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# GELMON 2017

## 4<sup>th</sup> International Workshop on Geoelectric Monitoring



**GELMON 2017**  
**4<sup>th</sup> International Workshop on Geoelectrical Monitoring**  
**Book of Abstracts**  
**November 22<sup>nd</sup> – November 24<sup>th</sup>, 2017**  
**Vienna, Austria**

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## TABLE OF CONTENTS

<b>PREFACE</b>			<b>I</b>
<b>PROGRAMME OVERVIEW</b>			<b>II</b>
<b>GEOTECHNICS</b>	<b>Wednesday</b>	<b>11:30 – 12:30</b>	<b>1</b>
A Study on the Methods for Detection of Underground Cavity			1
Assessment of soft ground at tidal reclaimed land by integrated analysis of geoelectrical monitoring and CPTU data			2
Preliminary evaluation of ground collapse from sandy soil with varying volumetric water content in a soil chamber			3
Experimenting a permanent geoelectrical monitoring system for stability assessment of levees			4
Monitoring of infrastructure slopes: an example of an operational railway cutting			5
A Case Study of the Ground Collapse due to Excavation Using Non-Destructive Testing			6
<b>MONITORING ON DAMS</b>	<b>Wednesday</b>	<b>14:00 – 15:30</b>	<b>7</b>
<b>KEYNOTE SPEAKER: TORLEIF DAHLIN</b>			
KEYNOTE LECTURE: Monitoring of embankment dams and waste deposits			7
Resistivity monitoring for dam safety inspection in Korea			8
Long-term ERT monitoring of embankment dams in Sweden			9
Temperature effect in resistivity monitoring in embankment dams			10
3D ERT monitoring during dyke overtopping experiment using multi-current transmission technique			11
<b>CONTAMINATION</b>	<b>Wednesday</b>	<b>15:30 – 17:30</b>	<b>12</b>
<b>KEYNOTE SPEAKERS: PANAGIOTIS TSOURLOS, ADRIÁN FLORES-OROZCO</b>			
KEYNOTE LECTURE: ERT time-lapse monitoring of a full-scale coal tar remediation			12
KEYNOTE LECTURE: Electrical monitoring of nano- and micro-scale particle injections for in-situ groundwater remediation			13
An interpretation of resistivity monitoring data obtained in Geumsan landfill site			14
The DC resistivity and time-domain IP monitoring system of Alingsås			15
Geoelectrical monitoring in landfill bioreactor to study waste mass biodegradation behavior			16
Resistivity monitoring for leachate detection in a livestock disposal site			17
Characterisation and monitoring of in-situ remediation of chlorinated hydrocarbon contamination using an interdisciplinary approach (MIRACHL)			18

<b>NATURAL HAZARDS</b>	<b>Thursday</b>	<b>09:00 – 11:00</b>	<b>19</b>
<b>KEYNOTE SPEAKERS: ANDREAS KEMNA, JONATHAN CHAMBERS</b>			
KEYNOTE LECTURE: Use of geoelectrical monitoring methods for characterizing thermal state, ice content and water flow in permafrost environments			19
KEYNOTE LECTURE: Geophysical characterization, monitoring and early warning of slope failure: a review of methodological developments at the Hollin Hill landslide observatory			21
Application of time-lapse ERT in active layer monitoring at Crater Lake, Deception Island, Antarctica			22
Joint inversion of electric and seismic data applied to permafrost monitoring			23
Identification of outliers, electrode effects and process dynamics in electrical self-potential monitoring data			24
Data Quality Analysis of ERT data of geoelectrical permafrost monitoring on Hoher Sonnblick and on Kitzsteinhorn (Austrian Central Alps)			25
Integrating tachymetric surveying and ERT measurements to construct the sliding plane of an active landslide near Maria Eck monastery (Bavarian Alps, Germany)			26
Integrated monitoring of an active landslide in Lias Group Mudrocks, North Yorkshire, UK			27
Geoelectrical and geotechnical monitoring on a landslide in Wolfsegg am Hausruck, Austria			28
<b>TECHNICAL INNOVATION, LAB</b>	<b>Thursday</b>	<b>11:00 – 12:00</b>	<b>29</b>
Towards a geophysical system for the remote autonomous monitoring of the near surface			29
Time-lapse ERT measurements to monitor rainfall triggered landslides at the laboratory scale			30
4D ERT monitoring of subsurface water pipe leakage during a controlled field experiment			31
Geoelectrical monitoring during waste biodegradation process at laboratory scale			32
Towards a real-time 4D Electrical Resistivity Tomography			33
Considerations regarding surface to borehole ERT			34
Development of new underground exploration method			35
High-speed geoelectrical monitoring of artificial rain experiments at a slope using a large-scale rainfall simulator			36

<b>HYDROLOGY</b>	<b>Thursday</b>	<b>14:00 – 16:00</b>	<b>37</b>
<b>KEYNOTE SPEAKERS: FREDERIC NGUYEN, GIORGIO CASSIANI</b>			
KEYNOTE LECTURE: Recent developments using ERT-derived temperature for monitoring and characterizing aquifers			37
KEYNOTE LECTURE: Characterization and monitoring of the riparian and hyporheic zones			38
Joint assessment of soil hydraulic properties by constraining geoelectrical tomography measurements with X-ray Computed Tomography pore architecture information			39
Infiltration of treated wastewater in a soil-based constructed wetland: usage of time-lapse ERT to monitor saline tracer injection.			40
Hydrogeophysical monitoring of water infiltration in an experimental waste rock pile using 3D time-lapse Electrical Resistivity Tomography			41
Long-time resistivity monitoring of a freshwater/saltwater transition zone using vertical electrode systems			42
Monitoring infiltration and subsurface stormflow in layered slope deposits with 3D ERT and hydrometric measurements			43
Spatialization of subsurface properties and states using geophysical and geostatistical methods			44
<b>BIOSPHERE AND GEOPHYSICS</b>	<b>Thursday</b>	<b>16:00 – 17:30</b>	<b>45</b>
<b>KEYNOTE SPEAKER: MAXIMILIAN WEIGAND</b>			
KEYNOTE LECTURE: Monitoring crop root systems using electrical impedance tomography			45
Agroforestry in temperate regions: where does the water go? Electrical resistivity tomography as a tools to help us find out.			46
A forward model for electrical conduction in soil-root continuum: a virtual rhizotron study.			47
Developing an electrode design for EIT field measurements on crop root systems			48
<b>CO2 AND OPEN SESSION</b>	<b>Thursday</b>	<b>16:00 – 17:30</b>	<b>50</b>
Geoelectrical investigations at a planned ICDP drill site in the geodynamic active Eger Rift to understand subsurface CO2 migration processes			50
Demonstration of applicability of geoelectrical imaging as monitoring tool for the complete life-cycle of a CO2 storage reservoir			51
Integrating ERT and other near-surface geophysical techniques for the investigation of a maar structure near Neualbenreuth (Eastern Bavaria, Germany)			52

**ADVANCES IN INVERSION**                      Friday                      10:00 – 12:30                      **53**

**KEYNOTE SPEAKERS: THOMAS GÜNTHER, MYEONG-JONG YI**

KEYNOTE LECTURE: Advanced ERT inversion strategies with BERT & pyGIMLi	53
KEYNOTE LECTURE: Data Processing and 4D Inversion of ERT monitoring data	54
Effects of near surface resistivity changes on time lapse ERT inversion	55
3D resistivity inversion using a nonlinear partial derivative	56
Interpretation of resistivity data based on inversion with structural constraints for the detection of cavities during construction	57
Electrical Resistivity Tomography regularisation for piecewise smooth models	58
Towards unified and reproducible processing of geoelectrical data	59
4D inversion for automated near real-time ERT monitoring applications	60
Implementing positivity constraints in 4-D resistivity time-lapse inversion	61

## Preface

For the Geological Survey of Austria, it was again an honour to host more than 80 scientists from 16 countries all over the world. This broad international acceptance shows that the GELMON workshop has evolved to be an institution for scientific exchange and networking in the field of Geoelectrical Monitoring. The collection of abstracts presented in this book proves the wide variety of applications for the method of Geoelectrical Monitoring. Practical applications like monitoring of dams and dykes, landslides or contaminated sites were presented as well as scientific experiments like monitoring of tracer movement and small scale lab experiments. The last day of the workshop was dedicated to new developments of data processing and inversion.

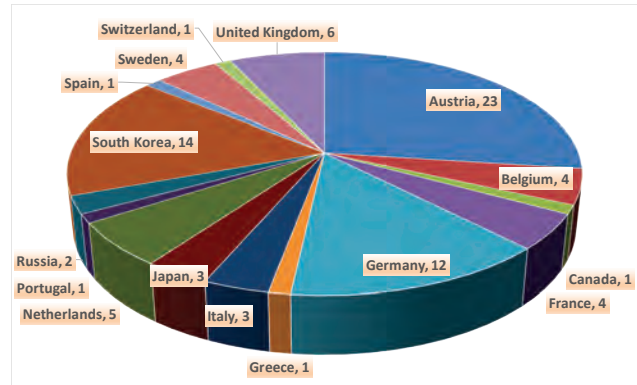


Figure 1: Country statistics of participants

The review of abstracts from the first GELMON 2011 to now shows the technological progress of the method, this year's contributions showed for instance that the Induced Polarization method, that is very demanding, as huge amounts of data is measured very quickly, is now on the transition from avant-garde to state of the art.

Nevertheless, not only the methods are evolving, also the GELMON itself is subject to changes. A new workshop format is introduced, only a handful of speakers were invited to hold keynote lectures while all other contributions were scheduled in the poster sessions with a short presentation. We think that this format is the right tool to ensure enough time for discussion even with a higher number of contributions.



Figure 2: Group foto of 2017's participants – we'd appreciate to see you again in Vienna 2019!

Finally we would like to acknowledge the support of the Korea Institute of Geoscience and Mineral Resources (KIGAM), the Earth Observation and Geohazard Expert Group (EOEG) of EuroGeoSurveys, the Austrian Academy of Science (ÖAW), the Federal Ministry of Science, Research and Economy (BMWFV), the Austrian Geophysical Society (AGS) and the Vienna Convention Bureau.



