3D TIME-LAPSE GEOELECTRICAL MONITORING OF MOISTURE CONTENT IN AN EXPERIMENTAL WASTE ROCK PILE: VALIDATION USING HYDROGEOLOGICAL DATA

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Abstract

The hydrogeological behavior of heterogeneous and unsaturated media can be challenging to assess, especially where classical hydrogeological instrumentation cannot be directly installed - such as in the core of waste rock piles. In this paper, the authors present the results of several 3D Electrical Resistivity Tomography surveys carried out in 2017 for time-lapse monitoring of water infiltration events in an experimental waste rock pile. This pile was built according to a recently proposed waste rock disposal method at the Lac Tio mine (RTFT, Québec, CA) that aims at diverting water flow from potentially reactive waste rock, thus limiting metal leaching and contamination of the effluent.

The pile has been instrumented with soil moisture sensors and lysimeters to monitor water content over time and collect percolating water. In addition, 192 buried electrodes have been used to carry hourly measurements with an optimized protocol of 1000 configurations uploaded on a Terrameter LS (ABEM) to monitor internal flow of water sprinkled on the top of the pile with a water truck. Time-lapse 3D ERT data were inverted to yield the 3D model of soil electrical resistivity over time before, during and after induced infiltration events in the pile.

While resistivity results show consistent variations associated with increased moisture content, conversion of resistivity into volumetric water content is not straightforward. This challenge is related, in part, to changes in the distribution of water resistivity over time in the pile, which in turn strongly affects resistivity within the waste rock. Laboratory column measurements have been conducted to assess the relationship between global (waste rock) resistivity, water resistivity and moisture content for samples from the pile. The images of water content obtained with ERT are then validated with hydrogeological measurements and modeling of the pile. This assessment indicates that geoelectrical monitoring is an efficient tool to monitor water moisture in a complex media.

Introduction

A pilot-scale experimental waste rock pile was built at the hemo-ilmenite Lac Tio mine (Rio Tinto Fer et Titane, QC, Canada) to test the hydrogeological behavior of inclined capillary barriers. The upper part of the waste rock pile is made of a flow control layer (FCL) composed of relatively fine grained and compacted materials placed above the coarse non-economic ilmenite (reactive) and anorthosite (less reactive) waste rocks. The capillary barrier effect due to the contrast of grain size along the inclined interface should divert water from the core of the pile and help prevent potential generation of contaminated drainage (Aubertin et al., 2013; Plante et al., 2014; Bussière et al., 2015; Bréard-Lanoix et al., 2017 and Martin et al., 2017).

Classical hydrogeological instrumentation such as moisture content and suction probes is used to monitor the hydrogeological state of the pile at specific locations in the pile (Dubuc et al., 2017). Lysimeters and flowmeters measure exfiltration flows and allow geochemical analyses of the leachates (Poaty, 2019). In addition, innovative geophysical instrumentation is used to provide complementary information with a 1000 m-long fiber optic cable measuring distributed temperature (Wu, 2020) and 192 electrodes which allow 3D time-lapse geoelectrical monitoring of the pile (Dimech et al., 2017). Combination of these different techniques is expected to provide a global understanding of the hydrogeological behavior of the pile.

Electrical resistivity tomography (ERT) is a proven technique to efficiently reconstruct the internal geometry of mine waste rock piles (Campos et al., 2003; Poisson et al., 2009; Anterrieu et al., 2010 and Chouteau et al., 2010). In addition, as the electrical resistivity of porous media depends on moisture content and water electrical resistivity, geoelectrical monitoring is useful to image volume and quality of subsurface water flows for various applications (Loke et al., 2013; Chambers et al., 2014; Kuras et al., 2009, 2016 and Hübner et al., 2017). Hence, a 3D time-lapse geoelectrical monitoring was performed to image water infiltration into the experimental waste rock pile before, during and after an artificial rainfall.

This paper presents some results of the hydrogeophysical monitoring carried out in 2017. It focuses on the methodology followed to reconstruct 3D moisture content distribution from 3D time-lapse electrical resistivity of the waste rock. Laboratory measurements were carried out with samples from the experimental waste rock pile to determine relevant petrophysical relationships. Moisture content distributions are then compared with local measurements to help validate the hydrogeophysical approach.

