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GELMON 2020

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Dear participants and readers of this abstract book of the GELMON 2020 workshop,

Due to the ongoing covid 19 pandemic crisis the GELMON 2020 workshop switched to an online format. Nonetheless we are happy to present you 26 abstracts from scientists around the world, which cover a wide range of topics in geoelectric monitoring. A focus is set on geoelectric monitoring of contaminated sites, followed by embankment, permafrost, data processing and inversion and many others.

Enjoy reading and stay healthy,

Birgit Jochum, David Ottowitz and Stefan Pfeiler

(GELMON organization team / Geological Survey of Austria)

Prof. Dr. Jung-Ho Kim
(1954-2019)

In 2019 the geoelectric monitoring community lost an excellent scientist, an appreciated colleague and a dear friend. We dedicate this abstract book to Jung-Ho Kim.

TIME SCHEDULE

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Permafrost monitoring through resistivity time-series analysis: the PERMOS ERT Database

Christin Hilbich[1], Cecile Pellet[1], Coline Mollaret[1], Benno Staub[2], Jeannette Noetzli[3], Christian Hauck[1]

(1) Department of Geosciences, University of Fribourg, Fribourg, Switzerland
(2) Vereinigung Kantonaler Gebäudeversicherungen (VKG), Bern, Switzerland
(3) WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland

keywords: Permafrost, ERT monitoring, database

Mountain permafrost monitoring has a long tradition in Switzerland and is institutionally organised within the Swiss Permafrost Monitoring network PERMOS since 2000. Since 2005, annually repeated ERT measurements are included in the monitoring strategy of PERMOS, and permanently installed ERT profiles exist at 5 different sites in Switzerland, including a rock glacier, talus slopes and bedrock sites. The longest time series is collected on the Schilthorn summit since 1999, including quasi-annual manual measurements until 2009, and automated data acquisition with up to daily resolution since then. By now, the Schilthorn data set comprises more than 1070 individual measurements, and data from the other sites range from 14 to 80 measurements in total per site.

To allow for a comparative analysis of the long-term resistivity evolution in the context of climate-induced permafrost degradation, this huge amount of data requires systematic and automated data management and processing. Automated filter routines were developed (Hilbich et al. 2011, doi.org/10.1002/ppp.732; Rosset et al. 2013, doi.org/10.3997/1873-0604.2013003), and later extended to a systematic data processing (Mollaret et al. 2019, doi.org/10.5194/tc-13-2557-2019), including the analysis of contact resistances and the application of automatic processing routines (multi-site data import, filtering, data inversion, time series analysis, and visualisation).

This systematic processing approach was developed in combination with standardized data archiving within the PERMOS database, which regroups all monitoring variables of the PERMOS network, namely ground temperatures, kinematic data, meteorological data and ERT. A unique database structure was developed for ERT monitoring data, which enables the storage of not only the final data product (i.e. inverted resistivity) but also the raw data and the relevant meta-information pertaining to the field site (i.e. elevation, landform type, etc.), the individual surveys (i.e. configuration, instrument, etc.) as well as the processing steps (i.e. site-specific filter thresholds, inversion errors, etc.). The PERMOS ERT database aims at ensuring the long-term archiving of permafrost data, the traceability and reproducibility of the processing steps as well as a timely access to the data. Today, it includes more than 1000 data sets (divided within 5 sites), which are publicly accessible via a web interface. This online browsing tool enables user-defined querying of the database and provides standardized tools for data visualization and time series analysis, as well as download of selected data sets.

The joint analysis of all ERT data within the database reveals a consistent long-term resistivity decrease observed for all field sites. It confirms significant ground ice degradation for a variety of landforms and substrates and for a period of up to 20 years, which is of a unique value in permafrost science. The remarkably high overall quality of the data sets often acquired under harsh and remote measurement conditions (despite a couple of data sets with weak quality because of too high coupling resistances in winter time) justifies the reliability of the results and the integrative interpretation of all available time series.

Towards a geoeletrical database for permafrost monitoring to enable the processing and repetition of historical measurements

Coline Mollaret[1], Christin Hilbich[1], Cécile Pellet[1], Christian Hauck[1]

(1) Department of Geosciences, University of Fribourg, Fribourg, Switzerland

keywords: permafrost, database

Electrical imaging has been widely applied for permafrost detection and monitoring over different spatial scales. Only very few permafrost sites worldwide are continuously monitored with ERT as part of national monitoring programmes (~10). On the contrary, a much larger number of individual ERT surveys from the past exist (estimated to be >200 alone in the Swiss Alps). These data sets are neither included in a joint database nor have they been analysed in an integrated way. Within a GCOS Switzerland-funded project we address this important historical data source.

In a first step, historical data on permafrost terrain from UniFR groups and their collaborating national and international partners were collected and metadata archived (> 150 profiles). Some of the historical measurements were already repeated in summers 2019 and 2020 (e.g. Etzelmüller et al. 2020, Hilbich et al. 2019). The resulting resistivity changes on time scales of 10 to 20 years are presented and analysed according to several sites characteristics such as geomorphology, elevation and surface type. These results are analysed in the context of climate change, showing the value of repeated ERT measurements to detect the climate signal of permafrost change after time spans up to 20 years.

In a second methodological step, the Reproducible Electrical Data Analysis (REDA) scientific Python library (Weigand and Wagner, 2017) will be used for the homogenisation of processed ERT data. It is aimed to reprocess the historical data in the most integrative and reproducible manner. Technical challenges for reprocessing a large number of data sets in an integrative way will be discussed. Furthermore, the structure and the ongoing implementation of the international open-access database for permafrost ERT surveys is described.

Etzelmüller, B., Guglielmin, M., Hauck, C., Hilbich, C., Hoelzle, M., Isaksen, K., Noetzli, J., Oliva, M., Ramos, M. (2020): Twenty years of European Mountain Permafrost dynamics – the PACE Legacy., Environmental Research Letters, 15. Doi: https://doi.org/10.1088/1748-9326/abae9d.

Hilbich C., Hauck C., Pellet C., Isaksen K., Etzelmüller B. (2019): Permafrost degradation in Norway documented through repeated geophysical surveys after 10 and 20 year. Swiss Geosciences Meeting, 2019, Fribourg.

Weigand, M., Wagner, F. M. (2017): Towards unified and reproducible processing of geoelectrical data. 4th International Workshop on Geoelectrical Monitoring, Nov. 22-24, Vienna, Doi: https://doi.org/10.5281/zenodo.1067502

Geophysical monitoring of hydrological dynamics in a transitional permafrost system

Sebastian Uhlemann[1], Baptiste Dafflon[1], John Peterson[1], Craig Ulrich[1], Ian Shirley[1,2], Sofia Michail[3], and Susan S. Hubbard[1]

1. *Lawrence Berkeley National Laboratory, Earth and Environmental Sciences Area, Berkeley, USA*
2. *University of California, Berkeley, USA*
3. *ETH Zurich, Institute of Geophysics, Zurich, Switzerland*

keywords: permafrost, infiltration, climate change

Increasing temperatures in the Arctic are rapidly changing the Arctic ecosystem. Yet, we are missing a predictive understanding of the interactions within the bedrock to atmosphere column that are driving ecosystem evolution and carbon-climate feedback. A critical knowledge gap within these systems are the dynamics of surface water - groundwater interactions, and infiltration and groundwater flow processes, which drive permafrost thaw and biogeochemical processes. Geophysical techniques have been shown to be a valuable tool to assess the intermediate depths (1 - 10's of m) that are particularly important to understanding the impact of climate change on permafrost thaw dynamics and related hydrological dynamics. In this study we assess the variability of hydrological properties and processes in transitional permafrost environments, and the impact of vegetation and snow-pack distribution on those properties.

As part of the Next Generation Ecosystem Experiments (NGEE) Arctic project, we present data from a 127 meter long electrical resistivity tomography monitoring transect located on the Seward peninsula, Alaska, USA, that spans across different vegetation types, snowpack thicknesses and permafrost table depths. The system has been recording data daily between March and November of 2018 and 2019. Here, we focus on the subsurface response of disturbances due to snowmelt and extreme rainfall, and the long-term changes in resistivity. The results highlight considerable variability along the monitoring transect. Areas covered by tall shrubs are characterized by increased snow accumulation, which insulates the ground from cold air temperatures and allows for rapid infiltration of snowmelt. Low-lying graminoid dominated areas have thinner snowpack, resulting in near-surface permafrost and surficial freezing. This lowers the hydraulic conductivity of the shallow subsurface and prevents snowmelt and rainfall from infiltrating into the subsurface. The results highlight the heterogeneity in thermal and hydrological fluxes in transitional landscapes, with increased fluxes in unfrozen areas and presence of lateral flow between the domains that could be a driving factor in talik formation. Calibrated long-term resistivity changes indicate that permafrost temperatures increased by about 0.20°C over the two year monitoring period. This rate is in agreement with independent temperature measurements and general trends observed in similar environments. Our results show that topography, vegetation and snow thickness are main drivers for talik development, and that hydrological properties change significantly with warming permafrost temperatures. These results will eventually help to improve predictions of Arctic feedback to climate changes.

Seasonal and annual dynamics of frozen ground in a mountain permafrost site in the Italian Alps detected by Spectral Induced Polarization

Theresa Maierhofer[1,2], Timea Katona[1], Umberto Morra Di Cella[3], Paolo Pogliotti[3], Elisabetta Drigo[3], Christin Hilbich[2], Christian Hauck[2], Adrian Flores-Orozco[1]

(1) Department of Geodesy and Geoinformation, TU-Wien, Vienna, Austria
(2) Department of Geosciences, University of Fribourg, Fribourg, Switzerland
(3) ARPA (Agenzia Regionale per la Protezione dell'Ambiente), Aosta valley, Italy

keywords: spectral induced polarization, permafrost, monitoring

Permafrost regions are currently undergoing considerable changes due to climate change related to warming and thawing events yielding a decrease in the ice content reported for permafrost sites worldwide. Thus, long-term monitoring of the thermal state of permafrost has become an essential task in the European Alps. Geophysical methods are increasingly being used to support and interconnect spatially sparse borehole data and investigate the spatial distribution and temporal evolution of permafrost in a quasi-continuous manner. Electrical resistivity tomography (ERT) is a widely applied technique for the quantification of ice-rich permafrost, commonly associated with a significant increase in the electrical resistivity upon freezing. However, air is also characterized by high electrical resistivity values hindering a direct interpretation of the ERT results. Theoretical and laboratory studies have revealed that ice exhibits a characteristic induced electrical polarization response in the low frequencies (< 1 kHz), with the frequency-dependence of the electrical properties being also related to changes in temperature and ice content. Thus, the application of the spectral induced polarization (SIP) method has been recently proposed as a suitable technique in permafrost studies.