## General Workshop Programme Overview

### Wednesday, Nov. 22<sup>nd</sup>:

11:00	Workshop opening Robert Supper	Head of Applied Geosciences Division Geological Survey of Austria
	Wolfgang Lenhardt	President of the Austrian Geophysical Society
	Peter Seifert	Director of the Geological Survey of Austria
11:30 – 12:30	GEOTECHNICS	
14:00 – 15:30	MONITORING ON DAMS	
15:30 – 17:30	CONTAMINATION	

### Thursday, Nov. 23<sup>rd</sup>:

09:00 – 11:00	NATURAL HAZARDS (PERMAFROST AND LANDSLIDES)
11:00 – 12:00	TECHNICAL INNOVATION AND LAB EXPERIMENTS
14:00 – 16:00	HYDROLOGY
16:00 – 17:30	BIO-GEO INTERACTION, CO <sub>2</sub> , OPEN SESSSION

### Friday, Nov. 24<sup>th</sup>:

10:00 – 12:30	ADVANCES IN INVERSION
12:30 – 13:30	DATA REPOSITORY, FINAL DISCUSSION, CLOSING REMARKS

## A Study on the Methods for Detection of Underground Cavity

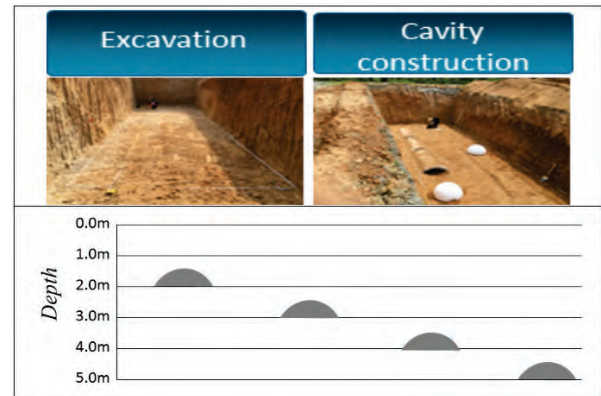
Yushik Han<sup>1</sup>, Heejeung Sohn<sup>1</sup>, Ki-cheong You<sup>1</sup>

(1) Geotechnical Engineering Research  
Institute of Korean Geotechnical Society,  
Seoul, Korea

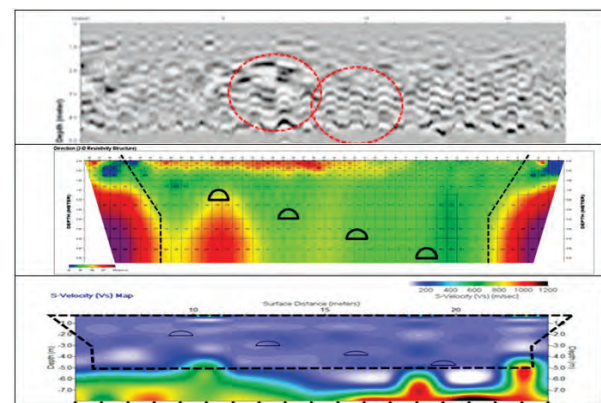
keywords: Ground Penetrating Radar,  
Electrical Resistivity, Multi-channel Analysis  
of Surface Wave

Sinkholes that have occurred in South Korea have been created mainly due to artificial causes rather than natural causes, it is necessary to have a technique that can predict and evaluate risk factors related to ground subsidence(Han and Hwang, 2017).

Representative methods for exploring the Earth's subsurface include ground penetrating radar (GPR) exploration, MASW(Multi-channel Analysis of Surface Wave) exploration, and electrical resistivity survey. In this study, a test bed (depth of 5m) was constructed for exploration of underground cavities, and GPR, electrical resistivity and MASW field survey were conducted and compared. As a result, GPR (100MHz) exploration was possible to depth of penetration depth of 3.0m at low frequency. In the region where the soil is loosened in the electrical resistivity survey, the conductivity of the soil is high because of the characteristic of low resistivity. Therefore, it is difficult to detect underground cavities with small depths less than 1.5m depth. MASW(Multi-channel Analysis of Surface Wave) survey showed a sensitive response depending on the loose and dense condition of the ground.



Construction of Test bed (left top of Cavity construction, left bottom of Cavity burial location).



Detection results of Underground Cavity (right top of GPR result, right middle of electrical resistivity result, right bottom of MASW result).

### ACKNOWLEDGEMENTS

This research was supported by the Korea Agency for Infrastructure Technology Advancement under the Ministry of Land, Infrastructure and Transport of the Korean government. (Project Number: 17SCIP-B108153-03)

### REFERENCES

Han, Y. and Hwang, H. W. (2017): Discussion on the Sinkhole forming Mechanism, , International Conference on Recent Innovations in Engineering and Technology, pp. 9~11.

## Assessment of soft ground at tidal reclaimed land by integrated analysis of geoelectrical monitoring and CPTU data

Ji Yoonsoo<sup>1</sup>, Oh Seokhoon<sup>2</sup>

(1) *Research Institute for Earth Resources, Kangwon National University, Korea*

(2) *Department of Energy and Resources Engineering, Kangwon National University, Korea*

keywords: geoelectrical monitoring, soft ground, geostatistics, CPTU

Evaluation of soft grounds is essentially required for construction of geotechnically stable structures. At construction sites, methods of obtaining data through in-situ tests such as boring investigations or identifying the physical properties of grounds through indoor tests after sampling are widely used. The on-site ground survey method provides accurate information on the position of one point but has a problem of difficulties in precisely identifying wide areas. On the other hand, geophysical explorations enable acquiring information on a relatively large area rather than in-situ tests but have a limitation of difficulties in providing quantitative information. Therefore, in this study, an integrated analysis technique that provides quantitative information for a large area was proposed by combining the advantages of the two methods, and the reliability of the analysis technique was confirmed by applying it to soft ground assessment.

To that end, a reclaimed ground where the distribution of soft grounds should be evaluated was selected as a study area. Piezocone Penetration Tests (CPTU) and boring investigations were used as geotechnical survey methods, and geoelectrical monitoring were performed as geophysical explorations. In this study, long-term data (10 months) were acquired to identify the applicability of geoelectrical monitoring. The geoelectrical monitoring data were processed using time-lapse inversion (Res2DInv, 2013), and 4D inversion (IP4DI, 2013).

To overcome the limitation of qualitative geophysical explorations, quantitative soft ground evaluation was performed through the integrated analysis with geotechnical survey data. The integrated analysis was performed using a variogram based geostatistical simulation method. The in-situ ground survey data used in the simulation are CPTU tip resistance and the geophysical exploration data used in the simulation are electrical resistivity. After analyzing the spatial correlations between individual physical properties, the Sequential Gaussian Co-Simulation (COSGSIM) was applied. Through the COSGSIM, accurate but spatially limited ground information provided by CPTU could be expressed as three-dimensional distribution data. To verify that the COSGSIM data were correctly estimated, drilling data at locations where CPTU and geophysical explorations were not performed were examined. Through the verification of simulation results using drilling data, it was identified that the depths where soil textures change and the locations judged to have soft grounds based on the N values in standard penetration tests were identical. For quantitative evaluation, simulation results were used to calculate the volume of the soft ground, which confirmed the usefulness of the geostatistical integrate technique.

## Preliminary evaluation of ground collapse from sandy soil with varying volumetric water content in a soil chamber

Heejeung Sohn<sup>1</sup>, Yushik Han<sup>1</sup>, Ki-cheong You<sup>1</sup>,  
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Seoul, Korea*

keywords: volumetric water content, time domain Reflectometry(TDR), Ground Penetrating Radar(GPR), relative dielectric permittivity

Recently, interest has arisen in the study of the stability of soil during ground excavation, by predicting changes in groundwater level using the GPR and TDR exploration. In this study, the changes in volumetric water content within the soil in the vertical direction were measured continuously by the TDR exploration, and the change in the horizontal direction was measured by the GPR. The result of this experiment can be used as a basis for analysing the major contributing factors of ground relaxation and the formation of cavities. Some soil index properties were obtained from some field tests that include: particle size distribution, unit weight, and water content. In order to reproduce the groundwater seepage in the soil chamber, a porous mat was installed below the chamber to control the groundwater level. The variation of volumetric water content in the sand layer was obtained by conducting the TDR test which can measure the permittivity of the sandy soil layer. In addition, the GPR exploration was conducted to determine the dielectric constant response to soil within the large area of the soil chamber. The result of this study can be used to predict the potentials of ground collapse, by monitoring the  $\theta$ -t curve. The curve can be obtained from the GPR measurements of changes in volumetric water content ( $\theta_0$ ,  $\theta_r$ ,  $\theta_s$ ) and the TDR measurements of change in groundwater level in the soil chamber.

### ACKNOWLEDGEMENTS

This research was supported by the Korea Agency for Infrastructure Technology Advancement under the Ministry of Land, Infrastructure and Transport of the Korean government. (Project Number: 15SCIP-B108153-01)

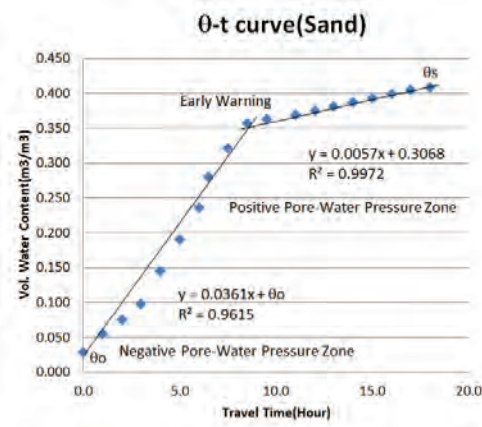


Figure: soil chamber test (top),  $\theta$ -t curve measured by soil chamber test (bottom).

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Sohn, H. and Yoo, K. (2017): "Accuracy Analysis of Empirical Equation Between Dielectric Constant and Volumetric Water Content Using Soil Lab Test and GPR Travel Time", Proceedings, 79th EAGE Conference and Exhibition 2017, Paris, France.

## Experimenting a permanent geoelectrical monitoring system for stability assessment of levees

Greta Tresoldi<sup>1\*</sup>, Diego Arosio<sup>2</sup>, Azadeh Hojat<sup>3,1</sup>, Laura Longoni<sup>1</sup>, Monica Papini<sup>1</sup>, Luigi Zanzi<sup>1</sup>

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keywords: levee stability, seepage, water content

Levees are the last defence for human lives and properties against threatening river floods. Unfortunately, no objective procedure to assess the stability of the embankments is currently defined in Italy and only visual inspections are mandatory according to the current law.

The aim of this work is to assess the stability of earthen levees in real time and in an indirect, cost effective and reliable way, thanks to permanent geoelectrical monitoring. A prototypal resistivity meter was designed and installed on an embankment of an irrigation canal near Mantova (northern Italy) in order to control soil saturation and seepage through the levee.

The device is designed to be installed permanently: it is powered by a solar panel and it works remotely, sending data through internet connection to a web database. In the same site a meteorological station was installed to correlate external variables, such as water level, temperature and rainfall, to the measured data. Data from two years of operation have been collected and analysed so far. The long-period seasonal variations of resistivity within the levee body associated with the level of water in the irrigation canal have been characterized.

Rainfalls and temperature variations also affect the resistivity maps and the data from the meteorological station are used to consider these effects.

In order to monitor soil water content, an empirical and site dependent function that links inverted resistivity values to water content levels was developed using the data obtained from core samples (Figure). Applying this calibration function, water content maps can be used to implement the analysis of seepage and stability risks and to activate alarms when fixed thresholds are overcome.

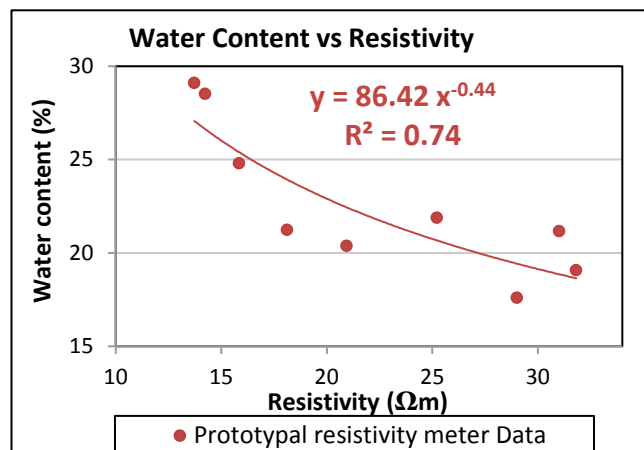


Figure: Water content vs resistivity relationship.

### ACKNOWLEDGEMENTS

The prototype of resistivity-meter has been developed in collaboration with LSI-Lastem. The research was partially funded by Fondazione Cariplo, grant n° 2016-0785.