Experimental site description

The 60 m-long, 7 m-high, 10 m-wide (top) experimental waste rock pile built at the Lac Tio mine consists of non-economic ilmenite ore with less than 76 % of minerals content. The sulfides in these waste rocks can be oxidized by water and air (Plante et al., 2014), which could lead to water contamination (essentially by Ni). The approach tested consists in limiting water infiltration in the core of the pile using the capillary barrier effect developed at the base of a 1 m-thick flow control layer (FCL) of relatively fine-grained sand and non-reactive waste rock (anorthosite). This FCL has been placed upon the coarse ilmenite waste rocks as shown in **Figure 1**. The FCL has a slope of 5 % to favor lateral diversion of the precipitation water toward the downslope limit of the pile, which is composed of coarse non-reactive anorthosite waste rock. This design has been validated numerically and with laboratory analyses and is currently tested under field conditions (Fala et al., 2003, 2005; Broda et al. 2014 and Bréard-Lanoix, 2017).

Hydrogeological instrumentation provides local measurements of temperature, moisture content, and suction in the FCL, below the capillary barrier in the coarse waste rocks and at the bottom of the pile (GS3, Decagon, 2016 and MPS-2, Decagon, 2017). Six 10 m × 10 m lysimeters collect percolation water and allow both flow measurement and geochemical analyses of the leachates. Hydrogeological instrumentation can be precise but only provides localized measurements, so the investigated volume can be non-representative of the surrounding medium, especially in heterogeneous materials such as mine waste rocks. To help overcome this limitation, 192 circular electrodes, buried in the FCL and at the base of the pile, allow 3D monitoring of the resistivity in the whole pile over time (Dimech et al., 2017).

Measurements presented here have been recorded over 10 days in June 2017 to reconstruct the hydrogeological state of the pile before, during and after an induced precipitation event of approximatively 50 mm in 10 hours applied using a water truck (Dubuc et al., 2017). A specific acquisition system was designed and optimized measurement protocols were defined for quick, complete and efficient geoelectrical monitoring of the pile (as described in Dimech et al., 2017).

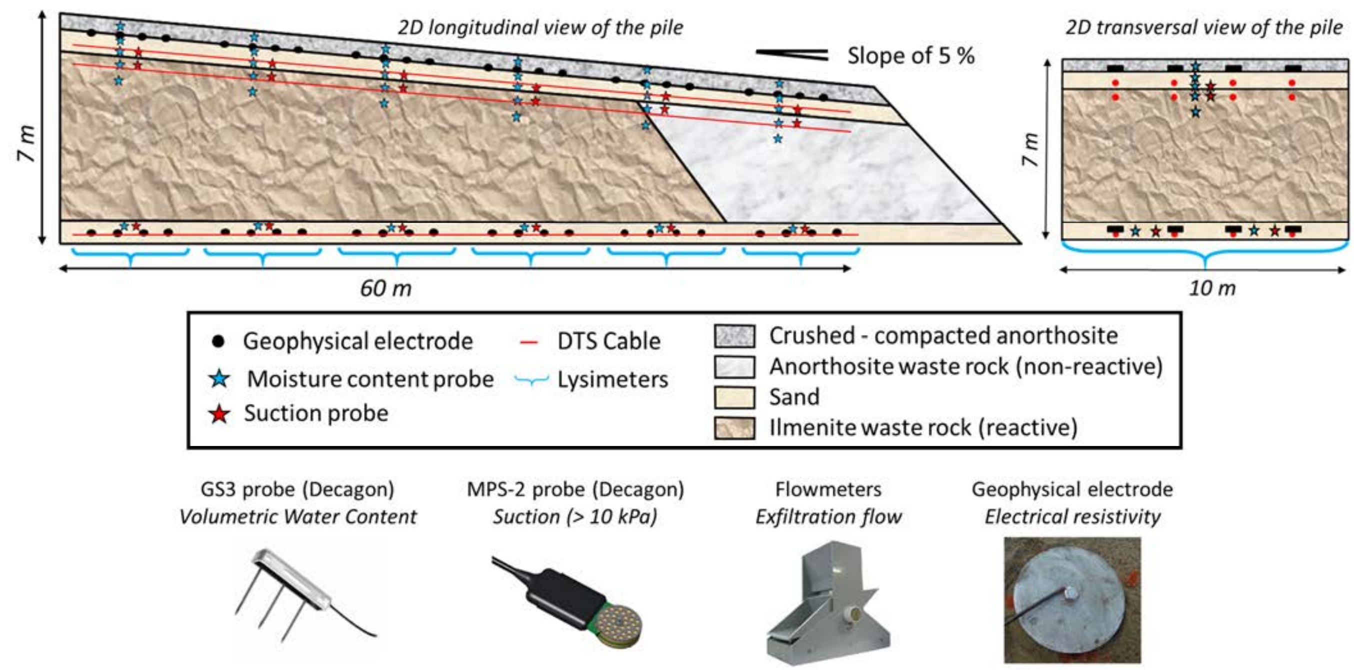

Figure 1: 2D longitudinal and transversal sections of the experimental waste rock pile showing the internal structure and the instrumentation (hydrogeological and geophysical). Adapted from Dimech et al. (2017).