We present here for the first time SIP imaging results collected at a representative permafrost site covering a one-year monitoring period, with measurements in the frequency range between 0.1 and 225 Hz. The selected study area Cervinia Cime Bianche (Italian Alps) is a long-term permafrost-monitoring site situated at an elevation of ~3100m and provides comprehensive geophysical and borehole temperature data for validation. To minimize the contamination of the SIP data with parasitic electromagnetic fields, we took particular care in the installation of coaxial cables and the use of an adequate measuring protocol. SIP data were collected as normal and reciprocal pairs for the quantification of data error and we developed an analysis of data quality taking into account changes in time and in the frequency to remove outliers and erroneous measurements. Our results show clear changes in SIP anomalies for summer and winter months, which can be associated to freeze and thaw processes within the subsurface.

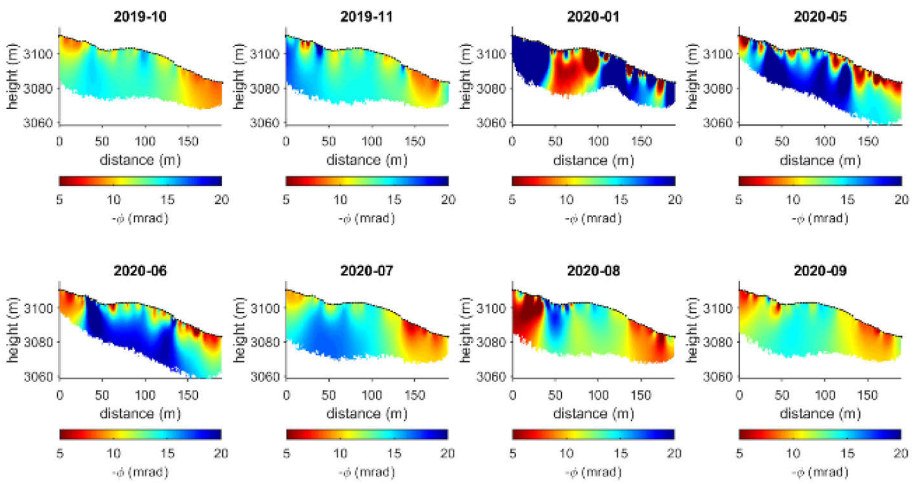


Figure caption: SIP data collected on a monthly basis covering one year of measurements. Here we present the phase of the complex resistivity at 0.5 Hz for 10 time stamps of the year 2019/20.

Cross-borehole complex geo-electrical monitoring of treatment zone installation in an urban area: Case study from Farum, Denmark

Léa Lévy[1], Thue Bording[1], Anders V. Christiansen[1], Gianluca Fiandaca[2], Rasmus Thalund-Hansen[3], Line Madsen[1], Poul L. Bjerg[3]

(1) HydroGeophysics Group, Department of Geoscience, Aarhus University, Aarhus, Denmark
(2) Department of Earth Sciences "Ardito Desio", University of Milano, Milan, Italy
(3) Technical University of Denmark, Lyngby, Denmark

keywords: contamination, cross-borehole, geo-electrical monitoring, induced polarization, urban area

We show the results from a pilot project on remediation of groundwater contaminated by chlorinated solvents. The remedial agent used to mitigate the contamination, consists of zero-valent-iron (ZVI) and microbial culture, and was injected in 7 wells in the depth range 13-20 m. Cross-borehole resistivity and time-domain induced polarization (IP) data were measured between nine electrode boreholes installed in the depth range 10-20 m. Seven rounds of data acquisition were carried out between July 2019 and June 2020, including four rounds after injection (August 2019).

We show how cross-borehole geophysical monitoring help evaluate the temporal and spatial distribution of the remediation cloud, composed of two main electrical conductors: ions in pore water, and connected solid iron particles that have yet to be dissolved. We critically discuss our results in light of groundwater and sediments analyses, conducted in parallel.

We also show how IP-based hydraulic conductivity predictions, validated through a comparison with hydraulic conductivity estimations based on numerous grain size analyses, could potentially have helped optimize the injection of remediation agent before-hand.

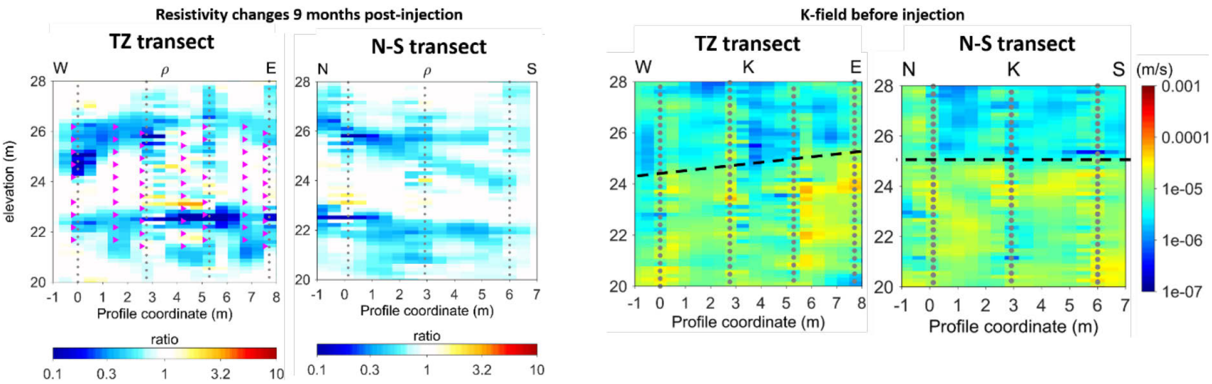


Figure caption: Left and center left panels show time-lapse inversion of resistivity, illustrating changes related to the remediation cloud spreading. Left: transect along the treatment zone (TZ). Center-left: transect perpendicular to the TZ (north-south). Right and center-right panels show hydraulic conductivity field derived from IP Inversion at the same two transects, based on inversion of data measured before injection. A lithological boundary between sandy till and meltwater sands, inferred from the DCIP inversion is emphasized with black broken line.

Cross-borehole electrical resistivity tomography for monitoring in-situ chemical oxidation remediation: Large-scale project at Kærgård Plantation, Denmark.

Léa Lévy[1], Anders K. Kühl[1], Thue Bording[1], Line Madsen[1], Anders Vest Christiansen[1], Jørgen Fjeldsø Christensen[2]

(1) HydroGeophysics Group, Department of Geoscience, Aarhus University, Denmark
(2) Region Syddanmark

keywords: contamination, geo-electrical monitoring, cross-borehole

Kærgård Plantation is one of the largest polluted sites in Denmark, with over 300.000 tons of pharmaceutical waste dumped in the sand dunes between 1956 and 1973. This site is located near the west coast of Denmark, in otherwise pristine nature.

An initial experiment aiming at cleaning up the plantation, was carried out in 2018, involving in-situ chemical oxidation remediation at a demo site covering 40 m^2. To monitor the spread of the oxidation agent, we used cross-borehole electrical resistivity tomography (ERT). Following the success of the initial experiment, a full-scale remediation monitoring project was implemented over an area of 700 m^2 in December 2019. This time, 30 boreholes, carrying 32 ring electrodes each, were installed, with an average distance of 6 m between boreholes.

New technical and scientific challenges arose with the full-scale project, from the production and installation of electrode boreholes to the data acquisition, processing, and inversion of large resistivity datasets. The oxidation agent was injected over a three-week period in December 2019, with geophysical data collection each day. Data analysis could not be reduced to a few 2D inverse problems, due to the different injection times for a given 2D transect.

We present the acquisition protocol and data handling workflow developed to handle such a dense array of information (more than one million data points per measurement round). By using both vertical and horizontal transects, we also show how time-lapse inversions clearly delineate the spread of the oxidation agent and pinpoint zones with limited spreading.

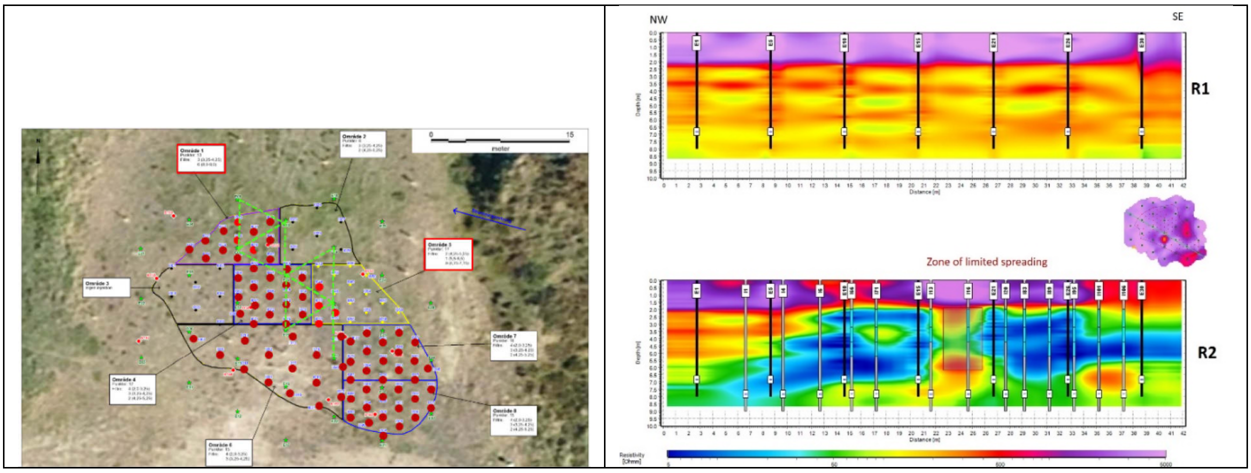


Figure caption: Left showing aerial view of the full-scale site. Right: NW-SE before and after injection. Electrode boreholes and injection wells are also shown.

Geoelectrical monitoring for following changes due to in-situ bioremediation of chlorinated solvents contamination

Aristeidis Nivorlis[1], Torleif Dahlin[1], Matteo Rossi[1]

(1) Engineering Geology, Lund University, Lund, Sweden

keywords: long-term monitoring, geoelectrical, remediation

Soil contamination is a widespread problem and actions need to be taken to prevent damage to the groundwater and the life around the contaminated sites. In Sweden more than 80,000 sites are potentially contaminated, therefore there is a demand for accurate and efficient methods for site characterization and soil remediation. In-situ bioremediation has the potential to offer a safer, more sustainable, and cost-efficient alternative for soil remediation as opposed to other remediation techniques which usually require excavation of the contaminated mass. However, monitoring the progress of in-situ treatments requires soil/water sampling and laboratory analysis, which, if done frequently, can increase the cost dramatically. For this reason, there is a demand for new methodologies that can be used to follow the progress of in-situ bioremediation. We are investigating the applicability of geoelectrical monitoring in a former dry-cleaning facility located in Alingsås (Sweden). The site is contaminated with chlorinated solvents and a pilot in-situ bioremediation plan was launched in November 2017 testing the efficiency of two different stimulants. We developed an autonomous and fully automated system for geophysical monitoring with the Direct Current resistivity and time-domain Induced Polarization (DCIP) method that aims to follow the changes in the subsurface. We present a complete workflow that includes data acquisition, pre-processing, inversion and visualization of the daily DCIP monitoring data. The proposed scheme is robust and shows that DCIP monitoring has good potential to record the changes due to the bioremediation; however, it needs to be paired with more information (temperature, geochemistry, contaminant concentrations) to better understand the changes that take place in the subsurface.

