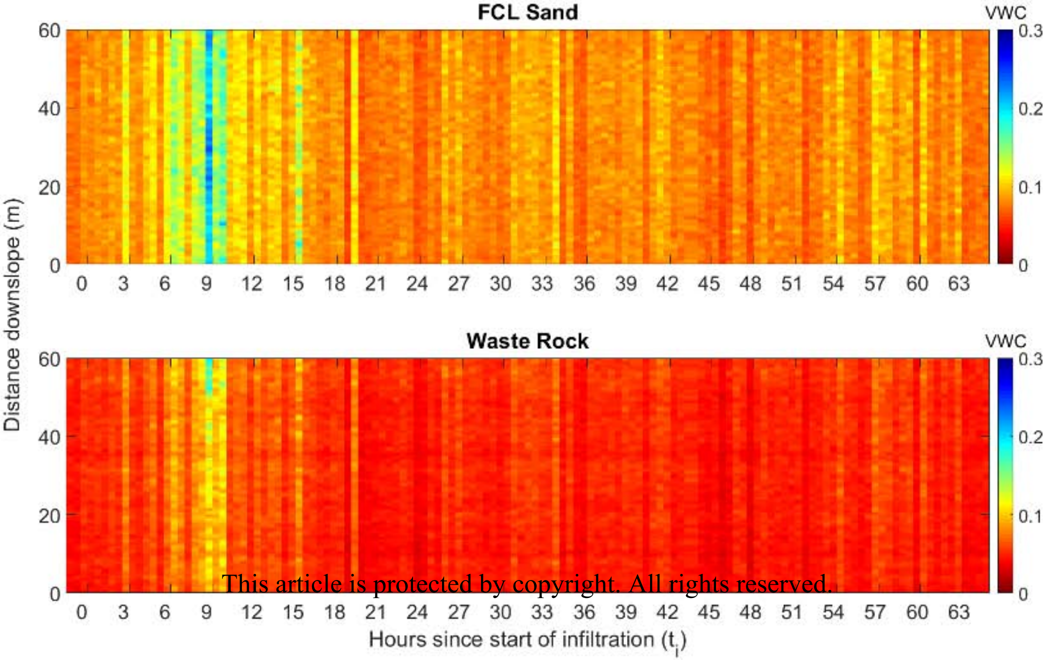
Figure 5: Distribution of volumetric water content in the flow control (sand) layer before (pre-) and after (post-) the infiltration test.

Figure 6: Volumetric water content prior to, and after 4, 8, and, 12 hours after the infiltration test has started, separated into 5 quintans.

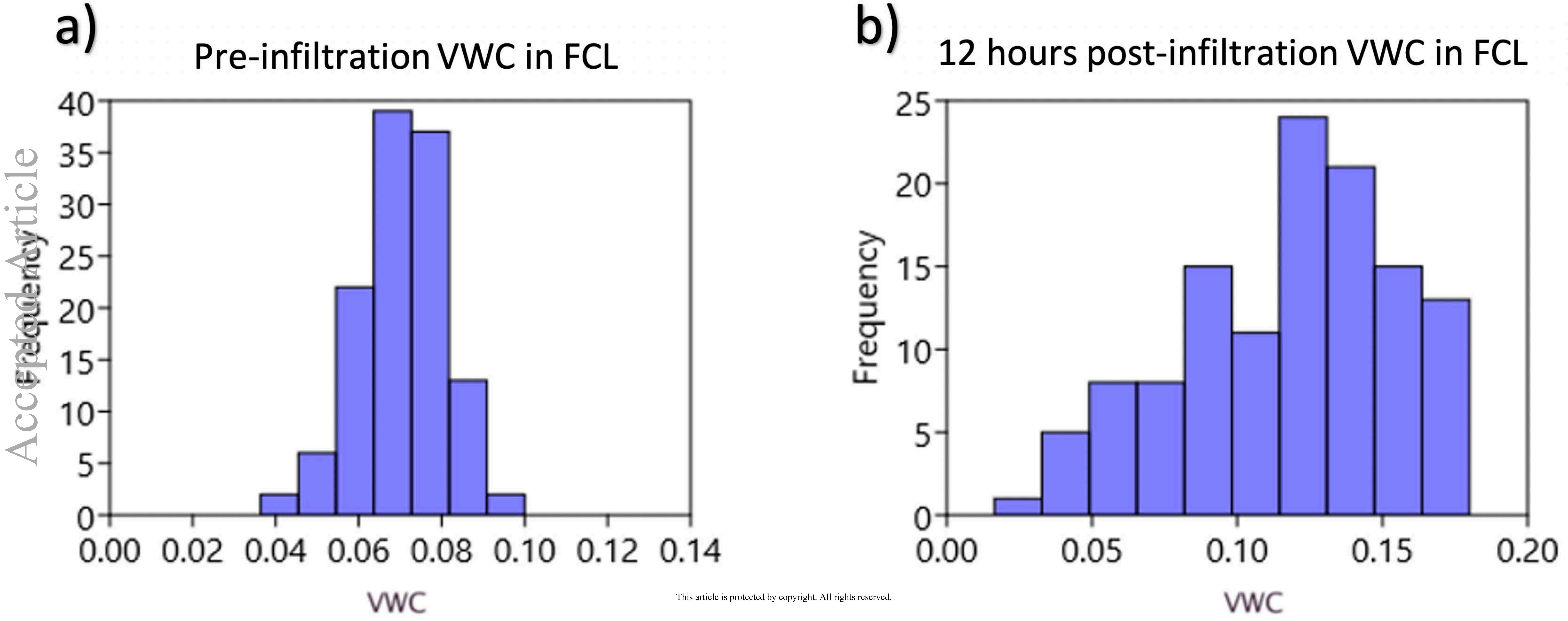
Figure 7: Comparison of volumetric water content measured by the active distribute temperature sensing and the GS3 moisture probes in the Flow Control (sand) Layer and the waste rock underneath, at different distances along the pile. The grey bar represents the manufacturer stated accuracy of ± 0.03.