Methodology

Time-lapse geoelectrical monitoring of the pile

3D time-lapse geoelectrical database is processed to generate a set of instantaneous images of the distribution of electrical resistivity in the pile with a temporal resolution of 1 hour during 10 days. This database is inverted using E4D (Johnson et al., 2010) to yield the 3D model of electrical resistivity over time. **Figure 2** presents the numerical 3D model of the pile constructed from both external and internal surveys during the pile construction (Dimech et al., 2017). A photograph of the site is also shown to compare the 400 000 elements model with the actual pile geometry. The internal mesh follows actual interfaces with sharp boundaries, for instance between the FCL (grey anorthosite and yellow sand) and the coarse ilmenite (brown) with different electrical properties (**Figure 2b**). Both spatial and temporal smoothings are applied for the inversion process, and final time-lapse images have a mean RMS value of 2.5 %. 3D time-lapse inversion results are then exported as Matlab files and post-processing is performed to recover the 3D moisture content distribution over time. These final images are finally compared with local hydrogeological measurements from the GS3 probes to assess the validity of the hydrogeophysical method, and to evaluate the heterogeneity of the FCL and the representativeness of local hydrogeological measurements.

Column measurements and petrophysical relationships

Archie's law is the most commonly used petrophysical law to estimate volumetric moisture content from resistivity measurements. However, this empirical law does not directly apply for conductive matrices such as ilmenite-rich rocks where Archie parameters can be difficult to assess. As a result, some laboratory column measurements were carried out with samples from the experimental waste rock pile (sand, crushed anorthosite and ilmenite). The methodology presented in Intissar (2009) was extended with a new protocol to assess the relationship between global resistivity, water resistivity and moisture content.

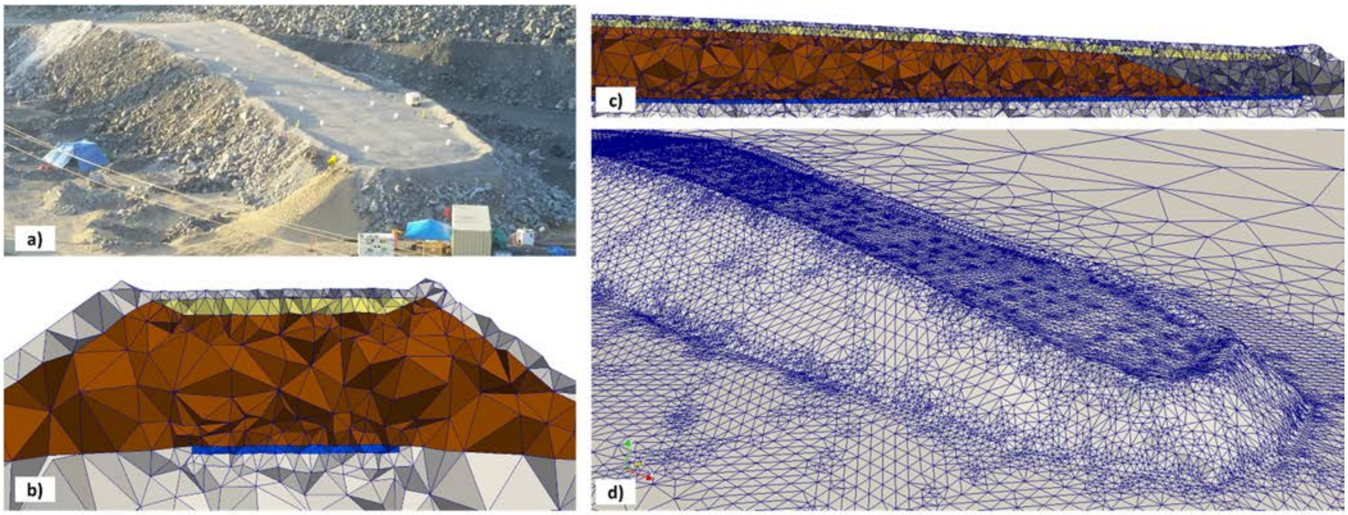

Figure 2: a) Photograph of the experimental waste rock pile. b) & c) Transversal and longitudinal views of the pile 3D meshing with 400 000 tetrahedron elements. Internal structure of the pile from survey points is visible. d) Surface topography of the pile meshing is similar to the actual one.