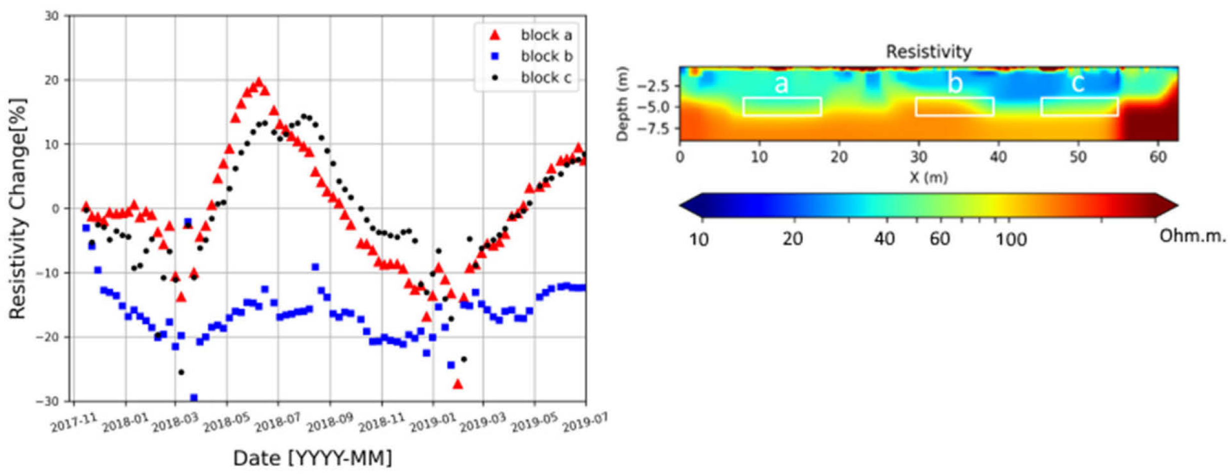


Figure caption: Time-lapse inversion of weekly averages for a period of 20-months after the initiated remediation experiement (left). Each point represents the average value of the change in resistivity (%) for the blocks a (red), b (blue) and c (black) highlighted in the reference resistivity model (right). The areas (a) and (b) represent areas treated with different fluids were area (c) represents the untreated reference area.The treated area (a) shows a similar behavior with the untreated area (c) in contrast with the treated area (b) which shows a different behavior consistently over the entire period of 20 months.

Investigating the coupled thermo-hydro-mechanical behavior for nuclear waste storage using resistivity monitoring and distributed fiber optic sensing

Sebastian Uhlemann[1], Jiannan Wang[1], Shawn Otto[2], Brian Dozier[2], Kristopher Kuhlmann[3], Yuxin Wu[1]

1. *Lawrence Berkeley National Laboratory, Earth and Environmental Sciences Area, Berkeley, USA*
2. *Los Alamos National Laboratory, Los Alamos, USA*
3. *Sandia National Laboratory, Albuquerque, USA*

keywords: nuclear waste storage, temperature dynamics, borehole monitoring

Salt bodies are an ideal repository for permanent isolation of heat-generating radioactive waste due to their ultra-low permeability and ability to creep and close fractures. However, brine movement stimulated by the waste generated heat and driven by thermal-hydro-mechanical (THM) processes also brings challenges, such as waste package corrosion and radionuclide transport. Understanding the brine migration in this environment is vital for safe radioactive waste disposal. At the underground Waste Isolation Pilot Plant (WIPP), we conducted joint in-situ observation with controlled heater, electrical resistivity tomography (ERT), and high-resolution distributed fiber optic sensing (DFOS) to study THM induced brine migration. Both ERT and fiber optic sensors were placed in the boreholes that are away from the heater borehole. While ERT is sensitive to changes in rock temperature and brine content, the high-resolution DFOS was calibrated for temperature sensing. To fully exploit the ERT resolution capabilities, an optimized survey design was employed for daily data acquisition.

During the heating and cooling processes, fiber optic sensing revealed high-resolution temperature distributions that are in agreement with independent temperature sensors and expected temperature dynamics. The resistivity changes from ERT correlate well with these observed temperature changes. While sole temperature changes can explain some of the observed resistivity changes, offsets, in particular around the heated zone, are indicative of brine movement and correlate with brine losses and restoration from the formation during the experiment. The results from the fiber optic sensing and the ERT measurement are consistent with the brine migration mechanism that is enhanced due to thermal expansion during the initial heating phase, and the salt contraction induced permeability and flow stimulation during cooling. These results are validated by separate numerical modeling, which also suggests a correlation between pore pressure in the static rock matrix and the temperature.

3D resistivity monitoring for seepage assessment at an earth dam abutment: System design and early results

Karl E. Butler[1], Daniel E. Boulay[1]

(1) Department of Earth Sciences, University of New Brunswick, Fredericton, NB, Canada

keywords: embankment dam, abutment, seepage

Interfaces between water-retaining embankments and rock or concrete abutments, known to be regions of elevated risk for the development of concentrated seepage, are not well suited to investigation by the 2D electrical resistivity imaging (ERI) methods most commonly employed along dam crests. We present here the design and early performance of a 3D ERI system commissioned to investigate such an interface at the 670 MW Mactaquac hydroelectric generating station on the Saint John River in eastern Canada. The station, which opened in 1968, includes a 500 m long embankment dam with a clay-till core, rising 32 m above its toe and up to 58 m above its foundation.

The ERI system currently employs five parallel lines (5 m apart), of 20 electrodes (3 m apart) running from crest to toe on the downstream face of the dam adjacent to the abutment. The electrodes include 70 stainless steel rods, 91 cm in length, and 30 'non-polarizing' paste electrodes used for a prior self-potential (SP) study. Moderate contact resistances (commonly < 2 kOhm except during mid-winter) and the use of multi-day/multi-survey averaging with outlier rejection have contributed to the collection of highly repeatable data sets from a low power (10 W) resistivity meter (Lippmann 4ptlight) sustained by a solar-charged battery. A pole-dipole electrode configuration is used to improve depth of exploration (~20 m); importantly, we discovered it was necessary to force the transmitter to apply a sufficiently large voltage across the ~500 m long current dipole to prevent current regulation from being adversely affected by strong anthropogenic noise at the site.

The first high quality data were acquired in June 25, 2019, and the system has been running autonomously since late Oct., 2019, although ground freezing and a wiring break limited data availability in the depths of last winter. Resistivity models obtained using the RES3DINV smoothness-constrained inversion code reveal a dominantly bimodal distribution of subsurface resistivities: 50 – 200 Ωm in the clay-till core, and generally 1000 – 4000 Ωm in the more heterogeneous rockfill zones. Resistivities are noticeably lower within ~10 m of the concrete abutment, which could be indicative of increased water content although the influence of the relatively conductive concrete itself has yet to be determined. Changes in resistivity over weeks to months show spatially coherent patterns, especially in the uppermost 8 m, probably related to changes in temperature and rainfall-related moisture, although we speculate that road salt applied on the dam crest could help explain one large change, up to 200%. Monitoring is expected to continue for at least four more years to further develop the data acquisition and processing techniques that will be needed to identify any seepage-related anomalies that would be expected to arise from seasonal changes in water saturation or in the temperature and TDS content of water seeping through from the dam reservoir.

Figure Caption: 500 m long embankment dam and Diversion Sluiceway at Mactaquac Generating Station.

Reservoir leaking assessment using electrical resistivity imaging (ERI) with capacitively-coupled system

Jeong-Ryul Choi[1], Seung-Sep Kim[1], Nackwon Sung[2]

(1) Deptartment of Astronomy, Space Science and Geology, Chungnam National University, Daejeon, Republic of Korea
(2) Korea Rural Community Corporation, Cheong-ju, Republic of Korea

keywords: Capacitively-coupled resistivity, ERI monitoring, reservoir assessment

As of 2014, there are 17,477 agricultural reservoirs used in Korea. Among them, 12,148 reservoirs (~70%) were built more than 50 years ago. Thus, reservoir leaking assessment on such aged structures becomes very important to prevent massive leaking and sudden structure failures. Electrical resistivity imaging (ERI) is regularly applied to examine leaking points, if any, and verify effects of grouting to stop water leaking and reinforce the reservoir. In this study, we utilized the Ohm-Mapper resistivity meter with two receivers and one transmitter to assess reservoir leaking detection. For comparison, we also obtained the data from the electrical resistivity monitoring system, which installed measuring rods in a fixed space. The system was developed and operated by the Korea Rural Community Corporation. For the Ohm-Mapper survey, we pulled the system along the ground to produce continuous apparent resistivity data, whose locations were specified by a real-time kinematic (RTK) GPS receiver. The temporal variation of ERI monitoring results exhibits the variation of estimated resistivity values at the water leaking zone, especially before and after the grouting procedures, implying a slow redeveloping of the water leaking. Thus, we demonstrated that the ERI monitoring with the Ohm-Mapper system can be effective to perform a fast assessment on water leaking at reservoirs.

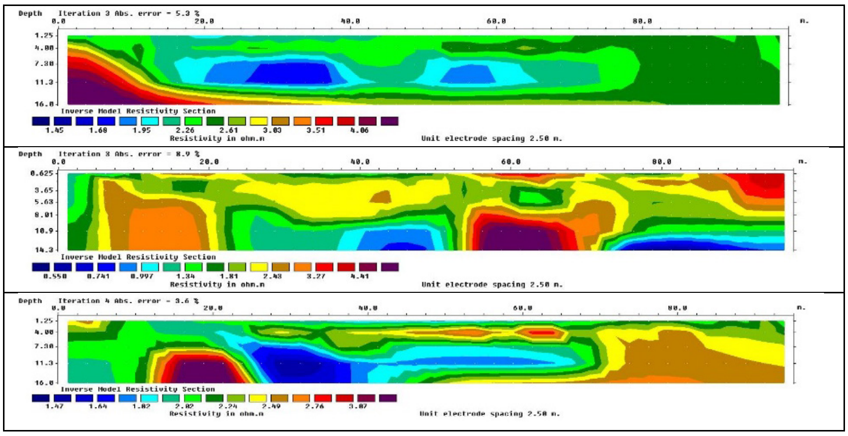


Figure caption: Electrical resistivity imaging results before grouting (top), 2 months after grouting (middle), and 1 year after grouting (bottom). The temporal variation implies the water leaking zone is slowly reactivated after application of grouting procedures.