## Monitoring of infrastructure slopes: an example of an operational railway cutting

Sebastian Uhlemann<sup>1,2</sup>, Jonathan Chambers<sup>1</sup>, Philip Meldrum<sup>1</sup>, Paul Wilkinson<sup>1</sup>, Russell Swift<sup>1</sup>, David Hutchinson<sup>3</sup>

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- (2) *ETH Zurich, Institute of Geophysics, Zurich, Switzerland*
- (3) *Network Rail Infrastructure Ltd, York, UK*

keywords: infrastructure, landslide, moisture dynamics

The British railway network is one of the busiest in the world; annually more than 1.3 billion passenger journeys are made and more than 100 million tonnes of freight are transported. In the context of ageing infrastructure assets, remote condition monitoring has been identified as one of the most cost-effective techniques to inform about asset degradation and performance, while requiring fewer site visits. We present data delivered by a novel, pro-active infrastructure monitoring and evaluation (PRIME) system, which remotely acquires ERT and conventional geotechnical point sensor data. Using laboratory-derived petrophysical relationships, resistivity variations are translated into moisture dynamics. The study site, an

operational railway cutting, has a history of slope instabilities; a relict landslide is situated in the centre of the monitoring area. This grass-covered area provides contrast to surrounding densely vegetated woodlands and offers the opportunity to use resistivity data to study the effects of vegetation on the shallow moisture dynamics and assess their impact on the slope stability. Our results show that evapotranspiration and canopy cover led to strongly increasing resistivities in summer, indicative of significant loss of moisture in the vegetated part of the slope, while the grassland only showed minor variability. In winter, rainfall and groundwater dynamics led to rapid saturation of the entire slope, during times when biological activities were at their minimum and no canopy was present. Resistivity and moisture dynamics show significantly greater variability in the vegetated than in the grass-covered part (Fig. 1). This may lead to faster weathering of the surficial materials in the vegetated part, as the material cycles between states of very low saturation, where desiccation cracks may occur, and full saturation. These insights into the moisture dynamics will aid engineers in designing future infrastructure slopes and intervention strategies for existing unstable slopes.

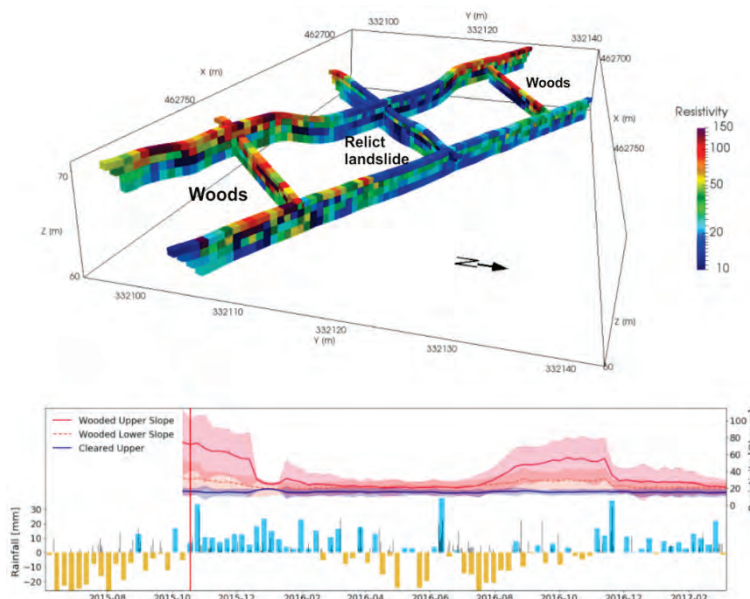


Figure 1: Resistivity baseline image, showing low resistivities of the relict landslide and high resistivities in the wooded areas. Lower panel shows resistivity dynamics and effective rainfall.

## A Case Study of the Ground Collapse due to Excavation Using Non-Destructive Testing

Ki-Cheong Yoo<sup>1</sup>, Yushik Han<sup>1</sup>, Heejeung Sohn<sup>1</sup>, Jinwoo Kim<sup>1</sup>

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keywords: Ground collapse, Non-destructive Testing, Ground Penetrating Radar(GPR), Relative dielectric permittivity

A ground collapse can be caused by natural and artificial factors. Ground collapses that have occurred frequently in Korea were observed and classified into different types by the main contributing factor. In this study, ground collapse induced by groundwater level disturbance in an excavation site was analyzed. Also, ground loosening region around the excavation site was detected and analyzed using non-destructive testing, such as GPR (Ground Penetrating Radar) survey and Electrical Resistivity. The result of the surveys showed that the ground was loosened widely over the surrounding area of the excavation due to groundwater discharge.

### ACKNOWLEDGEMENTS

This research was supported by the Korea Agency for Infrastructure Technology Advancement under the Ministry of Land, Infrastructure and Transport of the Korean government. (Project Number: 15SCIP-B108153-01)

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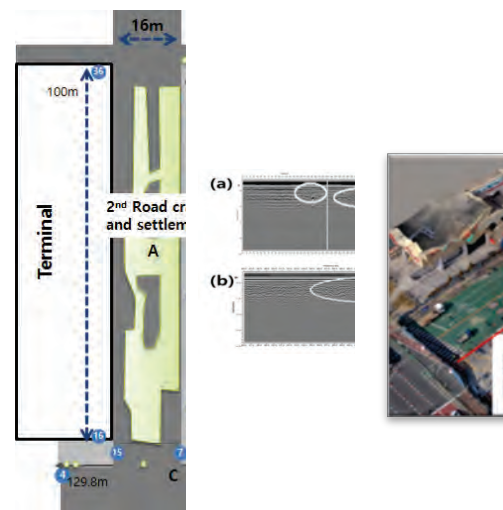


Figure: Outline of the ground sinking in the OO area in Korea(Left), GPR Exploration Result(a) A: Second road crack and settlement, (b) B: First road crack, (c) C: First ground sinking and Third road crack)(Center), Electrical Resistivity Result(Right)

## KEYNOTE LECTURE: Monitoring of embankment dams and waste deposits

Torleif Dahlin<sup>1</sup>

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

keywords: embankment dams, anomalous leakage, internal erosion

Electrical resistivity tomography (ERT) monitoring with automatic daily measurement has been carried out on three embankment dams in northern Sweden over several years, on two of them since over 10 years. Data are transferred in zip archives to a server at Lund University on a daily basis. The data are evaluated with time-lapse inversion of weekly averages derived from time-base de-spiking and filtering using automated routines based on the approach described by Sjö Dahl et al. (2008). The evaluation and interpretation focusses on relative variation and long term changes in the resistivity, with the aim to get an early warning for anomalous leakage and internal erosion inside the embankment dam. A method for seepage flow quantification has also been presented (Sjö Dahl et al. 2009). Time-domain induced polarisation (IP) is measured along with the resistivity in on-going monitoring, but so far IP data are not included in the automated evaluation.

Short term monitoring has been made on some waste dumps in southern Sweden on a number of occasions, with typical duration of a couple of weeks. Initially the objective was to track the water flow paths during injection tests in a biocell reactor, which was successfully achieved via patterns of decrease in resistivity. The results, however, also revealed patterns of increasing resistivity that were initially thought to be caused by noise but were eventually linked to gas production and migration in the biocell reactor. Following this ERT monitoring was successfully tested for tracing both water and gas migration inside waste deposits (Loke et al. 2009; Rosqvist et al. 2011).

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## Resistivity monitoring for dam safety inspection in Korea

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keywords: Resistivity monitoring, embankment dam, leakage detection, inversion

Resistivity monitoring has been applied to wide range of engineering and environmental problems with the help of automatic/rapid data acquisition, data communication and effective interpretation software. Especially, the resistivity monitoring at embankment dams can provide helpful information about leakage zones. However, significant challenges still remain in data acquisition system, noise suppression and time-lapse inversion for more detailed and quantitative interpretation.

There are 18,000 reservoir dams in Korea. More than 16 % of them are reported to undergo leakage problems and need to be repaired. For the leakage detection, we devised a resistivity monitoring system and installed the system at 9 test dam sites as shown in Figure 1. The resistivity data set automatically collected every 6 hours is stored to the data base via internet. Because the system is linked to the earthquake observation system, it automatically measures a resistivity data set after a significant shock and the influence of earthquake can be evaluated immediately.

The interpretation of collected resistivity monitoring data is divided into two steps. First, time series of resistivity data is filtered to suppress a spike type noise and then median filtering is applied to remove the high frequency noise caused by diurnal variation, assuming that resistivity value does not change abruptly with time. Next, the filtered time series are resampled at equally spaced but sparse time step. Then time-lapse inversion is performed for the resampled data sets. In the inversion process, the standard deviation of each time-series is used for data weighting. Furthermore, the regularization parameters between data misfits and model constraints are adjusted automatically by comparing their norms at a current iteration.

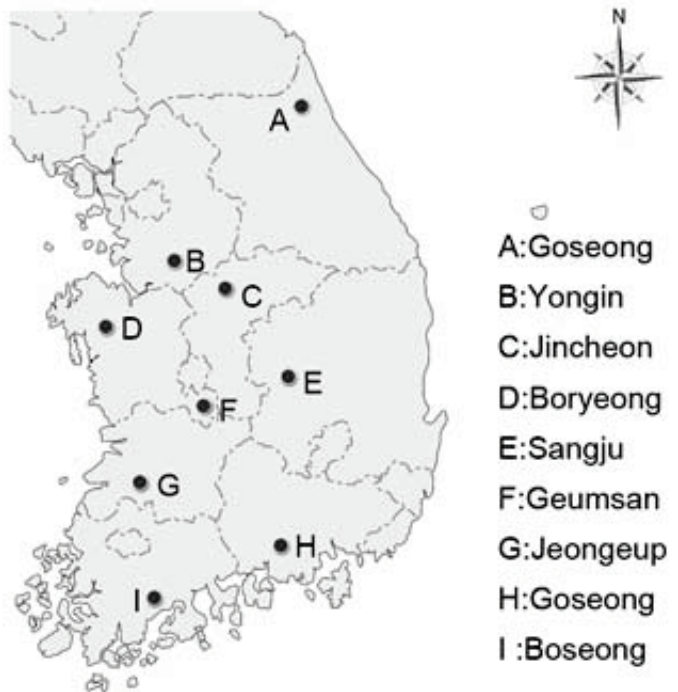


Figure: Location map of reservoir dams installed with automatic resistivity monitoring system in Korea.

## Long-term ERT monitoring of embankment dams in Sweden

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keywords: embankment dams, anomalous leakage, internal erosion

Electrical resistivity tomography (ERT) monitoring with automatic daily measurement is carried out on two embankment dams in northern Sweden since over 10 years. On one of the sites, Hällby, monitoring started in 1996, but the on-shore electrodes and the instrument were replaced in 2006. Data are transferred in zip archives to a server at Lund University on a daily basis. The data are evaluated with time-lapse inversion of weekly averages derived from time-base de-spiking and filtering using automated routines based on the approach described by Sjödah<sup>1</sup> et al. (2008). The evaluation frequency varies from once a year to once every three or four years depending on the need of each dam. The evaluation and interpretation focusses on variation and long term changes in the resistivity, with the aim to get an early warning for anomalous leakage and internal erosion inside the embankment dam. Time-domain induced polarisation (IP) is also measured along with the resistivity, but so far IP data are not included in the automated evaluation.