Figure 3a shows the laboratory column designed to establish petrophysical relationships for the waste rock. 32 electrodes are connected to the Terrameter LS via a specific connection box (see Dimech et al. (2017) for more details); an optimized protocol monitors instantaneously the electrical resistivity in the column. Some inversions were carried out to reconstruct the 3D electrical resistivity distribution to evaluate the heterogeneity within the column, as shown on **Figure 3b**. Apparent resistivities at different heights in the column were used to evaluate a mean value for the material electrical resistivity inside the column.

The experimental protocol consists in evaluating the influence of both water electrical resistivity and volumetric moisture content on the global electrical resistivity. The column was filled with waste rocks and electrolytes with different conductivities were used to saturate the column from the top. Once the waste rock specimen was saturated, a mean value for global resistivity was measured. The column was then desaturated by opening the tap at the base, while the exfiltration flow rate and water resistivity were continuously monitored. 3D ERT measurements were also carried out to estimate different global resistivity values associated with different moisture contents in the column.

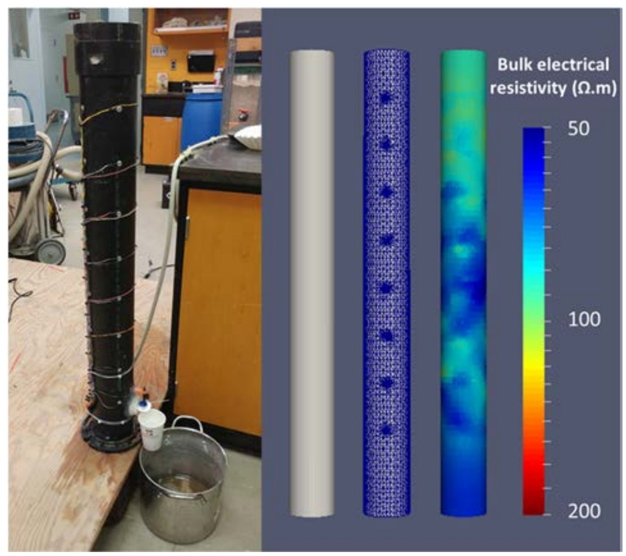

Figure 3: a) Photograph of the column with 32 electrodes used to assess petrophysical characteristics of waste rock. b) Visualization of the 3D numerical model for the column and 3D resistivity distribution for ilmenite specimen.

Table 1: Some physical properties for the rock samples in the laboratory column

Properties	Sand	Anor.	Ilmen.
Wet bulk density d (-)	1.8	1.7	3.2
Solid grain density d_s (-)	2.5	2.4	5.6
Moisture content VWC (%)	21.9	9.6	28.3
Porosity ϕ (%)	36.3	34.9	48.0
Degree of saturation S_r (%)	60.2	27.5	58.9

Results

Petrophysical relationship for each type of rock sample

Table 1 presents some physical properties of the laboratory columns filled by the waste rock specimen where d and d_s are respectively the wet bulk density and the solid grains density (-), VWC is the volumetric water content at rest (%) and ϕ and S_r are respectively the porosity and the degree of saturation (%). Porosity values are relatively high compared to in-situ typical measurements, which indicates that the waste rock in the columns has not been compacted enough (this was necessary to avoid damaging the column). The density values are nonetheless consistent with the results of previous laboratory studies (e.g. Intissar, 2009 and Peregoedova et al., 2013). Laboratory column tests results are detailed in **Figure 4**. These illustrate the impact of both water electrical resistivity and volumetric water content on global electrical resistivity for the column with crushed anorthosite. **Figure 4a** presents global electrical measurements for different water resistivity values (black triangles) for a completely saturated column (VWC = ϕ = 35 %, see **Table 1**). **Figure 4b** shows the different values of electrical resistivities measured as the water was flowing out of the column (with ρ_w = 31 Ω·m). These two graphs were used to assess the petrophysical relationship presented on **Figure 5a** for anorthosite. A similar protocol was followed to recover petrophysical relationships for sand and ilmenite, as shown on **Figure 5b,c**. The petrophysical relationships obtained from laboratory column measurements are consistent with the theory described in Attia et al. (2008). As anorthosite and sand grains are resistive, no surface conduction is observed for water resistivity values comprised between 1 Ω·m and 200 Ω·m. This indicates that Archie's law would be directly applicable for these materials. As ilmenite grains are conductive, both grain conduction and surface conduction occur with resistive water (ρ_w > 100 Ω·m), which means that a correction is required for Archie's law to take into account the grain conduction in ilmenite.