Pre-study for geoelectrical monitoring for detection of internal defects and anomalous seepage in the Älvkarleby test embankment dam

Reyhaneh Nooroz[1], Torleif Dahlin[2], Per-Ivar Olsson[2], Aristeidis Nivorlis[2], Thomas Günther[3], Christian Bernstone[4]

1. *School of Civil Engineering, University of Tehran, Iran*
2. *Engineering Geology, Lund University, Lund, Sweden*
3. *Leibnitz Institute of Applied Geophysics, Hannver, Germany*
4. *Vattenfall AB, Stockholm, Sweden*

keywords: embankment dam, internal defects, anomalous seepage

Electrical resistivity tomography (ERT) can be used to monitor the interior of hydropower embankments dams, and thereby detect zones with anomalous material properties and flow induced variation in the resistivity caused by changes in total dissolved solids (TDS) and temperature. Furthermore, monitoring of embankment dams in connection with a substantial change in the reservoir water level can detect anomalous leakage paths via differential wetting of zones with different hydraulic properties. In Sweden, where the available hydropower energy capacity is utilised, installation of electrodes must be done post-construction of embankment dams, which for practical reasons generally means installed along its crest, in the top of the core, using a 2D ERT approach. This has the advantage of focusing the sensitivity to the core itself, which is the part of the dam that shall stay impervious over time. However, the orientation of the electrode layout in combination with the 2D approximation leads to severe 3D effects, which distorts the inverted model resistivities and geometry. Furthermore, the resolution decreases with depth, which is a major limitation for high dams. A way ahead would be if electrodes could be installed on deeper levels inside the dam close to the core, which might be possible using modern drilling technology. This electrode lay-out concept was investigated with numerical modelling using extended gradient, cross-line bipole-bipole and corner arrays between horizontal-horizontal, vertical-vertical and vertical-horizontal lines respectively. To interpret the data 3D inversion is required to handle the structure's geometry due to the zoned construction with materials that have large contrasts in resistivity. A test embankment dam installation was built during the autumn of 2019, with electrodes and various sensors installed inside the dam to evaluate the applicability of the suggested approach. We present results of numerical modelling simulating potential defect scenarios where several measurement sequences of close to 8,000 data points using the abovementioned arrays are inverted all at once. In order to resolve subtle variations inside the core, the finite element grid design is based on prior knowledge about the internal material distribution, with broken smoothness constrains at known material boundaries. In combination with region-based control of the resistivities of the different material zones, the inversion in combination with a time-lapse approach it shows promising results.

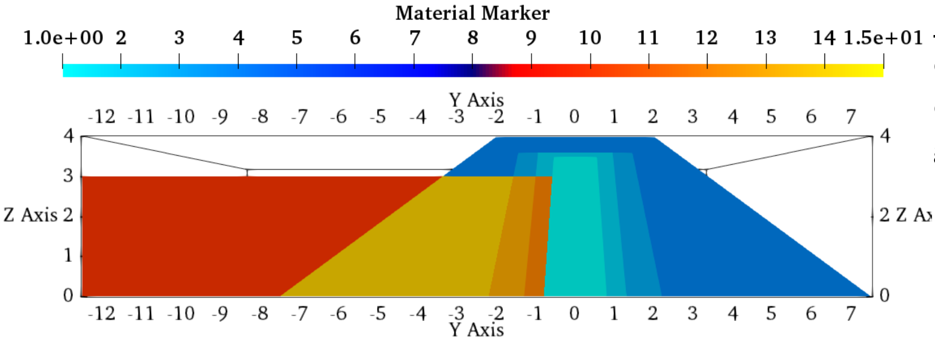


Figure caption: Side view of Älvkarleby test embankment dam model geometry. The colours indicate different material zones, and do not reflect the relation between the resistivity of

The latest installation of G.RE.T.A. along the tailings dam of a copper mine in Chile

Greta Tresoldi[1], Azadeh Hojat[2,3], Leopoldo Cordova[4], Luigi Zanzi[3]

(1) *LSI lastem s.r.l., Settala, Italy*
(2) *Shahid Bahonar University of Kerman, Kerman, Iran*
(3) *Politecnico di Milano, Milan, Italy*
(4) *Geosinergia Ingeniería Y Medio Ambiente Ltda., Santiago, Chile*

keywords: tailings dam, mining, alarm, ERT

During 1915-2020 (August), 351 failures of tailings dams have occurred, from which, 10 very serious incidents occurred from 2010. Therefore, monitoring tailings dams is becoming a burning subject, especially that no standardized method exists to ensure the stability of these structures.

During last decades, electrical resistivity tomography (ERT) has been increasingly applied to monitor earthen embankments similar to tailings dams. We recently proposed a permanent geoelectrical monitoring to assess heterogeneities and integrity of tailings dams, both in terms of cavity formations and water accumulation.

G.RE.T.A. (Geo REsistivimeter for Time-lapse Analysis), is an Italian autonomous programmable system designed by LSI Lastem with the scientific support of Politecnico di Milano. The system includes a remotely controlled low-power resistivity meter with two cables equipped with 48 electrodes (plate, mesh or rod), that can be also buried in shallow trenches. The device is permanently connected to a cloud software to send real-time data, where they are automatically inverted. In order to monitor subsurface variations, time-lapse data analysis algorithms make differences for any desired measurements in real-time. Thresholds of resistivity variations can be set by the user and alarms will be launched when the defined secure changes are not satisfied, indicating anomalous changes. A couple of G.RE.T.A. are in operation along the levees of rivers or irrigation canals and the latest advanced device was installed in August 2020 by Geosinergia Ingeniería Y Medio Ambiente, on the tailings dam of a copper mine located north of Santiago, Chile.

The ERT profile is placed at the base of the tailings dam in order to recognize possible under-seepages that can pollute the groundwater and the surrounding exposed area, with the presence of a city. The system is positioned downstream of two retaining ponds and the aim is to understand whether the variations of water level in the ponds provokes any underseepage.

In this case the surface installation is selected: rod electrodes are used with the Wenner array with a = 3 m (total length of 141 m) approaching a maximum penetration depth around 23 m.

Figure caption: Installation of G.RE.T.A. on the tailings dam in Chile. The box contains the measuring and communication modules, the system is powered by a solar panel. The 2 cables are equipped with 48 electrodes, 3 m apart.

Geo-electrical monitoring of H2S mineralization into pyrite, upon re-injection in basalts at Nesjavellir geothermal site, Iceland

Léa Lévy[1,2], Pradip K. Maurya[1], Gianluca Fiandaca[3], Thue S. Bording[1], Line M. Madsen[1], Lydie Gailler[4], Svetlana Byrdina[5], Jón E. Jónsson[2], Ásdís Benediktsdóttir[2], Knútur Árnason[2]

(1) *HydroGeophysics Group, Department of Geoscience, Aarhus University, Aarhus, Denmark*
(2) *ISOR, Iceland GeoSurvey, Reykjavik, Iceland*
(3) *Department of Earth Sciences "Ardito Desio", University of Milano, Milan, Italy*
(4) *University of Clermont Auvergne, Clermont-Ferrand, France*
(5) *University of Savoie-Mont Blanc, Chambéry, France*

keywords: hydrogen sulfur, pyrite, geothermal, geo-electrical monitoring, electromagnetics

The hydrogen sulfur (H_2S) emitted from geothermal exploitation is an air pollutant: high concentrations of H_2S are corrosive and toxic. A solution to mitigate air pollution caused by geothermal exploitation is to re-inject geothermal gases (H_2S and CO_2) into basaltic rocks, where the gasses should mineralize into pyrite and calcite, respectively. Several re-injection projects are currently on-going in Iceland. The GEMGAS research project (Geo-Electrical Monitoring of H_2S Gas Sequestration) aims at developing a methodology for geophysical monitoring of H_2S sequestration by formation of pyrite (FeS_2), with focus on a re-injection project in the Nesjavellir geothermal reservoir, starting in September 2020 and with injections in the depth range 200-500 m.

With repeated measurements before and after injection, we aim at providing a dynamic view of electrical resistivity and polarization structure changes upon formation of pyrite in basalts. Five complementary methods are combined: surface Direct Current (DC) and Time-Domain Induced Polarization (IP), Self-potential (SP), Transient Electro-Magnetic (TEM), borehole logging, and finally DCIP using two metallic wellbore casings as current electrodes.

Preliminary results from the two "baseline" rounds of measurement carried out in 2019 and 2020 illustrate important issues related to the dense metallic and electrical infrastructure buried at the site. We present improvements made to the data quality by changing the acquisition strategy between 2019 and 2020. We also give an overview of the variability between the two baseline rounds before H_2S injection, in particular through time-lapse inversions.

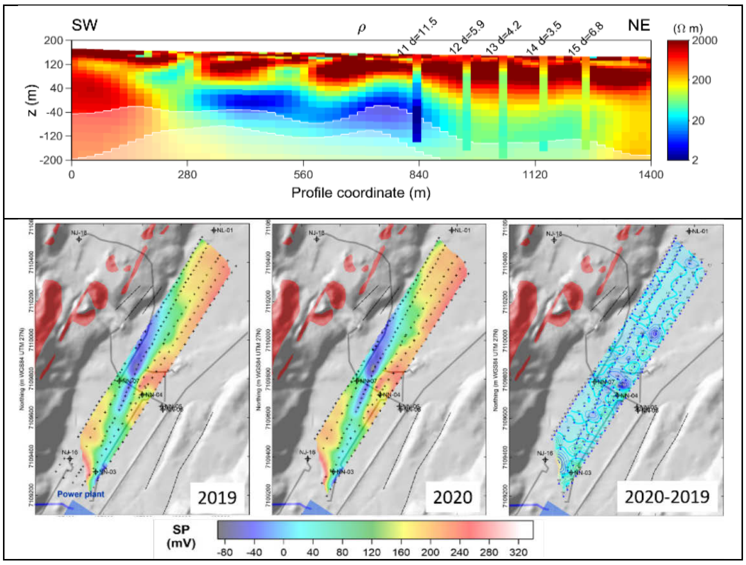


Figure caption: Top panel: superposition of DC (2D) and TEM (1D) resistivity models obtained from 2019 data along one of the DCIP profiles. Bottom panel: self-potential maps obtained in 2019 and 2020, as well as a map of the difference between the two years.

Time-lapse monitoring of landfill leachate through time-domain induced polarization with temperature corrections

Thue Bording[1], Léa Lévy[1], Gianluca Fiandaca[2]

(1) HydroGeophysics Group, Department of Geoscience, Aarhus University, Aarhus, Denmark
(2) Department of Earth Sciences "Ardito Desio", University of Milano, Milan, Italy

keywords: landfill, temperature correction, time-lapse

We present the results from a year-long geophysical monitoring setup from the now-defunct Pillemark landfill on the Danish island of Samsø. The landfill is located in the vicinity of a waterworks, and it is therefore of great concern that the underlying groundwater aquifer is not being contaminated. Samsø receives a massive influx of tourists in the summer months and as such the groundwater level in the aquifer fluctuates wildly during the year. Given varying hydraulic gradients, we expect that potential leaching would also be time varying. The field setup consisted of a 100 m profile installed permanently in a 30 cm deep trench, placed between the landfill and the waterwork and orthogonal to the regional groundwater flow direction. Geophysical data were collected daily, and temperatures were measured in a borehole nearby at different depths down to 8 m. Data acquisition was fully automatic by a computer system installed in the field.

In general the contact resistance was low, but increased after extended periods without rainfall. All datasets were inverted independently for outlier detection and removal, and then subsequently time-lapse inverted using an asymmetric generalized minimum support norm scheme, which includes modelling of temperature effects. The time-lapse inversions show changes in soil water content in the upper 5-8 m, but also a possible deeper plume having seasonal variations.