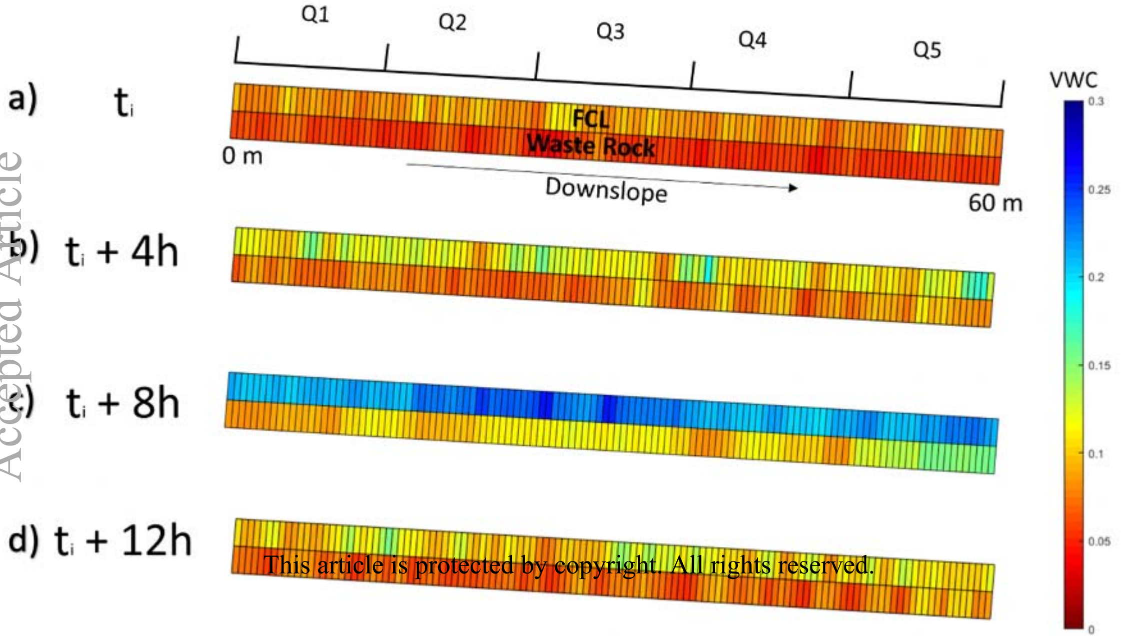

a)
b)
Flow Control Layer:
Crushed Anorthosite
Sand
Waste Rock:
Ilmenite
Anorthosite
Instruments:
Upper Fibre Optic Cable
Lower Fibre Optic Cable
GS3 Moisture Probe
Height (m)
Length (m)
0
1
2
3
4
5
6
7
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70