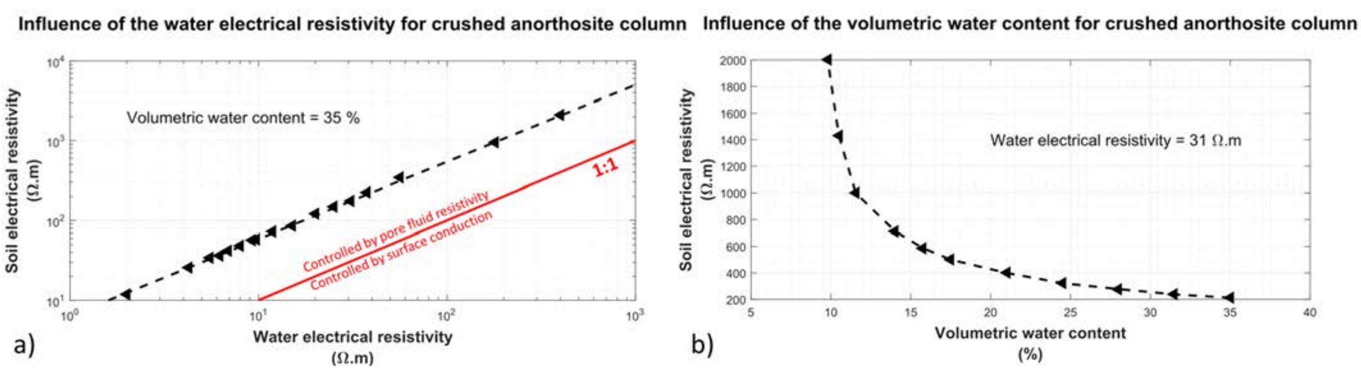

Figure 4: a) Influence of the water electrical resistivity and b) of the volumetric water content on the global electrical resistivity values for the crushed anorthosite in the column.

3D time-lapse resistivity distribution

3D time-lapse inversion results are shown in **Figure 6** for a longitudinal section of the experimental waste rock pile. The infiltration event occurred at t = 0 h. Global resistivity values before water infiltration are consistent with results presented in Chouteau et al. (2010) and Dimech et al. (2017). The FCL layer, composed of crushed anorthosite over compacted sand, shows resistivity values ranging from 1000 Ω·m to 5000 Ω·m; the ilmenite waste rocks are fairly conductive with resistivity values ranging from 20 Ω·m to 1000 Ω·m; the coarse anorthosite part of the pile is highly resistive with resistivity values higher than 15000 Ω·m. The water sprinkled on the top of the pile for the infiltration test was highly conductive ($\rho_w \approx$ 10 Ω·m). As a result, the FCL layer has become more conductive after this infiltration test as shown in **Figure 6**, especially downslope of the pile where resistivity values have dropped from 5000 Ω·m to about 300 Ω·m after 15 hours. In the meantime, the core of the pile has become more resistive, which was somewhat unexpected. This increase of global resistivity values from 200 Ω·m to almost 1000 Ω·m is attributed to an increase of the electrical resistivity of the water measured by the GS3 probes in the ilmenite waste rock. These results illustrate the need for a better understanding of the water electrical resistivity variations in the pile over time as well as the need for a better integration of the petrophysical relationship between global and water electrical resistivity and volumetric moisture content.