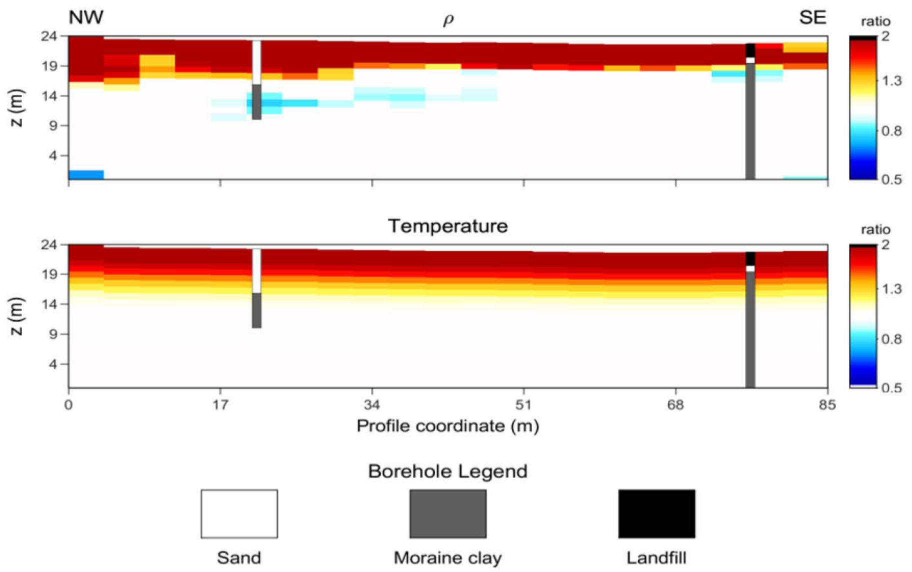


Figure caption: Results from time-lapse resistivity inversion, including temperature corrections, showing the resistivity changes 6 months after the beginning of monitoring. The ratio plot corresponds the dates September 9th (2016) versus March, 27th (2016) and illustrates seasonal variation in the top 8 m, as well as an inferred plume push at elevation 14 m, confirmed by water samples from a monitoring borehole 8 m away from the profile (orthogonally to the figure plane).

Monitoring the "pollutant" flow in a supervised test-site using 4-D Electrical Resistivity Tomography in boreholes.

Nikos Papadopoulos[1], Kleanthis Simyrdanis[1]

(1) *Laboratory of Geophysical Satellite Remote Sensing and Archaeoenvironment (GeoSatReSeArch), IMS, FORTH, Rethymno, Greece*

keywords: environmental pollution, boreholes, ERT, monitoring

This work describes the simulation of an environmental scenario where a conductive "pollutant" is slowly concentrated in a confined small area below the ground surface. An apparatus was manually constructed and buried at IMS foundation land (Heraklion, Crete). The "pollutant" was made of salty coloured water with resistivity 0.5 ohm-m. It was slowly introduced in a small area consisted of coarse sandy material through plastic tubes. The area was completely filled with the pollutant after approximately 8,5 hours and electrical tomographic data were collected continuously in regular time intervals for total eight consequent time phases.

Specifically, the target was surrounded by four vertically PVC plastic pipes (named North, South, West, East) and two vertical ones. On each plastic pipe 12 metallic rings were equally spaced every 20cm (72 in total). A multi-strand cable was connected with all the rings with the resistivity meter. For each pair of boreholes (WE, SN) two protocols were selected: (a) full protocol (1608 measurements) and (b) an optimum (507 measurements). Additionally, a 3D full and optimum data set was selected with 9648 and 3042 data set, correspondingly. The optimum data set was based on Jacobian matrix optimisation technique.

The results showed clearly the resistivity change through time, as the "pollutant" gradually was filling the area of the box. Although the whole experiment took place in a controlled small area (excavated pond size was 2x3x2.5m), the results are promising for applying the resistivity optimisation technique for monitoring a real case pollution scenario, since the presence of a conductive pollutant can be identified due to the resistivity contrast with the environmental resistivity values.

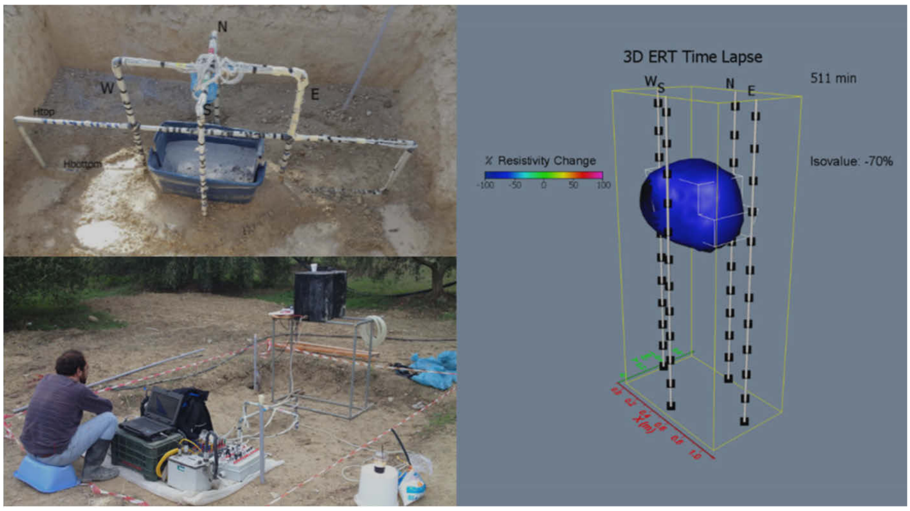


Figure caption: Underground target's position with coarse soil filled slowly with salt water (pollutant) (top left). Monitoring using electrical tomography data acquisition (bottom left). Resistivity data results with the conductive "pollutant" indicated with blue color at the final phase T7 (right).

Monitoring System for remediation of a brownfield

K. Tsakirmpaloglou[1] , T. Martin[1] , O. Kaufmann[1] , P. Goderniaux[1]

(1) Geology and Applied Geology, UMONS, Mons, Belgium

keywords: ERT/IP monitoring, brownfield, remediation

The need of monitoring underground processes and locating targets with an easy and reliable way, led to the use of geoelectrical monitoring techniques. Geoelectrical methods are widely used in a variety of environmental fields and areas. These techniques are developed for assessing among others geotechnical, environmental or hydrogeological processes (Loke et al., 2013). A vast majority of geoelectrical instruments specially designed for monitoring are now in operation and allow the near real-time collection of large amounts of data which are later processed with specific time-lapse inversion algorithms.

The main purpose of this work is the design, implementation, operation and the interpretation of a geoelectrical monitoring system for a brownfield remediation pilot over an old cookery site. The brownfield where the research project is conducted lies in the suburbs of Charleroi city, in Belgium. The site was used as an industrial area, with coking operations. Both the soil and subsoil as well as the groundwater are heavily contaminated down to six meters deep, with heavy metals, cyanides, and hydrocarbons such as BTEX and PAH. The shallow geology mainly consists of three distinct layers. The first layer, from ground to four meters depth, is composed of sand, gravels, slag and shale. The second layer is mainly composed of clay alluvial, while the last layer consists of shale and clay. The piezometric level appears near the surface, at about 1.6 meters deep. Based on soil samples collected in boreholes, and on geoelectrical measurements we concluded that the area shows a high spatial heterogeneity of both subsoil nature and contamination.

The remediation experiment that is conducted in this zone aims at enhancing the biodegradation of hydrocarbons by indigenous bacteria and/or fungi with in situ heating. A set of vertical loop heat exchangers, placed into boreholes down to six meters deep, are used to heat the subsurface medium. To follow the evolution of the underground conditions during the heating experiment, a monitoring system composed of a set of piezometers and piezair for regular air and water sampling, grids of temperature sensors, as well as geoelectrical imaging facilities were installed. The purpose of the monitoring system is to implement 3D models of the subsoil as well as, to monitor the evolution of the electrical properties derived from the bio-degradation process through 4D imaging. Given the underground heterogeneity, especially the high resistivities in the top layer and the rather high conductivity of the saturated backfill, a design based on down-hole electrodes placed on a regular grid has been selected in order to maintain a good resolution at depth. From processing the IP inversion results, we were able to locate high values of changeability, centered around the water table where oxygen availability is higher. This, according to the chemical analysis results, could be connected to hydrocarbon contaminated areas. We were also able to interpret some of the resistivity anomalies as high contaminated areas in the light of chemical analysis conducted on soil samples as well as on water samples from the boreholes in the test zone.

Loke, M.H., Chambers, J.E., Rucker, D.F., Kuras, O., Wilkinson, P.B. (2013): Recent developments in the direct-current geoelectricalimaging method. Journal of Applied Geophysics, 95, 135–156. https://doi.org/10.1016/j.jappgeo.2013.02.017

Generalized Minimum Support Norm for automatic data processing

Gianluca Fiandaca[1], Line M. Madsen[2], Anders Kühl[2], Thue S. Bording[2]

(1) Department of Earth Sciences "Ardito Desio", University of Milano, Milan, Italy
(2) HydroGeophysics Group, Department of Geoscience, Aarhus University, Aarhus, Denmark

keywords: automatic processing, minimum support, inversion

Data outliers significantly affect the inversion process, often forbidding to reach reasonable inversion models and misfits. This is particularly problematic when the L2 norm is used in data space, because in this case outliers play a dominant role in the objective function of the inversion.

In this study we propose to use a generalization of the minimum support norm, namely the asymmetric generalized minimum support (AGMS) norm, for defining the data misfit in the objective function of an iterative reweighted least squared (IRLS) gauss-newton inversion. The AGMS norm in the data misfit puts a cap on the weight of non-fitting data points, allowing for the inversion to focus on the data points that can be fitted. Outliers can be identified after the AGMS inversion computing a classic L2 misfit from the final inversion model.

Synthetic data from a 2D DC sequence comprising 1000 quadrupoles were generated and perturbed, adding random noise on 20% of the quadrupoles, with noise factor (i.e. the ratio between the changed data and the noise-free data) comprised between 0.5 to 0.9 and 1.1 to 2.0. Fifty realization of noised data (i.e. 50 datasets with 1000 quadrupoles, with 200 outliers in each dataset) were generated and processed following the AGMS automatic processing scheme.

As shown in the figure, more than 95% of the outliers were recognized in each noise realization, with only a small number of noise-free data erroneously identified as outliers. Furthermore, the inversion models were minimally affected by the outliers. This automatic processing scheme is very robust and works well also with a significant number of outliers; moreover, this it is fully general and can be applied not only to DC data, but to any geophysical problem simply using the appropriate forward modelling.