During the first 10 years at Hällby increasing annual variations and a long term trend increase in resistivity were detected in the left embankment dam. Together with other observations that indicated anomalous leakage and internal erosion, which lead to reinforcement of the dam. This necessitated re-installation of the electrodes and cables. During the past decade the monitoring results show normal annual variation which is mainly caused by temperature effects and so far no indication of anomalous trends have been detected in any of the dams (see example in Figure 1).

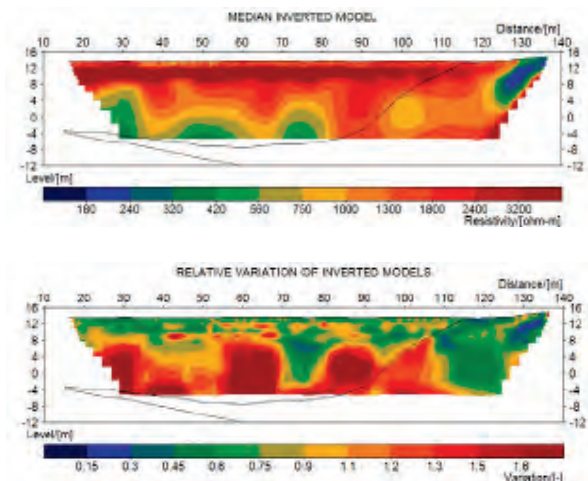


Figure 1: Example of typical results for evaluation over a period of one year showing (a) median resistivity, (b) variation

### REFERENCES

Sjödah<sup>1</sup>, P., Dahlin, T., Johansson, S. and Loke, M.H. (2008): Resistivity monitoring for leakage and internal erosion detection at Hällby embankment dam, *Journal of Applied Geophysics*, 65, 155-164.

## Temperature effect in resistivity monitoring in embankment dams

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keywords: Temperature effect, resistivity monitoring, embankment dam, leakage zone.

It is well known that electrical resistivity decreases with temperature. In most resistivity monitoring studies, temperature effects are undesirable and therefore, often considered as noise that may create artefacts and misinterpretation of the resulting images. As a result, temperature corrections in time-lapse (monitoring) series may be necessary to correct electrical resistivity in order to avoid misinterpretation when explaining resistivity changes linked to other physical processes such as changes in contamination or porosity. For resistivity monitoring in the embankment dams to detect leakage zones, temperature effects together with 3D effects can produce significant inversion artefacts and finally lead to misinterpretation.

In this study, resistivity monitoring is conducted at an embankment dam in Korea. Furthermore, temperature variation is monitored at two boreholes drilled at the upstream and downstream shell of the embankment dam. At shallow part of embankment dam, the temperature is strongly dependent on the air temperature. However, the influence of the air temperature decreases rapidly with depth. At deeper part, the temperature of upstream and downstream borehole converged to a constant temperature as shown in Figure 1, suggesting that the resistivity at depth is not affected significantly by the seasonal variation of air temperature.

Generally, leakage at embankment dams develops below the reservoir water level. When anomalous seepage flows occur, the resistivity at depth will decrease due to the increase of water content around the leakage paths. The temperature monitoring at boreholes shows that temperature effects at depth are negligible. Thus the changes in resistivity are considered to be caused by the leakages much more than changes in temperature. Of course, temperature effect should be corrected for the precise interpretation of resistivity monitoring data. However, the influence of temperature variation is considered not severe as the 3D effect in the interpretation of resistivity monitoring data at embankment dams.

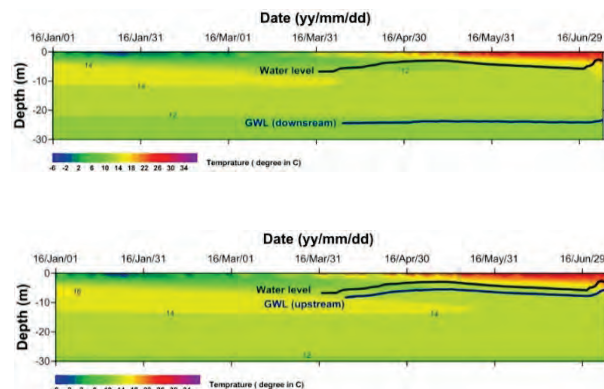


Figure 1: Temperature variations with time at the upstream (upper) and downstream (lower) boreholes.

### 3D ERT monitoring during dyke overtopping experiment using multi-current transmission technique

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keywords: dyke overtopping, ERT monitoring, multi-current transmission

We conducted a field experiment to simulate dyke overtopping using a model bank. We built a small scale model bank and water pool for simulating water level rising at river levee. We also set equipment for artificial rainfall above the model bank. As one of monitoring measurements of model bank while rising water level and raining artificially, we conducted time-lapse ERT survey on this model bank for the purpose of capturing water infiltration inside the model bank. To realize fine time resolution of ERT measurement for capturing water infiltration through high permeable material, we applied multi-current transmission technique, which has 8 transmitters and 8 receivers. In this technique, we can inject current at plural current electrodes simultaneously. By using our instrument based on this technique, we can improve measurement efficiency. We conducted a set of measurement which has 3072 data at the interval of 20 minutes. We performed 2D and 3D resistivity inversion. ERT measurement captured the water infiltration into the model bank by fine time resolution. The brackish saline water worked as a good tracer of ERT measurement in this case. 3D inversion using 2D survey lines data contributed to understand the spatial distribution of resistivity time variation.

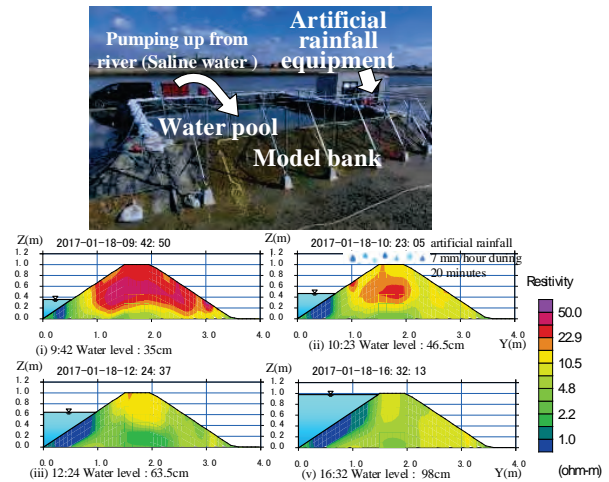


Figure: Overview of dyke overtopping experiment and an example of the result of 2D resistivity time variation of model bank

## KEYNOTE LECTURE: ERT time-lapse monitoring of a full-scale coal tar remediation

Lais M. Trento<sup>1</sup>, Panagiotis Tsourlos<sup>2\*</sup>, Jason I. Gerhard<sup>1</sup>, Michaye McMaster<sup>3</sup>, Andrew Sims

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keywords: time lapse ERT, DNAPL remediation,

In this work we evaluate the ERT time lapse monitoring as a complementary method to monitor the first full-scale application of Self-sustaining Treatment for Active Remediation (STAR) smouldering technology in real-time. A shallow treatment region (with ignition point at 2.4 meters below ground surface) was evaluated at an industrial site with coal tar contamination, and resistivity surveys were conducted before, during and after treatment to provide insight into the spatial extent of the STAR smouldering reaction, groundwater and gas mobility, influence of air flow and the capture zone of vapor extraction system. This research presents a proof-of-concept that ERT can be used to complement the conventional data set collected during application of STAR technology at remediation sites. Qualitative analysis of differential ERT images improves the understanding of the effect of STAR in the subsurface, in terms of the extraction system capture zone, air and groundwater mobility, and spatial extent of the smouldering reaction, when compared to analysing a conventional dataset (e.g. temperature, gas, in-situ boreholes). Geophysical data analysis helps to better understand and correlate data to physical processes. The results presented here are promising for future coupling of ERT to in-situ STAR applications especially in the case that the ERT measurements are deployed in a full 3D mode.

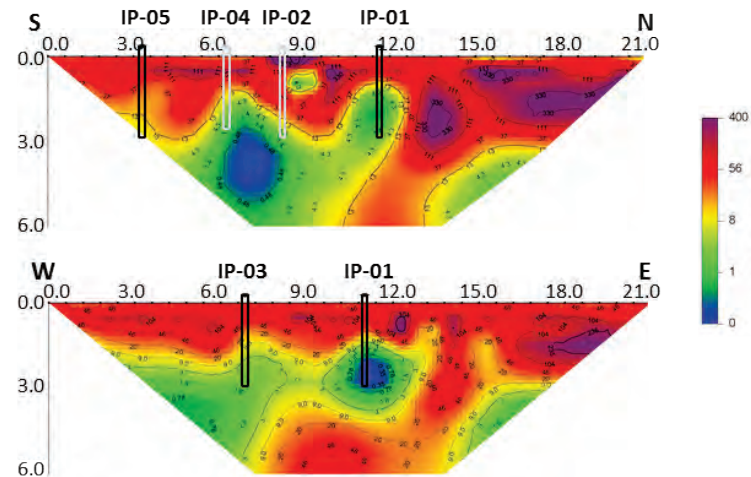


Figure: (a) Photo of ERT line (blue cable) installed on site. (b) S-N and W-E cross sections of ERT background independent inversion.

## KEYNOTE LECTURE: Electrical monitoring of nano- and micro-scale particle injections for in-situ groundwater remediation

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keywords: nanoparticles injection, Induced Polarization, groundwater remediation

The application of nano and micro-scale particles has emerged as a promising in-situ technology for the remediation of contaminated groundwater, particularly for areas difficult to access by other remediation techniques. The performance of nanoparticle injections is usually assessed through the geochemical analysis of soil and groundwater samples. However, this conventional approach only provides information on volumes close to the sampling points and is not suited for real-time monitoring. To overcome such limitations, we present the application of Induced Polarization (IP) imaging, which provides information on the low-frequency conductive and capacitive electrical properties of the subsurface, commonly expressed in terms of the complex resistivity. Changes in the complex resistivity during the injection permit a quasi-real-time monitoring and allow tracking the propagation of the injected particles. Our interpretation of the measured complex-conductivity response is based on borehole geochemical data and a novel electrochemical model, which permits to take into account the geometry of the pore space and the electrochemical properties of groundwater and particle surfaces. Here, we present IP monitoring results for data collected during two different experiments: (i) the injection of nano-Goethite particles (NGP) used for the stimulation of the biodegradation of a BTEX plume (i.e., benzene, toluene, ethylbenzene, and xylene); and (ii) the injection of microscale zero-valent iron (mZVI) to enhance the chemical transformation of a chlorinated aliphatic hydrocarbon (CAH) plume. Our IP imaging results reveal large variations (> 50%) in the

proximity of the injection points; yet also important changes were observed at different locations close to the surface indicating the creation of preferential flow paths (i.e., fractures) during the injection and the delivery of particles into volumes not targeted during the design of the experiment. Temporal changes in the electrical images are consistent with variations in particle concentrations detected in groundwater and soil samples, as well as geochemical parameters such as pH and oxidation-reduction potential. Our results demonstrate the applicability of IP imaging for the real-time monitoring of nano- and micro-scale particle injections and the detection of stimulated geochemical changes in the subsurface.