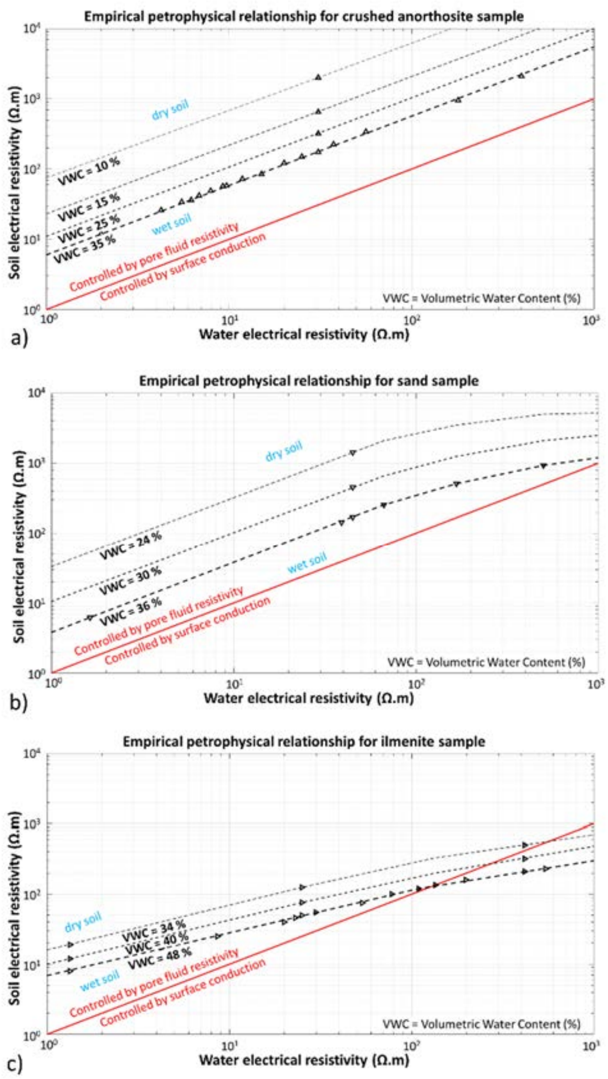

Figure 5: Petrophysical relationships between global and water resistivity and moisture content for a) anorthosite, b) sand and c) ilmenite.

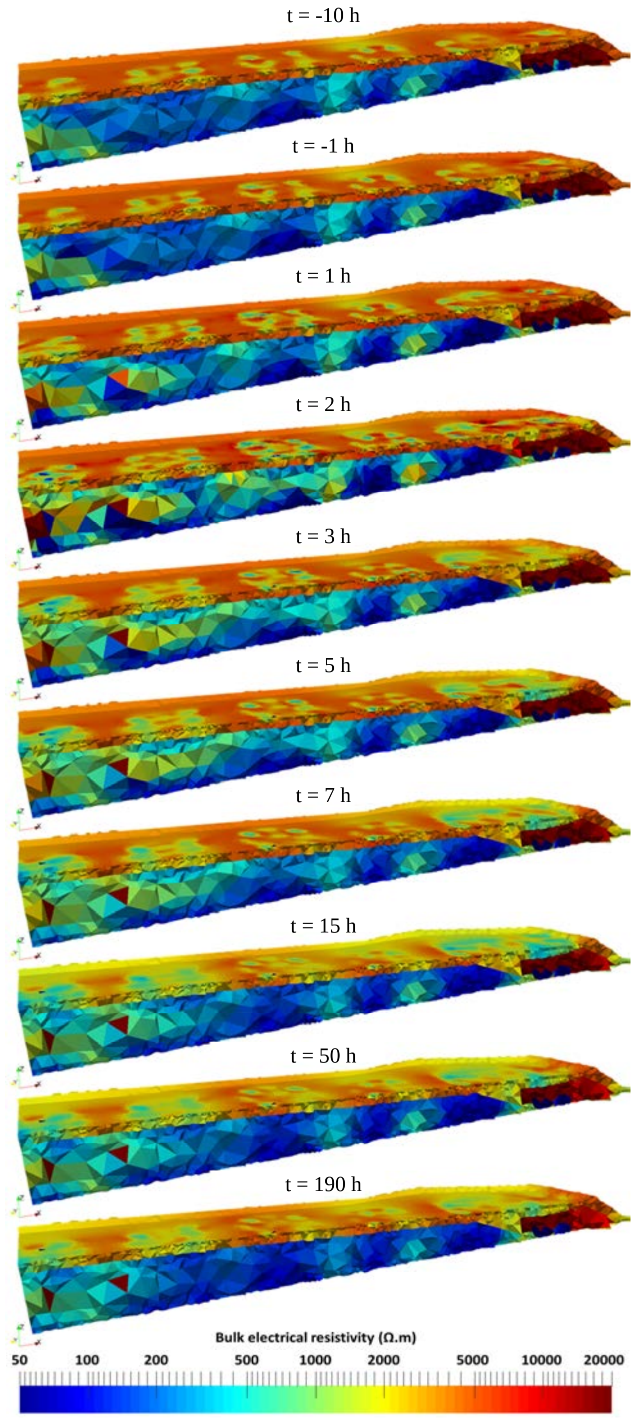

Figure 6: Time-lapse visualization of the 3D geoelectrical monitoring of the experimental waste rock pile before, during and after the infiltration test (at t = 0 h). Static resistivity values are consistent with results shown in Dimech et al. (2017).

Discussion

3D time-lapse inversion results can be used to reconstruct the global electrical resistivity distribution over time in the entire experimental waste rock pile. However, as this electrical resistivity is affected by both water quality (i.e. water electrical resistivity) and water quantity (i.e. volumetric water content), it is necessary to use empirical petrophysical relationships to separate both effects. A GS3 probes database has been used to recover the variation of water electrical resistivity over time in the crushed anorthosite. A conceptual model for water resistivity variation in the pile is shown in **Figure 7**.