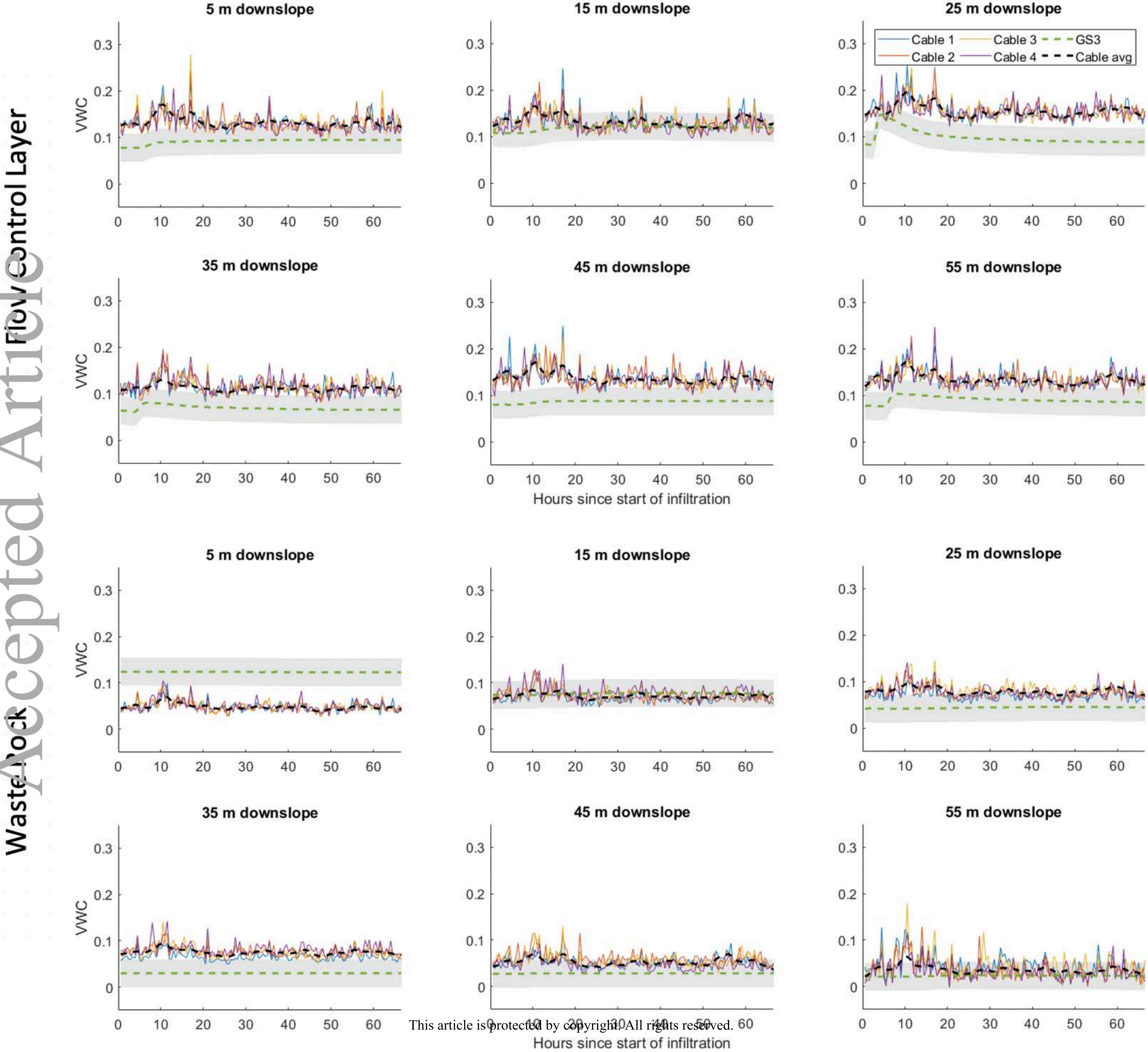

Mirror
Image
60 m
60 m
Waste Rock
Sand
0 m
10 m
10 m
0 m
DTS
Warm
Bath
Cold
Bath



FCL Sand
Waste Rock
VWC
0.3
0.2
0.1
0
60
40
20
0
0 3 6 9 12 15 18 21 24 27 30 33 36 39 42 45 48 51 54 57 60 63
Distance downslope (m)
Hours since start of infiltration (t_i)


a)
Pre-infiltration VWC in FCL
Frequency
40
35
30
25
20
15
10
5
0
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
VWC
b)
12 hours post-infiltration VWC in FCL
Frequency
25
20
15
10
5
0
0.00
0.05
0.10
0.15
0.20
VWC


Q1
Q2
Q3
Q4
Q5
a)
tᵢ
FCL
Waste Rock
0 m
Downslope
60 m
b) tᵢ + 4h
c) tᵢ + 8h
d) tᵢ + 12h
VWC
0.3
0.25
0.2
0.15
0.1
0.05
0


Flow Control Layer
Waste Rock
5 m downslope
15 m downslope
25 m downslope
35 m downslope
45 m downslope
55 m downslope
VWC
Hours since start of infiltration
Cable 1
Cable 2
Cable 3
Cable 4
GS3
Cable avg