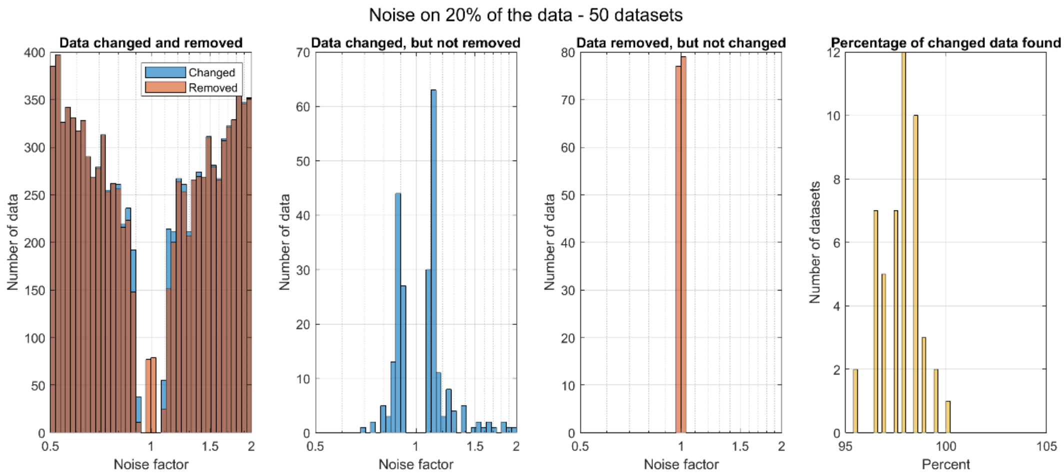


Figure caption: Data rejection based on the asymmetric minimum support norm for fifty realization of a 2D DC data sequence comprising 1000 quadrupoles. From left to right: changed data and removed data as a function of noise factor; data changed but not recognized as outliers; data erroneously identified as outliers; percentage of outlier recognition in the 50 datasets.

Generalized Minimum Support Norm for time-lapse inversion

Gianluca Fiandaca[1], Thue S. Bording[2], Léa Lévy[2], Line M. Madsen[2]

(1) Department of Earth Sciences "Ardito Desio", University of Milano, Milan, Italy
(2) HydroGeophysics Group, Department of Geoscience, Aarhus University, Aarhus, Denmark

keywords: automatic processing, minimum support, inversion

Often in geophysical monitoring experiments time-lapse inversion models vary too smoothly with time, owing to the strong imprint of regularization. Several methods have been proposed for focusing the spatiotemporal changes of the model parameters. In this study, we present and apply a generalization of the minimum support norm, namely the asymmetric generalized minimum support norm, which favour compact time-lapse changes. Inversion results from synthetic direct current resistivity models that mimic developing plumes show that the focusing scheme significantly improves size, shape and magnitude estimates of the time-lapse changes. Inversions of the synthetic data also illustrate that the focusing settings are easily chosen. Inversions of full-decay time-domain induced polarization (IP) field data, both from surface and cross-hole monitoring acquisitions, show that the focusing scheme performs well for field data and multiparameter inversions. Our tests show that the asymmetric generalized minimum support norm reacts in an intuitive and predictable way to the norm settings, implying that they can be used in time-lapse experiments for obtaining reliable and robust results.

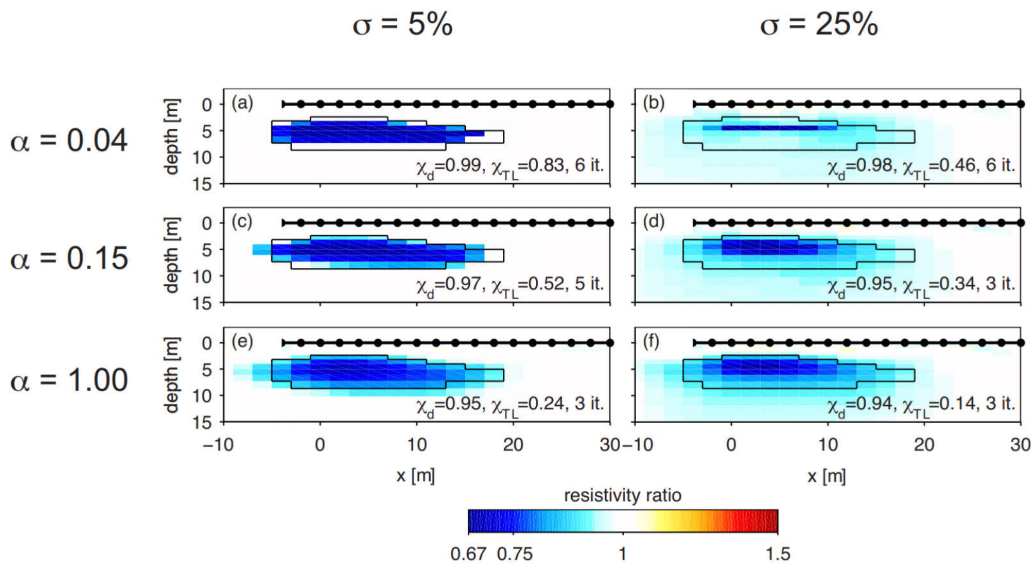


Figure caption: comparison of asymmetric minimum support inversion results when varying the σ and α norm settings (which control the size and the sharpness of the time-lapse changes, respectively). The synthetic data were created using an input model with a resistivity ratio of 0.75 within the outlined plume (black line) and 1 outside, and adding 2 per cent Gaussian noise. The left and right columns show inversions with an a-priori σ of 5 per cent and 25 per cent, respectively

Inversion Based Processing of Time Domain Induced polarization data

Anders K. Kühl[1], Thue Bording[1], Gianluca Fiandaca[2]

(1) HydroGeophysics Group, Department of Geoscience, Aarhus University, Aarhus, Denmark
(2) Department of Earth Sciences "Ardito Desio", University of Milano, Milan, Italy

keywords: Processing, IP, Automisation

With modern large scale or long time monitoring surveys, large amounts of IP data can be acquired and the data processing is often highly time intensive and requires a deal of experience. Here we present a novel approach to automatically process decay curves from time domain IP data.

This is done by iteratively inverting the data using the Generalized Minimum Support (GMS) norm and the L2 Norm. Each decay is inverted for individually, using a fixed geometry 3-Layer buried electrodes model, which can generate any physical decay shape. Constraints are added between 3-Layer models of quadrupoles that were measured spatially adjacent, in order to better remove outliers.

The GMS Norm puts a cap on the weight of non-fitting data points, allowing for the model to focus on the data points that can be fitted. After a GMS inversion cycle, the L2-error of the gates is calculated and those with an error above a chosen threshold are removed.

This approach effectively removes both random and systematic noise, as well as EM effects, which are not modelled in the forward response. The constraints help in removing outlying decays, that otherwise might be fittable with the three layer models.

Comparison with manually processed data and final inversion models show that this automatic processing scheme removes less datapoints than a manual processor while having similar misfits.

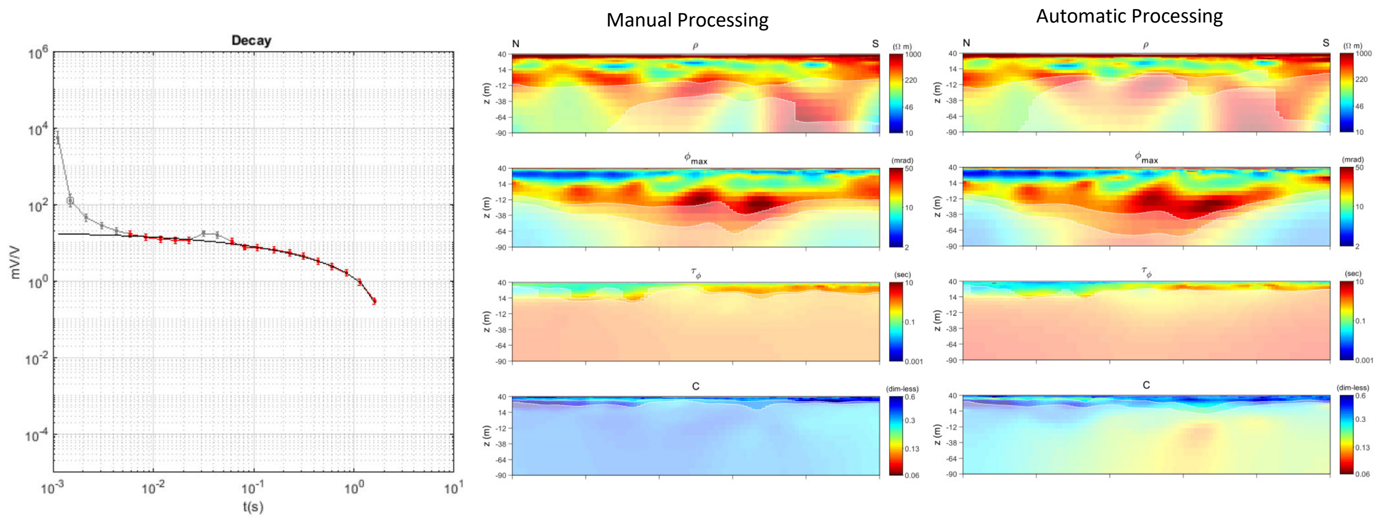


Figure caption: Left: A decay after processing. Removed gates in grey, kept gates in red, circles for negative data, black model used to fit. Center: A Maximum Phase Angle inversion using Manual processing. Right: Same as Center but using the Automatic Processing scheme

Application of a novel data analysis for time lapse multi frequency data in Induced Polarization imaging

Timea Katona[1], Theresa Maierhofer[1], Pauline Oberender[2], Adrian Flores-Orozco[1]

(1) Department of Geodesy and Geoinformation, TU-Wien, Vienna, Austria
(2) Working Group on Karst and Caves, Natural History Museum Vienna, Vienna, Austria

keywords: spectral induced polarization, data processing, permafrost, frost weathering

In spectral induced polarization monitoring, an adequate error quantification is essential to achieve reliable inversion results for both different frequencies and times. Thus, we developed a data processing method to evaluate signal strength and quantify data error. The collection of normal and reciprocal data has been widely accepted for the identification of outliers and parameterization of error models; yet, the acquisition is time-consuming and not suited for the monitoring of fast processes. Moreover, acquisition of reciprocals may be limited in particular electrode configurations with different dipole lengths for current and potential dipoles, and hinder the use of multichannel instruments, i.e., increasing the acquisition time (i.e., multiple gradient). To overcome this limitation, we present a different strategy for analysing multidimensional data sets as collected in time-lapse spectral induced polarization imaging measurements. Our method assesses the variations in the signal strength, related to both the magnitude of the voltage and phase-lag recorded. Moreover, we also investigate the consistency between these phase and voltage readings. In this regard, we can evaluate high and low polarizable areas as well as highly conductive or highly resistive anomalies within the same framework. The assumption is that the phase values should be clouded when plotted against the voltages (as illustrated in Figure 1). The spatial inconsistency within the point cloud indicates then the outliers. Moreover, we investigate through a moving average algorithm the consistency between measurements as a function of the signal-to-noise ratio, along different times and frequencies. To validate the performance of our new approach compared to the NR method, we run benchmark tests based on spectral induced polarization data collected at permafrost and frost weathering sites. Our results show that the new process successfully quantifies random errors at different frequencies.