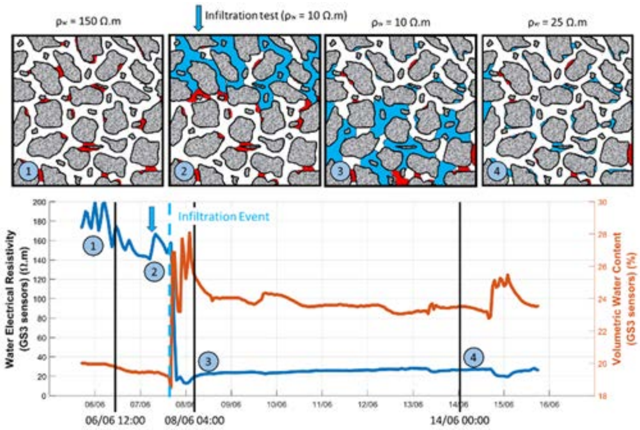

Figure 7: Conceptual model of water infiltration in the crushed anorthosite layer ate the top of the experimental waste rock pile. Conductive water (blue: $\rho_w = 10$ Ω.m) sprinkled on the pile replaces resistive water (red: $\rho_w = 150$ Ω.m).

The top part of **Figure 7** illustrates the matrix of crushed anorthosite. Resistive water (in red, $\rho_w = 150$ Ω.m) was present in the pores before the infiltration test. This resistive water has been progressively replaced by conductive water from the water truck (in blue, $\rho_w = 10$ Ω.m) during and after water infiltration. The bottom part of **Figure 7** presents water electrical resistivity variations over time measured by the GS3 probe located in the crushed anorthosite layer upslope of the pile. Numbered labels indicate the different infiltration states of this layer. Volumetric water content measured by the same GS3 probe is also displayed, indicating that the artificial infiltration event rapidly increased the volumetric water content from 20 % to 24 % (up to a maximum of 28 %).

The three vertical black lines on **Figure 7** show the dates selected to compare moisture content calculated from 3D geoelectrical monitoring and local GS3 measurements. The values for water electrical resistivity are 150 Ω·m, 20 Ω·m and 25 Ω·m respectively on June 6th at 12:00 (before infiltration), on June 08th at 04:00 (8 hours after infiltration) and on June 14th at 00:00 (6 days after infiltration). Global resistivity values (along a longitudinal profile at the center of the pile) are extracted from the 3D time-lapse resistivity values obtained by inversion. The petrophysical relationship shown in **Figure 6a** is then used to calculate volumetric moisture content values along the profile in the crushed anorthosite layer for the three dates, as shown in **Figure 8a**. Finally, volumetric water contents measured by GS3 probes are compared to provide a local reference dataset.

Volumetric water contents calculated from the 3D time-lapse geoelectrical monitoring of the pile and laboratory petrophysical relationship (**Figure 8a**: black lines) are close to local measurements from GS3 probes (**Figure 8a**: blue dots) in the crushed anorthosite. The top layer is relatively dry before the infiltration test (image #1) with an average VWC value of approximatively 20 %. The infiltration test had a significant effect on this crushed anorthosite layer, increasing the average VWC value up to 26 % (image #2), especially upslope and downslope of the pile where the average VWC value approximates 30 %. This top layer generally became dryer after 7 days (image #3) with an average VWC value of 21 %. However, calculated VWC values indicate that some places remained wet, mainly upslope. Calculated volumetric water content values also show heterogeneity in the crushed anorthosite layer, while GS3 measurements are relativity homogenous along the experimental waste rock pile.