## An interpretation of resistivity monitoring data obtained in Geumsan landfill site

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keywords: landfill, resistivity monitoring, time-lapse resistivity inversion

Significant increases in number of landfill in South Korea can generate serious environmental problems such as soil or ground water pollution, due to deterioration of the facilities. Monitoring landfill sites can mitigate the problems by detecting environmental contaminations before widely spreading. For the detection of leachate leakage, this study employed electrical resistivity (ER) survey among several possible geophysical exploration methods such as induced polarization survey, electromagnetic (EM) survey and so on.

In our target area, Geumsan Landfill located in the Chungcheongnam-do, South Korea, the first dumping of garbage like household waste has been made before installing a leachate treatment facility, while the second landfill has been made after the installation. Leachate from the landfill was confirmed through an analysis on the conductivity of groundwater measured in wells located nearby the landfill. Geophysical surveys have been performed to further investigate the pollution area. First, EM surveys were conducted to roughly define the size of the polluted region about the target area and determine configuration of ER survey. Based on the configuration, ER surveys have been done four times during about one month around the rainy season; the first two surveys were before the rainy season, while the others after.

This study interprets ER monitoring data to define and monitor moving route of the leachate. For the interpretation of the ER monitoring data, we make time-lapse (TL) resistivity inversion (4D inversion) to analyse the distribution of leachate, together with employing active time constraint. We further took consideration of geological features of the target site in an effort to enhance interpretation results, together with groundwater level and drilling analysis data under the landfill.

### ACKNOWLEDGEMENTS

This work was supported by KETEP funded by the Ministry of Trade, Industry and Energy (MOTIE) of South Korea (No. 20164010201120) and by the Korea Agency for Infrastructure Technology Advancement under the Ministry of Land, Infrastructure and Transport (No. 17SCIP-B108153-03).

## The DC resistivity and time-domain IP monitoring system of Alingsås

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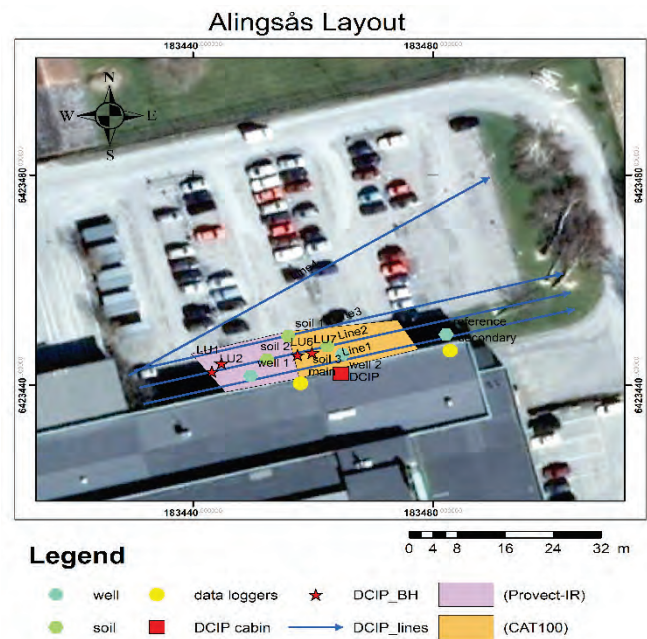
keywords: monitoring, remediation, contamination, DCIP

A monitoring system for Direct Current resistivity and time-domain Induced Polarisation tomography (DCIP) is being installed in Alingsås, Sweden. The aim is to follow changes in the DCIP signatures caused by the in-situ remediation of Tetrachloroethylene (PCE) and correlate the changes with other information (soil moisture/temperature, water conductivity, redox potential). For that purpose, we have successfully installed four DCIP electrode lines, four boreholes with ring electrodes around the chasing and several sensors for collecting complementary data (TDR, thermistors, weather station, etc.) during October. The sensors are needed to be able to take into account changes caused by other processes like e.g. rainfall and seasonal variation.

A dry-cleaning facility was operated at the site by the military for many years. The main solvent used was PCE, where a huge amount of the solvent was spilled into the ground. This contributed to an increasing concentration of PCE over the years until the use of PCE was stopped, resulting in the formation of a DNAPL plume beneath the building.

The site is relatively flat with a rather simple geology. At the top there is a layer of clayey sediments, followed by a thinner layer of sand and the bedrock. The conceptual model, which is made by the consultant company WSP, suggests that most of the PCE is trapped inside the clay layer. In early November 2017, a pilot test of in-situ bio-remediation will take place by injecting two different products that are designed to enhance the bio-degradation.

Preliminary results from the monitoring system will be presented.



The layout of the installed monitoring system in Alingsås.



## Geoelectrical monitoring in landfill bioreactor to study waste mass biodegradation behavior

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keywords: Waste biodegradation, Electrical resistivity, Induced polarization, in situ monitoring

Landfilling is still one of the most used waste treatments in France and all over the world. For a long time, the industrial operators act to increase the performances of the waste mass biodegradation and the concept of engineering under control is no longer debatable in European countries. Bioreactor concepts using leachate recirculation to reach optimal humidity or aeration process to change the microbial metabolism are applied to propose an active management process of municipal solid waste landfills. One of the key points is the measurement tools to follow the evolution of the waste mass impacted by the industrial strategy proposed. Even if the leachate and the biogas analyses are necessary, they are associated with a global trend of the medium studied and they couldn't highlight the evolution of the different zones, from the top to the bottom for example, which composed a waste cell.

At the beginning, geophysical methods were mainly implemented to localise old landfills or leachate plumes using the difference of electrical conductivity from natural soils surrounding those sites or the leachate. Among the techniques available, the Electrical Resistivity Tomography (ERT) rapidly began a robust method to investigate the landfill sites. Electrical resistivity variations recorded during leachate recirculation on bioreactors landfills are now widely known to study the volume of waste mass impacted by leachate diffusion. Waste temperature is also a physical parameter that this method can

analyse to detect zones where exothermic reactions are suspected when air is injected in aeration process.

In situ experimentations and laboratory test have demonstrated that ERT data could be affected by waste decomposition or by the effect of biogas production (Moreau et al., 2012). The long term observations using ERT monitoring allow questioning the relevance of this method to discuss on waste stability during the post-closure. According to those assumptions, a research program was elaborated with the landfill operator SAS Les champs Jouault to follow the evolution of electrical resistivity and Induced polarization datasets during the biodegradation process highlighted by the biogas production and the settlement observed. Moreover, the Distributed Temperature Sensing method using optical fibers cables allows taking into account the temperature evolution to avoid its impact on the electrical resistivity variations observed.

Four years of data collected in landfill site are analysed using different mathematical methods to calculate the average evolution of resistivity and chargeability. The whole volume of sensitivity studied with the ERT method is interpreted like specific zones localized below leachate reinjection device or between two, where the biodegradation evolution could be different. Results from Time Domain Induced Polarization technique are promising to monitor the waste mass behaviour during the landfill post exploitation period.

## Resistivity monitoring for leachate detection in a livestock disposal site

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keywords: resistivity monitoring, leachate detection, FMD, livestock disposal

Generally, livestock carcass disposal sites can become a significant environmental threat as there is a risk of the leachate leakage if the high density polyethylene film is damaged when livestock carcass is buried. It is very important to monitor soil and groundwater in order prevent possible contamination by leachate after disposal. This paper presents a resistivity monitoring technique for detecting leachate from a livestock carcass burial site. To detect possible leachate flow we have conducted a repeated geoelectrical field survey three times. As a result of the resistivity monitoring, we can interpret the range of soil contamination and leachate leakage points of the field site due to drainage of the leachate during the rainy season. To further support the field findings, we conducted laboratory scale experiments to measure resistivity by injecting artificial leachate into soil samples. Through the experimental results, an improved soil contamination evaluation can be achieved by using the obtaining empirical relations between the volume of the injected leachate and the measured resistivity of the soil sample. The resistivity measurement could be useful to select observation points for groundwater contamination assessment and is an effective method for detecting leachate in livestock carcass burial sites.

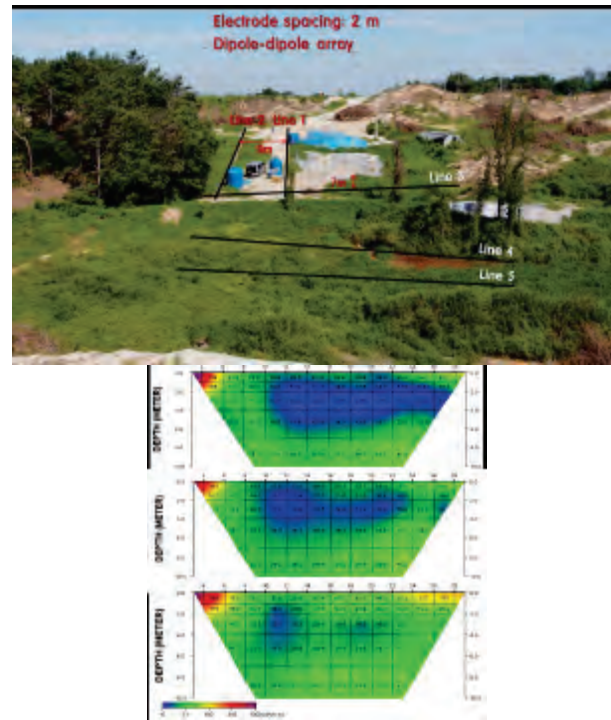


Figure: Field site view and arrangement of survey lines for resistivity monitoring (left). Time lapse resistivity sections of the survey line 3 (right).

## Characterisation and monitoring of in-situ remediation of chlorinated hydrocarbon contamination using an interdisciplinary approach (MIRACHL)

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keywords: chlorinated hydrocarbon contamination, remediation, resistivity, IP, DCIP

There is growing concern about sites contaminated with carcinogenic chlorinated hydrocarbons spilled by from use as dry-cleaners and industrial solvents, and there are around 2000 sites in Sweden alone. The contaminants pose a threat to drinking water resources and ecosystems. Furthermore urban development demands for more housing is often addressed via densification of cities by developing housing in often contaminated derelict industrial areas, with associated problems and health issues. In order to tackle these problems remediation is needed.

The main remediation technique in Sweden is the costly and micro-ecologically damaging excavation and landfilling, i.e. moving the pollutants from one site to another. This strategy leads to large transports and the exposure of dangerous compounds. The Swedish EPA recommends the use of in-situ remediation methods, which would lead to large savings for clean-up, and contribute to EU Water Directive requirements and to reaching the national environmental objectives. Today, however, the monitoring of the remediation action and confirmation on a “good enough” outcome is very uncertain, due to the current investigation techniques with point source monitoring.

There is a need of better monitoring approaches to reduce uncertainties around in-situ remediation and pave the way for more costs efficient procedures.

In the MIRACHL project, integrated monitoring with geophysical and biogeochemical methodologies is used to better understand and follow in-situ remediation processes of sites contaminated by chlorinated hydrocarbons. Direct Current resistivity and time-domain Induced Polarisation tomography (DCIP) monitoring during the remediation will together with biogeochemical sampling and analyses help follow the development underground. Degradation of the chlorinated hydrocarbons is expected to result in measurable changes in the DCIP signatures as chloride ions are split off from the polluting hydrocarbons, together with e.g. precipitation of iron compounds. With the combined monitoring approach, we aim for a comprehensive coverage of changes underground to develop an understanding of hydrological, chemical and biological processes.

MIRACHL (<http://mirachl.com/>) is a collaboration between universities, authorities and industry, with a multi-disciplinary team, where the methodology will be tested and calibrated in full scale on several tests sites. The first site to be monitored is Alingsåstvädden, a laundry facility where large amounts of Tetrachloroethylene (PCE) have been spilled into the ground.