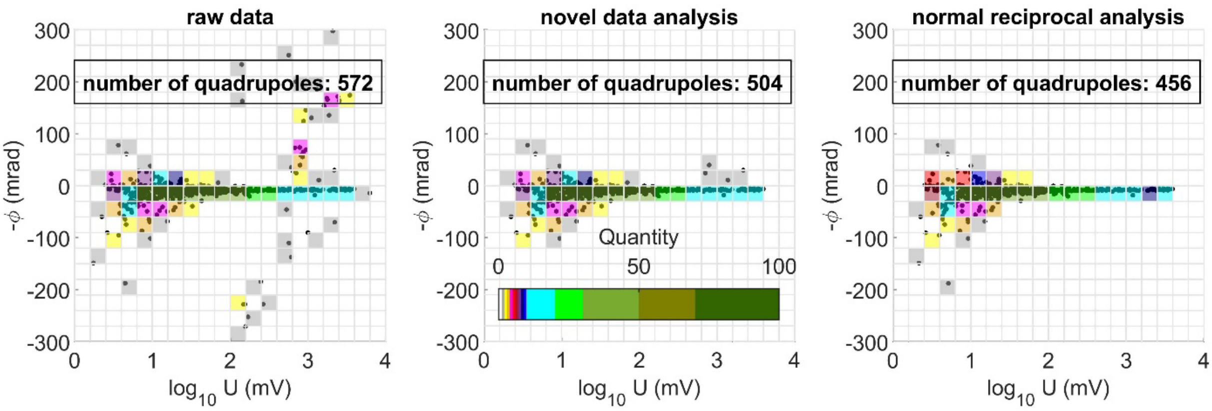


Figure 1: Bivariate histogram of the voltage and phase shift at 0.250 Hz of the raw data (left panel), and after the application of the novel data analysis (middle panel) and after the normal reciprocal analysis (right panel). The colors indicate the number of the data inside of each pixel. Data were collected at a permafrost monitoring site at Schilthorn, Swiss Alps.

ERT monitoring at a landslide-prone hillslope in the Napf region (Switzerland) for regional landslide early warning

Adrian Wicki[1], Christian Hauck[2]

1. *Swiss Federal Research Institute WSL, Birmensdorf, Switzerland*
2. *Department of Geosciences, University of Fribourg, Fribourg, Switzerland*

keywords: ERT monitoring, landslide early warning systems, soil water infiltration

In mountainous regions, rainfall-triggered landslides pose a serious risk to people and infrastructure. Regional landslide early warning systems (LEWS) have proven to be a valuable tool to warn the public about the imminent landslide danger. While regional LEWS are mostly based on empirically related rainfall exceedance thresholds, recent studies have shown that the inclusion of in-situ soil wetness information may considerably improve the forecast goodness. Most soil wetness measurements are based on sensor networks of soil moisture probes or tensiometers, which have a high temporal resolution but lack spatial coverage. In this respect, the use of electrical resistivity tomography (ERT) could add spatially distributed wetness information and potentially improve the identification critically saturated conditions.

To assess the potential of ERT monitoring for the use in a LEWS, two monitoring ERT profile lines were installed in spring 2020 at a hillslope prone for shallow landslides in the Napf region (Switzerland). The profile lines were installed both parallel to and along the slope each consisting of 48 electrodes at 25 cm spacing. Measurements were taken in Wenner-Schlumberger configuration with a remotely controlled Syscal Junior system. As a base routine, daily measurements were taken. During rainfall events, the measurements frequency was increased up to every 2 hours to better resolve infiltration processes. Finally, apparent resistivity datasets were inverted using a time-lapse inversion scheme.

Preliminary results show clear resistivity responses to the infiltration of rainwater and the subsequent progressing of the wetting front as well as the drying up due to evapotranspiration, which are in agreement with observations from collocated soil wetness sensors. Further work will include a correction for ground temperature changes, calculation of absolute volumetric water content and finally a signal comparison with in-situ sensor data during specific infiltration events to assess the information gain by ERT measurements to identify critically saturated conditions.

Geoelectric monitoring during pumping tests

Birgit Jochum[1], David Ottowitz[1], Alexander Römer[1], Gerhard Bieber[1], Stefan Pfeiler[1]

(1) Deptartent of Geophysics, Geological Survey of Austria, Vienna, Austria

keywords: ground water level, 4D-Inversion

In summer 2020, a pumping test lasting for 5 weeks was performed to characterize the hydraulic groundwater conditions. It was accompanied by a geoelectric monitoring profile, several water pressure probes, soil humidity probes and a pluviometer. The pumping test gave us the chance to understand, how a falling or rising water level influences the monitored geoelectric resistivity. The geologic/lithologic situation at the test site is as follows: quaternary fluvial deposits (2 m thick top layer of sand followed by the 6m gravelly aquifer) lying on top of water-impermeable Pannonian silt. The calculated water permeability is $3.5*10^{-3}$m/s.

A total of 260 data sets, consisting of 2344 data points each and gathered at an interval between 1-6 hours, was inverted for selected periods with the 4D-Inversion software developed by KIGAM (Kim et al., 2013). During the 5 weeks lasting pumping test, different pumping rates with pumps located in the vicinity of the geoelectric profile and precipitation events influenced the change of the ground water level. The pumping rates were increased several times, so a stepwise lowering of the ground water level, reaching a maximum change of 2.6m, was monitored with pressure probes. In this period, no significant el. resistivity changes were observed in the corresponding subsurface area. We assume that there is still a significant amount of adhesive water, which takes longer to run off. There are several other effects, such as soil moisture and temperature changes, which had a stronger influence on the el. resistivity in the superficial subsurface area. Moreover, a small leakage in one of the water pipes at profile meter 36.5 shows the influence of water infiltration. So the groundwater level decrease is masked by these effects. On the contrary, when the pumps were turned off at once, the aquifer is flooded within a few hours and causes a significant change of el. resistivity. Yet, the changes are only clearly visible directly at the location of the pumps.

It is obvious that there cannot be a difference in the absolute change of the el. resistivity between the ground water decrease and increase. The only significant difference is the time span for the change. This confirms our assumption from previous landslide monitoring, that you cannot see subsurface soil moisture changes with geoelectric monitoring if the water content does not change rapidly and distinctively.

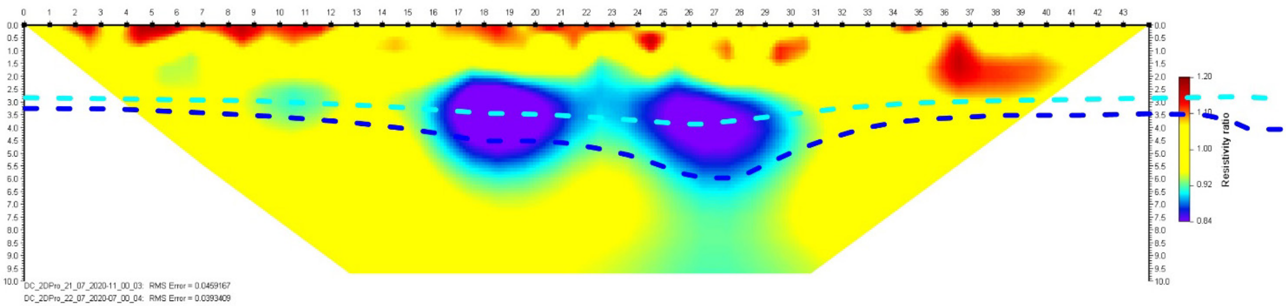


Figure caption: Resistivity ratio of the 4D inversion, before and 20 hours after shut off of the pumps, which are located at 19m and 26m and after the end of the profile. The dark blue line indicates water level before, the light blue level after shut off.

Kim J.H., Supper R., Tsourlos P., Yi M.J. (2013): Four-dimensional inversion of resistivity monitoring data through Lp norm minimizations. – Geophysical Journal International, 195(3), 1640–1656, Doi: https://doi.org/10.1093/gji/ggt324

Electrical and electromagnetic monitoring for engineering applications: a lab test for evaluating the concrete curing phenomenon with 4D-ERT

Luigi Capozzoli[1], Gregory De Martino[1], Valeria Giampaolo[1], Enzo Rizzo[1,2]

(1) Hydrogeosite Laboratory, National Research Council - Institute of Methodologies for Environmental Analysis (CNR-IMAA), Tito (PZ), Italy
(2) University of Ferrara, Ferrara, Italy

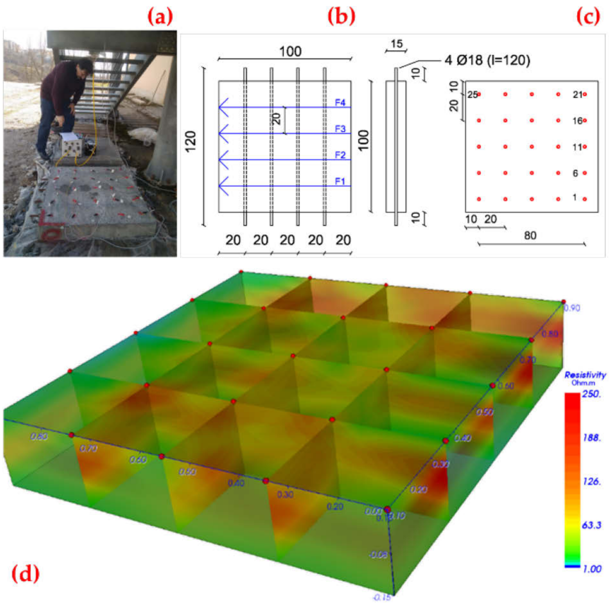
<u>keywords</u>: 3-D time-lapse ERT, GPR, concrete curing, water content, non-invasive diagnostic

The variation of the water content of structural elements realized according the reinforced concrete (RC) technology can be effectively monitored with use of electrical and electromagnetic geophysical method. Indeed, presence of water hardly increases electrical conductivity and dielectric constant of the concrete, while its absence or limited presence causes higher electrical resistivity behaviour and a greater velocity of propagation of EM waves.

The experiment consists in the evaluation of potentialities and limits of 4-D non-destructive geophysical techniques for monitoring the concrete curing phenomenon for a month immediately following placing and finishing. In particular, time-lapse 3-D ERT and GPR surveys have been applied to a RC (Concrete C28-35, Steel B450C) panel of sizes 1 x 1 x 0.15 m, as showed in fig. 1.

25 electrodes placed every ten centimetres and distributed on five rows have used to perform geoelectrical measurements using dipole-dipole array and the Syscal Pro (red circles in fig. 1c). The electrical resistivity measurements were repeated every day for one month and measured resistivity data were inverted using the ERTLab 3D software.

Simultaneously, GPR data (2 GHz antenna coupled to SIR 3000 GPR system) were acquired (blue arrows in fig. 1b). The hyperbolas generated by the presence of four rebars of the panel are automatically picked for estimating the dielectric permittivity of the concrete; moreover, the time of the first arrivals was monitored for 30 days.



A diffuse increase of the resistivity values due to the curing of the concrete has been detected for the entire volume investigated, except for the lower zones where there is, likely, the accumulation of water (fig. 1d). This is in according with the dielectric permittivity variations showing a negative trend related to the evaporation of the water.

<u>Figure caption:</u> behavior of the panel recorded with ERT. As expected, the continuous decrease of the water content in the panel monitored for 30 days, caused a constant increase of the electrical resistivity values and EM velocity.