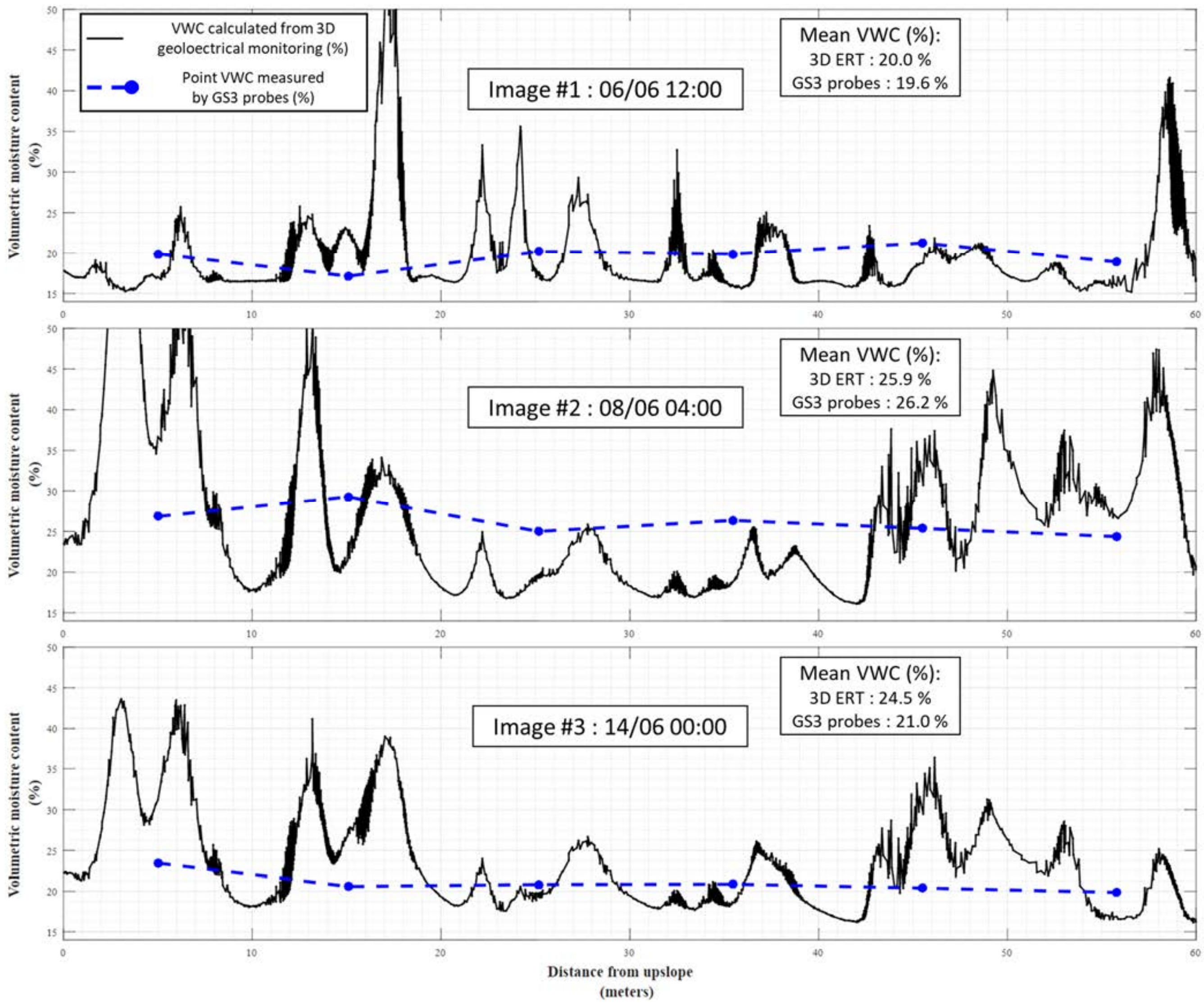

Figure 8: Reconstruction of the volumetric water content from the 3D time-lapse geoelectrical monitoring and laboratory petrophysical relationship along a longitudinal line in the top crushed anorthosite layer. a) Comparison between calculated VWC values (black line) and GS3 probe measurements (blue dots interpolated by dashed blue lines) at three different times before, during and after the infiltration event that occurred on June 7th 2017 at 19:30.

Conclusion

An experimental waste rock pile has been constructed and instrumented with multiple sensors for a high-resolution imaging of water infiltration. 3D time-lapse geoelectrical monitoring was carried out with 192 electrodes before, during and after an artificial infiltration event. Inversions using the high-resolution 3D model of the pile were conducted to reconstruct the 3D time-lapse global electrical resistivities in the pile. As this electrical resistivity is affected by both water quality and water quantity, some laboratory measurements were carried out to develop petrophysical relationships for the waste rocks. These empirical correlations were combined with a conceptual model of water infiltration in the top of the pile in order to convert 3D time-lapse resistivity distribution into volumetric water content imaging in the crushed anorthosite layer at the top of the pile. Comparison with local hydrogeological measurements tends to support the geoelectrical approach and suggests that 3D time-lapse geoelectrical monitoring is an appropriate and efficient tool for refining the understanding of the hydrogeological characteristics and behavior of complex media, such as a waste rock pile. Additional work is underway to assess more specifically the VWC in the two layers of the inclined FCL. This work presented here is part of a larger investigation with multiple results from the experimental waste rock pile and future work will seek to integrate different disciplines to provide realistic tendencies and conclusions.

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