## KEYNOTE LECTURE: Use of geoelectrical monitoring methods for characterizing thermal state, ice content and water flow in permafrost environments

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keywords: permafrost, ERT, IP, SP

Recent years have shown an increasing use of geoelectrical monitoring methods to better understand subsurface structures and processes in permafrost environments. With the methodological, technological and computational advancements over the last two decades, permafrost applications of electrical methods have evolved from simple qualitative mapping or sounding to quantitative imaging and monitoring, and interest in electrical properties has been extended from resistivity to induced polarization (IP) and self-potential (SP).

Electrical resistivity tomography (ERT) is the most widely used approach today to characterize and monitor the subsurface thermal state (frozen vs. unfrozen), with successful applications both in sub-arctic and high-mountain permafrost. Given the multiple petrophysical controls on resistivity, however, thermal state characterization based on resistivity alone strongly relies on adequately calibrated resistivity-temperature relationships. Moreover, resistivity can provide information on the thermal state, but it is not directly sensitive to water flow, which due to advective heat transport is one of the key controls on the complex physical process dynamics in thawing permafrost systems.

These limitations of ERT have recently directed our interest towards the use of the spectral IP (SIP) method for permafrost characterization. In a series of laboratory experiments, we investigated the SIP response of rocks over controlled freeze-thaw cycles. The results reveal the characteristic polarization response of ice in the higher SIP frequency range, which –

although methodologically and technically challenging – suggests potential of the SIP method for improved imaging and quantification of ice content in permafrost field studies. Results of first field measurements on a limestone rock wall at the Zugspitze mountain (Germany) are promising in this regard, as the high-frequency IP responses of frozen and unfrozen areas were found to be distinctly different.

With a view to monitoring the dynamics of water flow in the active layer of permafrost, we tested the applicability of the SP method at the Schilthorn mountain (Switzerland). Here, as typical of high-mountain slopes, variability in topography, precipitation and snow cover gives rise to complex spatio-temporal flow patterns in the active layer, which are not accessible by conventional monitoring methods. The SP monitoring data, collected on a permanently installed array of electrodes with high temporal resolution over entire seasonal thawing and freezing periods, reveal strong variations from the onset of thawing in spring until autumn, when the signals gradually return to relatively low variations coinciding with the re-freezing of the ground. While the results suggest that SP monitoring is capable of capturing water flow dynamics in permafrost settings, technical challenges do still exist, comprising for instance the effective removal of outliers and electrode effects in the data.

{Conclusions on next page}

We conclude that geoelectrical methods can play an important role in the monitoring and thus understanding of permafrost dynamics. ERT and SIP are capable of providing thermal state information, including estimates of ice/water content if calibrated petrophysical models are employed, with high spatial resolution. If complemented by SP, also water flow can be monitored with high temporal resolution. In conjunction, the state and flow information provided by these methods is of highest relevance for an adequate parameterization and calibration of hydro-thermal process models and thus the improved prediction of the future evolution of terrestrial permafrost systems under the influence of global warming.

## KEYNOTE LECTURE: Geophysical characterization, monitoring and early warning of slope failure: a review of methodological developments at the Hollin Hill landslide observatory

Jonathan Chambers<sup>1</sup>, Paul Wilkinson<sup>1</sup>, Philip Meldrum<sup>1</sup>, Sebastian Uhlemann<sup>1,2</sup>, David Gunn<sup>1</sup>, Oliver Kuras<sup>1</sup>, Cornelia Inauen<sup>1</sup>, Russell Swift<sup>1</sup>, Andrew Merritt<sup>3</sup>, Jim Whiteley<sup>1,4</sup>

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keywords: electrical resistivity tomography; landslide; early warning; monitoring; characterisation.

The Hollin Hill Observatory was established in 2007 to facilitate research into the development of geoelectrical and allied approaches for the monitoring and characterisation of landslides. The observatory is located in North Yorkshire UK on an active landslide characterised as a slow moving earth slide – earth flow. The slope comprises Lower Jurassic Lias Group rocks, which are particularly prone to failure and are a major source of lowland landslides in the UK. The overarching aim of our research at the site has been to develop a methodology for landslide assessment focussed around geoelectrical methods. This has included characterisation and ground model development, integrated monitoring using time-lapse electrical resistivity tomography complemented by conventional geotechnical and environmental sensing technologies, and a supporting programme of laboratory based measurement and modelling to calibrate and support the interpretation of the field-based observations. A key goal of the work has been to use the geophysical data and models to identify precursors to slope failure thereby providing early warning of landslide events, which is now beginning to be realised.

Here we review our approach to geophysical landslide assessment focussing particularly on key elements and advances including: rationale for site selection; three-dimensional subsurface characterisation; development of geoelectrical monitoring instrumentation; time-lapse geophysical data processing, including temperature corrections and electrode movement determination; petrophysical relationships and geophysical model calibration; and determination of geophysically derived property thresholds indicative of imminent slope failure. We conclude with a forward look to ongoing and future challenges in the development of a geophysics-based landslide early warning system.

## Application of time-lapse ERT in active layer monitoring at Crater Lake, Deception Island, Antarctica

Mohammad Farzamian<sup>1</sup>, Gonçalo Vieira<sup>2</sup>, Borhan Yaghoobi<sup>3</sup>, Fernando A. Monteiro Santos<sup>1</sup>, Christian Hauck<sup>4,5</sup>, Ivo Bernardo<sup>1</sup>, Miguel Ramos<sup>6</sup>

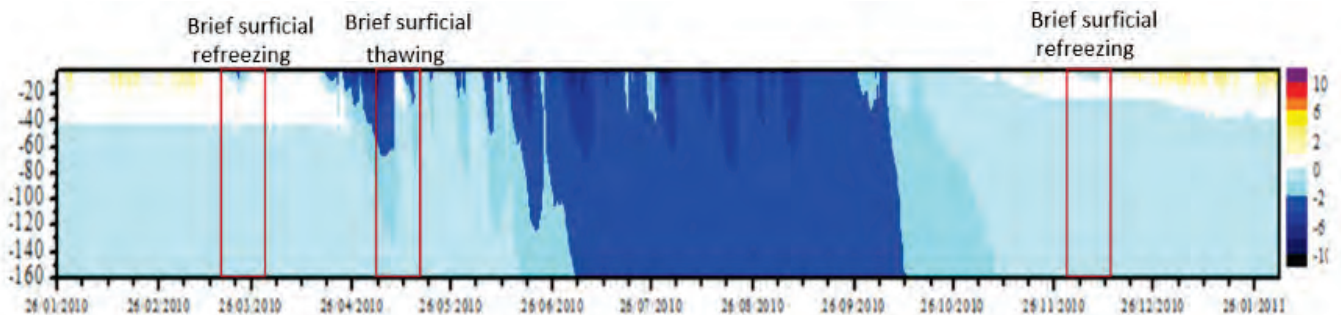
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keywords: Active layer, time-lapse ERT monitoring, Deception Island.

An automatic ERT monitoring system was installed under the Circumpolar Active Layer

20 electrodes spaced 0.50 m and a Wenner electrode array were used in this experiment and a total of 56 points were collected for each dataset. The ERT measurements started at the beginning of 2010 and repeated each four hours during one year. Consequently, a total of 2200 datasets were obtained during the experiment. Ground temperatures in shallow boreholes down to 1.60 m were recorded simultaneously with ERT measurement in the site.

Both apparent resistivity and 2D inverted resistivity are analysed in space and time, and hourly, daily and monthly resistivity variations are investigated. A special attention is given to the specific events marked in figure 1. In addition, a virtual borehole analysis is carried out to compare the spatiotemporal resistivity changes with ground temperature fluctuations at several depths.



Monitoring (CALM) program in the Crater Lake CALM-S at Deception Island to study the active layer. The region is one of the hot spots of climate change and one of the most ecologically sensitive regions of Antarctica, where permafrost is near its climatic limits. The climate is polar oceanic, with high precipitation and mean annual air temperatures (MAAT) close to  $-3^{\circ}\text{C}$ . The soils are composed by ashes and pyroclasts with high porosity and high water content, with ice rich permafrost at  $-0.8^{\circ}\text{C}$  at the depth of zero annual amplitude, with an active layer of about 30 cm (Ramos et al., 2017).

Figure 1: Borehole temperatures are plotted for the 1.6 m borehole for the investigation depth of the ERT profile. The borehole is very close to the middle of ERT profile and was used for the virtual borehole analysis.

ACKNOWLEDGMENT: This publication is supported by FCT- project UID/GEO/50019/2013 – IDL.

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## Joint inversion of electric and seismic data applied to permafrost monitoring

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keywords: permafrost, joint inversion

The non-uniqueness and limited resolution of inverse problems may result in misinterpreted inversion solutions. The improvement of the inversion and its quality check are consequently a basic and crucial step in the data processing. Electrical resistivity tomography (ERT) and refraction seismic tomography (RST) bring complementary information regarding the ice content, as elastic and electric properties are markedly different for ice, water and air. We believe that a joint inversion can help significantly to reduce the uncertainties in the individual inversions and will improve the interpretability of the subsurface model.

A petrophysical joint inversion using pyGIMLI (Rücker et al., 2017) is applied to a mountain permafrost long-term (> 10 years) monitoring site. Both ERT and RST measurements are conducted since 2005 at the Schilthorn monitoring site (Swiss Alps) at the end of summer, i.e. at the time of the year when the active layer thickness is largest (Hilbich, 2010; Hilbich et al., 2008, 2011). Assuming that the lithology and soil structure do not vary with time, changes in resistivity/P-wave velocity can be fully attributed to changes in the unfrozen water/ice content.

In this contribution, we discuss data quality and improvements by joint inversion over individual inversions. Ground truth data are available through temperature measurements within two boreholes along the profile and allow a joint interpretation with the geophysical data.

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<https://dx.doi.org/10.1016/j.cageo.2017.07.011>



## Identification of outliers, electrode effects and process dynamics in electrical self-potential monitoring data

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keywords: Self-potential monitoring,  
permafrost, data processing

Spatial self-potential monitoring data offer opportunities to map spatio-temporal subsurface process dynamics, such as water flow giving rise to streaming potentials. Process dynamics are, however, often masked by data outliers, varying contact potentials, and thermal electrode drift effects. Effective removal schemes are desired to elucidate process dynamics and provide appropriate input data to process-based inversion schemes, for the determination of spatio-temporal flow patterns for example.

Based on both synthetic and field data measured with a permanent monitoring setup at an Alpine permafrost site in Switzerland, where temperature-dependent electrode responses are particularly pronounced, we present a method to ensure the consistency of time-lapse self-potential data without detailed knowledge of the subsurface. Formulated as a linear inverse problem, all acquired voltages over time are inverted for a consistent and spatially smooth, yet temporally varying, potential distribution at the surface. To cope with electrode effects, additional shift and drift parameters are introduced at each electrode position and simultaneously inverted for.

We discuss the resolvability and distinctness of time-lapse self-potential maps and electrode effects during stable periods and during spring, where the most pronounced self-potential signals are visible in our data set due to the onset of snow cover thaw. Although preliminarily developed as an intermediate step to assess the suitability of the self-potential method to monitor permafrost hydraulics, the method is directly applicable to any type of time-lapse potential data.