Estimation of water content distribution using time-lapse electrical resistivity tomography and ensemble Kalman filter

Anne Isabelle[1], Gabriel Fabien-Ouellet[1], Thomas Pabst[1], Adrien Dimech[2], Li Zhen Cheng[2]

(1) Polytechnique Montréal, Montréal, Canada
(2) Université du Québec en Abitibi-Témiscamingue, Rouyn-Noranda, Canada

keywords: mining reclamation, data assimilation, electrical resistivity tomography, water content

Several strategies can be used to mitigate the risk of acid mine drainage associated with mine wastes. One of these methods is to build a cover with capillary barrier effects (CCBE) over the tailings to prevent the migration of oxygen to the reactive wastes. The performance of such cover relies on precise control of the degree of saturation in the moisture-retaining layer, which should remain above 85%. Current methods for evaluating the water content use point measurements (capacitance or TDR sensors) and their representativity is limited since the waste storage facilities often cover several hectares. Time-lapse electrical resistivity tomography (ERT) shows promise as it can monitor changes in the electrical conductivity (EC) of soil on a large scale. EC is directly related to saturation, but it is also affected by other factors such as temperature, porosity, and electrical conductivity of pore water. ERT should be combined with other information to obtain a quantitative and accurate estimation of the degree of saturation.

We propose to use ensemble Kalman filters (EnKF) to combine point moisture measurements, ERT and hydrogeological modeling to obtain a near-real-time estimate of water content distribution within the control layers of the covers. The ensemble Kalman filter (EnKF) is a probabilistic data assimilation approach used for nonlinear problems that has been used successfully in many hydrogeological and geophysical applications, although not widely used in mining engineering. A major strength of EnKFs is their ability to provide the posterior state distribution (i.e. water saturation here) through the ensemble covariance, thus leading not only to an estimate of the most likely state but also its uncertainty.

Our study focuses on a column water infiltration test reproducing the structure of a large-scale experimental CCBE (geometry and materials) under investigation at Canadian Malartic, a gold mine located in Quebec, Canada. We model the 1D flow of groundwater through the retention layer to predict variations in water saturation over time and space as well as the measurements of six probes placed within the column. Geoelectrical forward modeling calculates the resistance measurements of the array of 32 electrodes located on two opposite sides of the column wall. We generate independent realizations of hydrogeophysical parameters (porosity, hydraulic conductivity, water retention curves, EC relation of water saturation, …) which are constrained by laboratory measurements on waste samples. EnKF is then used to condition each realization to the probe and ERT measurements throughout the experiment.

The stability and accuracy of the EnKF algorithm are tested with synthetic experiments. We discuss the effect of different parameters: the size of the ensemble, the data co-variances and the adequacy of 1D flow modeling to reproduce the CCBE conditions. Using ERT in conjunction with probe measurements seems promising to predict spatiotemporal variations in water saturation. We finally test our approach on the drying cycle of the column infiltration experiment and discuss the performance of the EnKF to reproduce the observed water saturation variations.

Geoelectrical monitoring for detecting soil moisture changes in the main rooting zone of forest sites with different lithology in Lower Franconia, Germany

Julian Fäth[1], Julius Kunz[1], Christof Kneisel[1]

(1) *Institute of Geography and Geology, University of Würzburg, Würzburg, Germany*

keywords: Geoelectrical monitoring, soil hydrology, moisture content

For assessing the water supply of forest stands, knowledge about the small-scale distribution of the soil moisture as well as its temporal changes is a key issue especially in an era of climate change. Traditional methods, like taking soil samples or installing data loggers, solely collect parameters of a single point or of a small volume in the soil, respectively. Since time-lapse electrical resistivity monitoring is a suitable method to qualitatively monitor the soil moisture variability, we used this approach for a forest site to obtain high-resolution data of soil moisture variation, although, electrical resistivity is influenced by further parameters such as soil texture, organic content and salinity.

As a pre-study, a 2D geoelectrical monitoring was installed in a forest monitoring plot of the Bavarian Institute of Forestry (LWF) nearby Würzburg which represents one of the driest forest sites in Bavaria. For five years, geoelectrical measurements have been performed and are compared with monitoring data (measured by the LWF) such as e.g., throughfall, bulk precipitation, air temperature and point measurements of soil moisture content.

The weekly changing resistivity values are highly correlated with the variation of the soil moisture to a depth down to 1m representing the main rooting zone. We also address further relations between electrical resistivity and air temperature or precipitation events. Our results show that time-lapse electrical resistivity imaging is a suitable method for monitoring relative changes in soil moisture content also at forest sites, even if soil temperature and salinity variations cannot be considered in electrical conductivity measurements to isolate additional effects like changing salt distributions as in our case. Since we are currently instrumenting additional monitoring plots in Lower Franconia we will also present first new data for sites with different soil types.

Hydrogeological and geoelectrical monitoring of mining reclamation covers to assess the accuracy of moisture content estimations

Adrien Dimech[1], LiZhen Cheng[1], Bruno Bussière[1], Michel Chouteau[2], Gabriel Fabien-Ouellet[2] and Anne Isabelle[2]

(1) *Université du Québec en Abitibi-Témiscamingue, Rouyn-Noranda, Canada*
(2) *Polytechnique Montréal, Montréal, Canada*

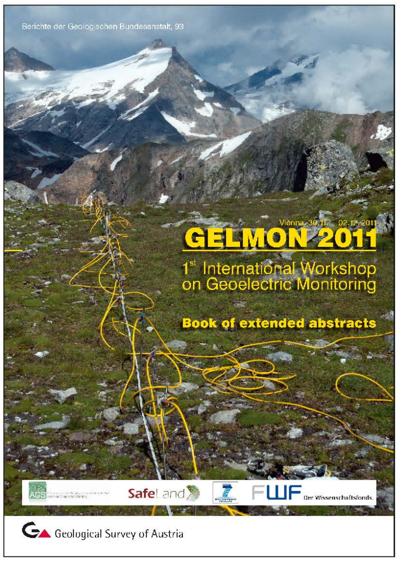
keywords: tailing storage facility, cover reclamation, geoelectrical monitoring, moisture content

Tailing storage facilities (TSF) are large structures used to store uneconomic mineral. They are generally reclaimed after mine operations with engineered covers that limit the flow of water or oxygen in order to prevent tailings oxidation. One of the most promising reclamation approaches is to build multilayer covers with capillary barrier effects (CCBEs), which act as oxygen barriers when a retention layer remains above 85% of saturation, reducing oxygen migration by a factor of 10 000. Long-term monitoring programs traditionally use moisture content sensors in the layers of interest in order to evaluate if the cover performance decreases over time. However, since they have a limited investigation volume, many sensors may be needed to perform a large-scale monitoring, which represents important costs for monitoring programs.

In this context, time-lapse electrical resistivity tomography (TL-ERT) is a promising tool to spatially extend point data since conductivity images can be converted into distributions of moisture content. Although TL-ERT has been successfully applied to monitor spatiotemporal changes in moisture content for different contexts, few studies assess the accuracy of TL-ERT regarding moisture content estimations for mine wastes. However, accuracy is critical when TL-ERT is applied to monitor CCBEs performance as small changes in saturation (typically around 85%) must be precisely detected to determine whether the cover meets the performance criteria as an oxygen barrier.

This study presents preliminary results from the hydrogeophysical monitoring of a large-scale experimental CCBE at the TSF of Canadian Malartic Mine, an active open-pit gold mine in Quebec. A total of 30 moisture content sensors and 372 stainless-steel electrodes buried at different depths in the cover are used to monitor the changes in water content, temperature and conductivity due to natural precipitations. The lateral spacing between electrodes ranges between 10 cm and 2m to form 2D and 3D imaging grids with different spatial resolutions. The electrodes are located at the bottom and the top of the 1m-high retention layer of the CCBE to maximize measurement sensitivity in the layer acting as the oxygen barrier. The monitoring database includes one year of continuous measurements from moisture content sensors and a total of 55 ERT images during a two-month period in summer 2020. The protocol used for each ERT image contains 2500 measurements with both inline and crossline, direct and reciprocal Wenner, dipole-dipole and gradient configurations.

We propose a methodology to assess the accuracy of moisture content distribution calculated from geoelectrical monitoring with both field measurements and numerical modelling. We compare (1) point moisture content measurements made by capacitance sensors, (2) distributions of moisture content modelled with PFLOTRAN and (3) moisture content distributions derived from ERT. The time-lapse resistance measurements are inverted using E4D and the conductivity distribution is converted into moisture content using petrophysical relationships determined from laboratory and in-situ sensors. These results will be useful to assess the accuracy of TL-ERT and will help to optimize the long-term autonomous monitoring of the experimental covers starting in winter 2021 with a PRIME instrument in collaboration with the British Geological Survey.



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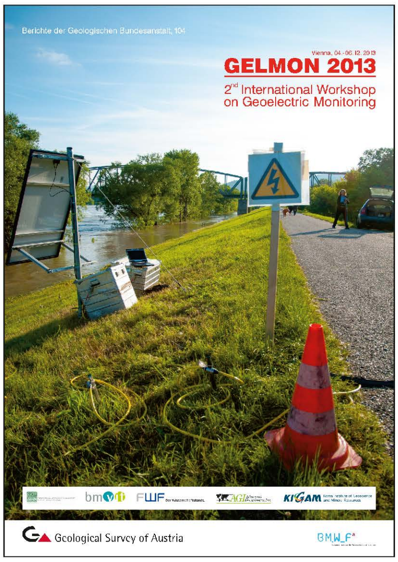

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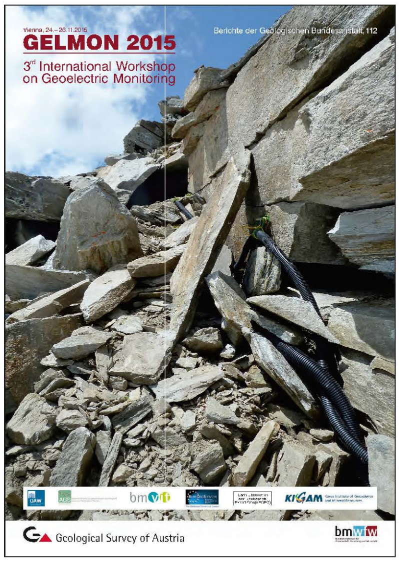

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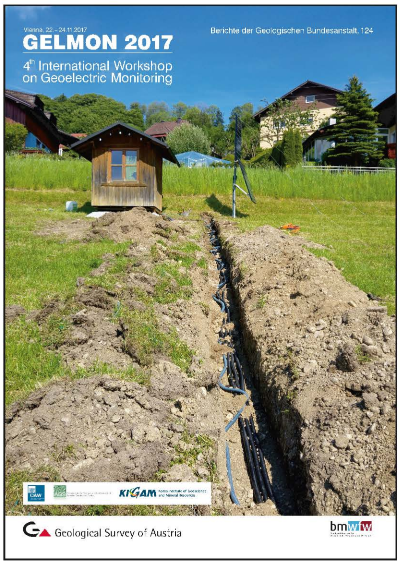

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