## Data Quality Analysis of ERT data of geoelectrical permafrost monitoring on Hoher Sonnblick and on Kitzsteinhorn (Austrian Central Alps)

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In the Alps infrastructure facilities such as roads, routes or buildings are affected by the changes of permafrost, which often cause enormous reparation costs. Investigation on degradation of Alpine Permafrost in the last decade has increased, however, the understanding of the permafrost changes inducing its atmospheric forcing processes is still insufficient. Within the project ATMOperm (Atmosphere - permafrost relationship in the Austrian Alps - atmospheric extreme events and their relevance for the mean state of the active layer) the application of the geoelectrical method to estimate thawing layer thickness for mountain permafrost will be investigated near the highest meteorological observatory of Austria on the Hoher Sonnblick and on Kitzsteinhorn. Based on an innovative time lapse inversion routine for ERT data (Kim J.-H. et al 2013) a newly developed data analysis software tool developed by Kim Jung-Ho (KIGAM) in cooperation with the Geophysics group of the Geological Survey of Austria allows the statistical analysis of the entire sample set of each and every data point measured by the geoelectrical monitoring instrument.

This gives on the one hand of course an enhanced opportunity to separate between „good“ and „bad“ data points in order to assess the quality of measurements. On the other hand, the results of the statistical analysis define the impact of every single data point on the inversion routine.

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### ACKNOWLEDGMENTS

The geoelectrical monitoring on Hoher Sonnblick has been installed and is operated in the frame of the project ATMOperm (Atmosphere - permafrost relationship in the Austrian Alps - atmospheric extreme events and their relevance for the mean state of the active layer) funded by the Austrian Academy of Science (ÖAW)

## Integrating tachymetric surveying and ERT measurements to construct the sliding plane of an active landslide near Maria Eck monastery (Bavarian Alps, Germany)

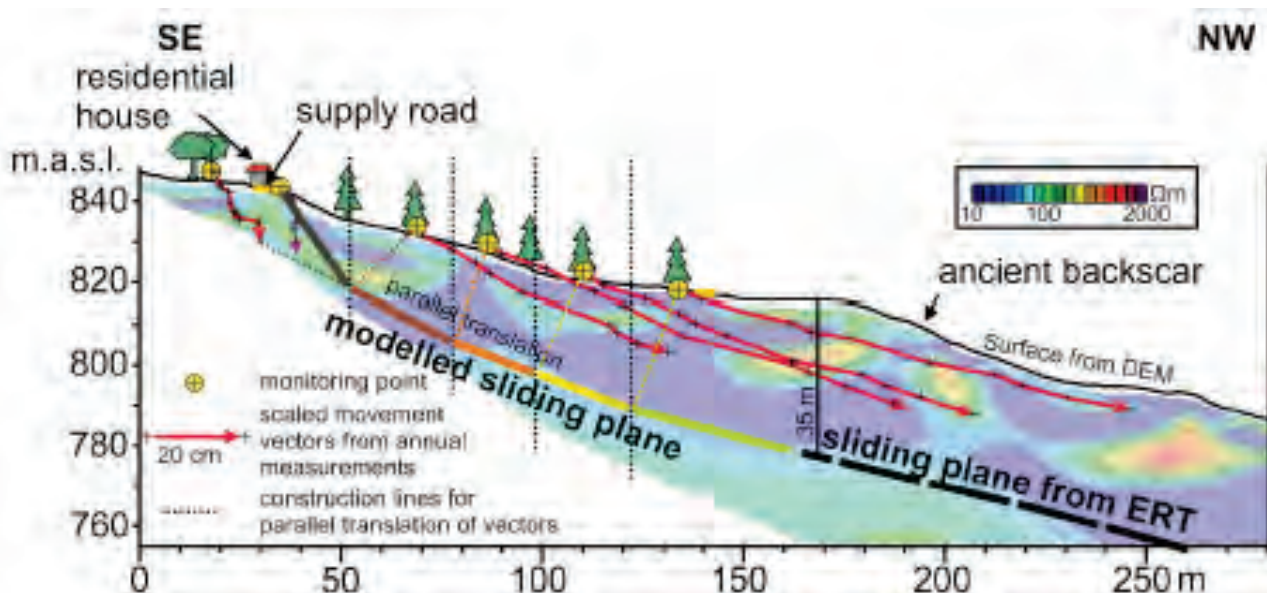
Johannes Großmann<sup>1</sup>, Thomas Galleman<sup>1</sup>,  
Christian Veress<sup>1</sup>, Stephan Sieblitz<sup>1</sup>, Erwin  
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keywords: landslide, ERT, sliding plane  
modelling

Results from long-term tachymetric monitoring prove slow subsidence movement of buildings at Maria Eck monastery, located on top of the flysch-dominated Fürstberg ridge in SE Bavaria, Germany. Since 2009 horizontal slope movement has also been observed in dip direction of the slope and directly below a residential house of the monastery (Fig. 1). Horizontal translation rates could be quantified as much higher (11 cm/year) compared to those measured directly at the residential house (5 mm/year). This implies the idea of a currently forming landslide with a backscar that separates areas, where vertical subsidence movement is dominating,

transition from a shallow zone, with a heterogeneous distribution of resistivity values (disintegrated landslide mass), to a deeper zone with rather homogenous resistivity values (sliding plane and bedrock) at 35 m depth. However, for an interpretation of a backscar the inversion results from ERT are considered as too diffuse. In order to constrain the possible location of the backscar, we are presenting a modelling approach that includes the 2D geometric construction of a listric sliding plane by translating the geometry of movement vectors from annually tachymetric monitoring parallel into depth. Given the depth to the sliding plane interpreted from ERT inversion as a starting point, the modelling approach produces a backscar that intersects the surface directly below the monastery's supply road. This result can be used as guidance for future stability analysis and for the design of remedial works.



from areas that are majorly influenced by horizontal translation movement downslope.

To constrain the landslide geometry ERT-measurements were carried out along profiles in dip direction of the slope. The sliding plane was interpreted along the

Figure: Cross-section of the northern Fürstberg ridge with ERT inversion results. For the sliding plane construction each movement vector is translated parallel into depth, starting with a sliding plane geometry interpreted from ERT inversion results.

## Integrated monitoring of an active landslide in Lias Group Mudrocks, North Yorkshire, UK

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keywords: landslides, integrated monitoring, geophysics

Geophysical monitoring of the internal moisture content and processes of landslides is becoming an increasingly common part of the long-term assessment of the subsurface condition of landslides prone to failure by increased infiltration. Geoelectrical monitoring has been proven to be effective at detecting changes in subsurface moisture content both preceding and following slope failure. Seismic methods show great potential for the monitoring of elastic properties of landslides as subsurface conditions move toward critical failure states, but until now have not been as widely applied as geoelectrical methods, and even less often as part of a combined geophysical monitoring approach.

We present the ongoing activities of an early-stage research project in to the monitoring of an active landslide in North Yorkshire, UK, integrating seismic methods in to a well-established geoelectrical monitoring campaign. This research project will consider the complementarity of geoelectrical and seismic monitoring methods, and how both methods can be utilised for the detection and monitoring of the evolution of landslide processes.

## Geoelectrical and geotechnical monitoring on a landslide in Wolfsegg am Hausruck, Austria

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keywords: geoelectrical monitoring, 4D inversion, landslide

In May 2017 the Geological Survey of Austria (GBA) installed a geoelectrical monitoring profile and 4 automatic inclinometers on a landslide in the Hausruck of Upper Austria. Beforehand extensive geoelectrical and borehole geophysical investigations on an area of 2 ha have been conducted by the GBA as well as EM and SIP measurements were done by the Technical University of Vienna. To interpret the causes for the movement mineralogical analysis have been carried out which give in combination with the borehole logs a good indication at which depth range there is the highest probability for the development of a sliding surface. Sliding surfaces in this area are coal-clay formations and the transition zone gravel-marl. Until now, the slope has moved up to 6 mm, but without the formation of a distinct slipping plane. The main focus of the geoelectrical monitoring is to image with the interpretation of difference images of the 4D-inversion (Kim et al. 2009) the change of water saturation with time. It is expected that due to the low hydraulic permeability of sliding relevant parts of the subsurface, the changes in resistivity at this depth range will be rather small as well as not directly linked to distinct precipitation events. Therefore, the emphasis has to be dedicated to the quality of the input data for the 4D-inversion (data acquisition, filtering,...) to minimize inversion artefacts that could mask the relevant subsurface information. Furthermore, for a reliable interpretation a long-term observation is essential. First results of the geoelectrical monitoring profile will be presented, showing the very near

surface effects of precipitation events that have not reached the sliding prone depth ranges yet. This finding is also supported by the fact that almost no displacement took place in the same period of time. Due to the operation of diverse monitoring systems (the installation permanent FO cables is planned for spring) and different geophysical and geotechnical investigations that took place at this site (good knowledge about the subsurface structure) a detailed and reliable interpretation of long-term resistivity changes in connection with the landslide dynamics is expected.

The measurements and research activities on the landslide of Wolfsegg im Hausruck are funded by the FWF (Austrian Science Fund) in the frame of a Joint Project with the French ANR "HYDROSLIDE" (HYDRO-geophysical observations for an advanced understanding of clayey landsLIDES, Project number: I 2619-N29).

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## Towards a geophysical system for the remote autonomous monitoring of the near surface

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keywords: electrical resistivity tomography; autonomous monitoring; information delivery

It is increasingly being recognised that geophysical techniques can complement conventional approaches by providing spatial subsurface information for near surface environmental and engineering applications. Here we describe the development and testing of a new geophysical monitoring system - in terms of both instrumentation and processing workflow development. It is built around low-cost electrical resistivity tomography instrumentation, combined with integrated geo-technical logging capability, coupled with data telemetry and web data delivery. The development of this approach has provided the basis of a decision support tool for monitoring and managing a range of near-surface problems. The hardware component of the system has been operational at a number of field sites associated with a range of natural and engineered slopes for up to two years. An automated data processing and analysis workflow is being developed to streamline information delivery. The automated processing workflow architecture has been established and is currently being

implemented. A prototype system enabling delivery of processed geophysical results to a web-dashboard has also been developed. We report on the monitoring results from a number of our test sites, discuss the practicalities of installing and maintaining long-term geophysical monitoring infrastructure, and provide an overview of the data processing workflow and information delivery. Once automation of data processing and delivery has been completed, we will be able to provide a practical decision-support tool for near-surface monitoring applications.

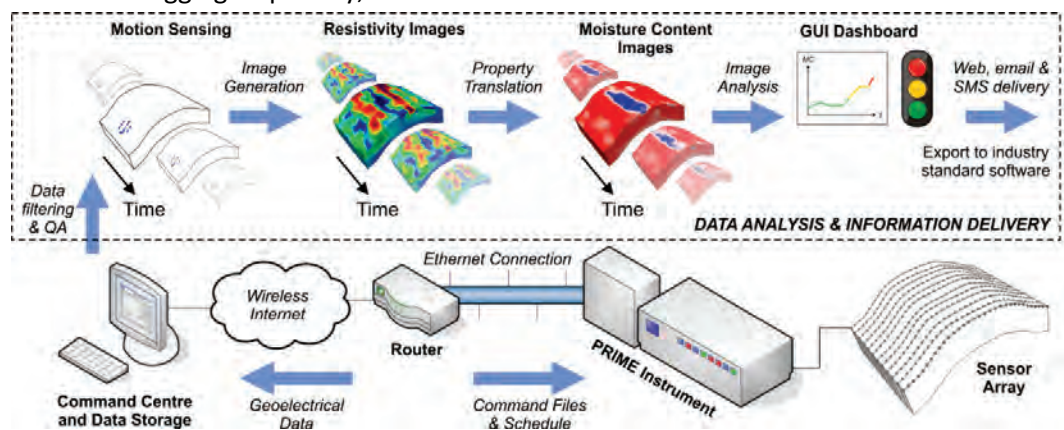


Figure: Resistivity monitoring system concept.

## Time-lapse ERT measurements to monitor rainfall triggered landslides at the laboratory scale

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To study landslide activities and monitor the conditions of the slope body, different parameters should be measured and evaluated over time.

Rainfall is considered as one of the main landslide triggering factors for a majority of landslides in Europe. Considering the importance of groundwater in the mechanisms that govern the stability of slopes, monitoring of the hydrological conditions of hazardous slopes is very critical. In a research initiated at the 'Applied Geology and Geophysics Lab' of Politecnico di Milano, Lecco campus, a landslide simulator was designed and used to reproduce small scale slopes. Integration of different geoenvironmental techniques (geology, photogrammetry, topography surveying, geophysics) was possible to monitor a variety of parameters. Considering the simulations for rainfall triggered landslides, we adapted laboratory scale cables and electrodes for performing time-lapse ERT measurements to monitor the water saturation of the soil. Four experiments were carried out in May and June 2017. Resistivity measurements were tried to be optimized after the first experiment (e.g., reducing the time of measurements, changing the azimuth of the profile). 48 electrodes were buried at the depth of 1cm along the slope dip direction, in the middle of the slope. The Wenner array with the spacing of 3cm was used for measurements. After failure of the downdip parts of the soil and losing the contact of the first electrodes with the soil body, resistivity measurements continued with half of the

profile (24 electrodes) until the whole profile experienced failure. As expected, inverted resistivity sections revealed the time changes in the water saturation of the soil body. Using the limited time-lapse TDR data, we calibrated Archie's law with our resistivity data to construct water saturation maps. Moreover, failures were detectable in resistivity sections, being compatible in time and space with the results of photogrammetry and topography surveying.

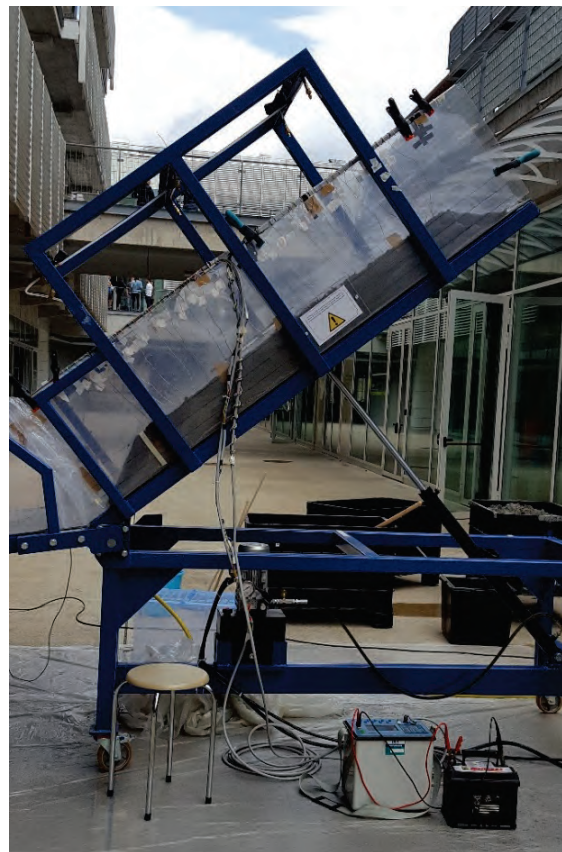


Figure: Landslide simulator and resistivity equipment for time-lapse ERT monitoring of the slope body.

### ACKNOWLEDGEMENTS

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## 4D ERT monitoring of subsurface water pipe leakage during a controlled field experiment

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D.A. Gunn<sup>1</sup>, B. Dashwood<sup>1</sup>, J. Taxil<sup>3</sup>, G.  
Curioni<sup>4</sup>

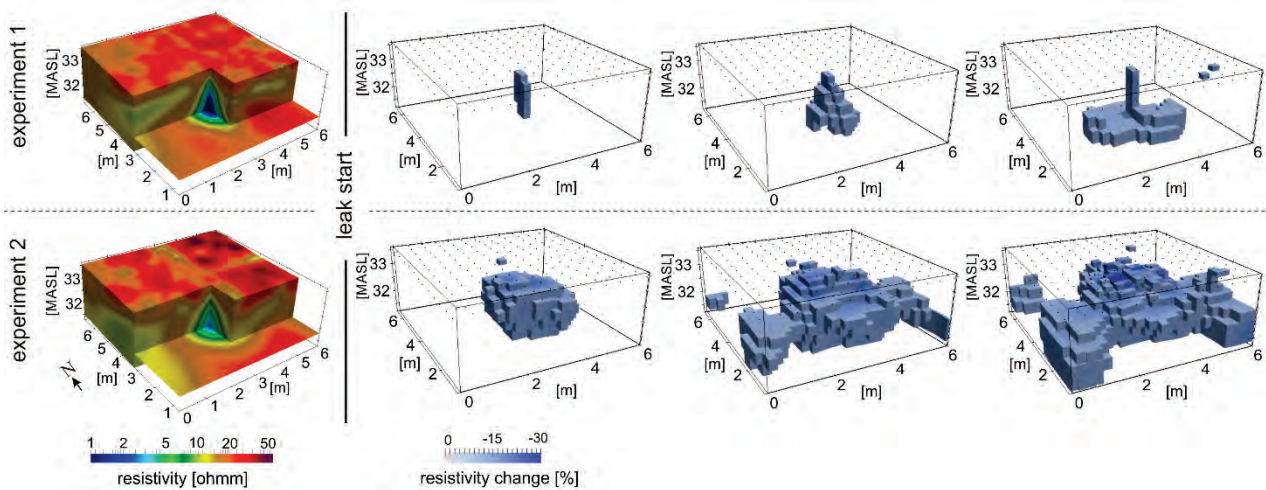
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keywords: monitoring, infrastructure, water supply, leakage

Locating and delineating leakage from subsurface pipelines is an important task for civil engineers. In this study we assess the efficacy of automated 4D Electrical Resistivity Tomography (ERT) for pipe leakage monitoring by conducting two controlled leak experiments at a test site in Bristol, UK.

and Evaluation) system, which facilitates remote scheduling and autonomous data collection and transmission. To obtain the resistivity changes of the subsurface a 4D inversion was carried out using a Gauss-Newton approach with spatial and temporal smoothness constraints.

Even though a pronounced artificial anomaly (probably related to the presence of a cluster of metallic soil moisture sensors) is present in the center of all resistivity time steps, we were able to reliably observe the onset, spread and cessation of the leakage. In-situ measurements with soil sensors at several depths above and below the leak complemented the ERT data and allowed us to assess their reliability and directly relate them to hydrogeological processes.



To simulate the leak a plastic pipe with a hole was buried below a flat, grassed area at a depth of 0.7 m, representing a standard UK mains water pipe installation. The water table at the site lies well below the surface meaning that the experiment took entirely place in the vadose zone, where changes in resistivity are primarily sensitive to water content variations. The ERT array covered an area of 6.5m x 6.5m around the leak location. Data acquisition was carried out with the BGS PRIME (Proactive Infrastructure Monitoring

Figure: The pre-leak resistivity models indicate a pronounced artificial anomaly at the center (left subplots). Nevertheless, the evolution of the two leak experiments can be well resolved as resistivity changes with respect to the pre-leak conditions (right subplots, displayed are only model cells with a resistivity decrease of more than 10%). The plume for experiment 1 with a total leakage amount of 2.76 m<sup>3</sup> is much smaller than the one for experiment 2 with a leakage amount of 20.7 m<sup>3</sup>.



## Geoelectrical monitoring during waste biodegradation process at laboratory scale

Jouen Thomas<sup>1</sup>, Clément Rémi<sup>1</sup>, Moreau Sylvain<sup>1</sup>, Simon Loisel<sup>2</sup>, Mazéas Laurent<sup>1</sup>

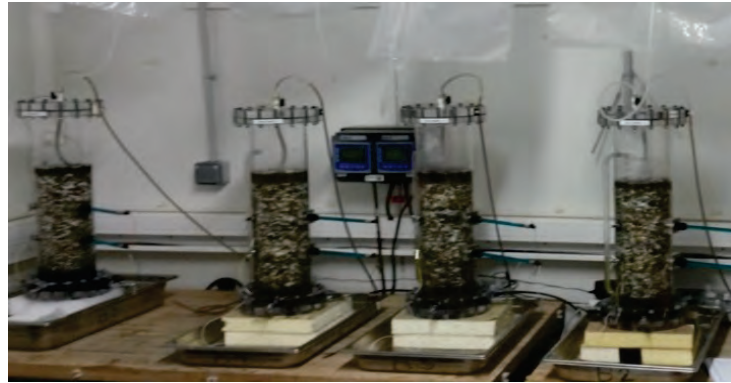
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keywords: Waste biodegradation, Electrical resistivity, Induced polarization, laboratory scale

Waste storage is the most commonly waste treatment method used around the world because it is a relatively simple and economical way for solid waste management. For this reason, non-hazardous waste disposal facilities formerly operated as mere filling pits are nowadays complex structures whose objective is to reduce environmental impacts and enhance biogas production. Waste storage industry professionals are currently interested in a spatializing method that can monitor waste biodegradation state in landfill. The transformation of solid waste into biogas carried out by microbial populations brought into play during the anaerobic digestion, involves changes in the physicochemical parameters of the medium. Indeed porosity, leachate conductivity, microbial growth, for example will be changed during the waste biodegradation cycle. This is those changes in the physical and chemical properties of the waste mass that could be detected by geophysical methods. For this reason three geophysical methods have been chosen to monitor the waste biodegradation state on landfill: Electrical resistivity, Induced polarization, Spectral induced polarization.

In order to evaluate the potential and limits of the chosen geophysical methods, an experimental laboratory device has been build. One kilo of municipal solid waste has been shredded, poured in four laboratory cells (Figure). Three were saturated with water and the same mechanical

characteristics to get repeatability and the last one placed at field capacity. All cells were then placed at 35° C in order to increase the biodegradation kinetic. Not to influence the electrical measurements, the columns were made of colourless Plexiglas (PMMA) and are equipped with two pairs of measurement electrodes, a pair of stainless steel and two of non-polarizable (Cu/CuSO<sub>4</sub>). Furthermore, analyses on the biogas and the leachate production allow following the waste biodegradation evolution.



The four experimental cells filled with waste

Measures started since March 2016 for the oldest and January 2017 for the youngest until now. The results show that the resistivity is mainly governed by the water content of the medium. Indeed, the resistivity was recalculated on the basis of water content and leachate conductivity measurements using an Archie law and these results compared to resistivity measured are superimposed but diverge on the end of the biodegradation process, suggesting that the transformation of organic matter into biogas could induce changes in the waste matrix. The induced polarization measurements always show a low chargeability at the beginning of the biodegradation process which increases progressively over time. A "low" chargeability for a young waste and a "high" chargeability for a waste at the end of biodegradation process is measured whatever the cell conditions observed. These results show that the induced polarization methods could be more sensitive than the resistivity for monitoring the waste biodegradation evolution at landfill scale.

## Towards a real-time 4D Electrical Resistivity Tomography

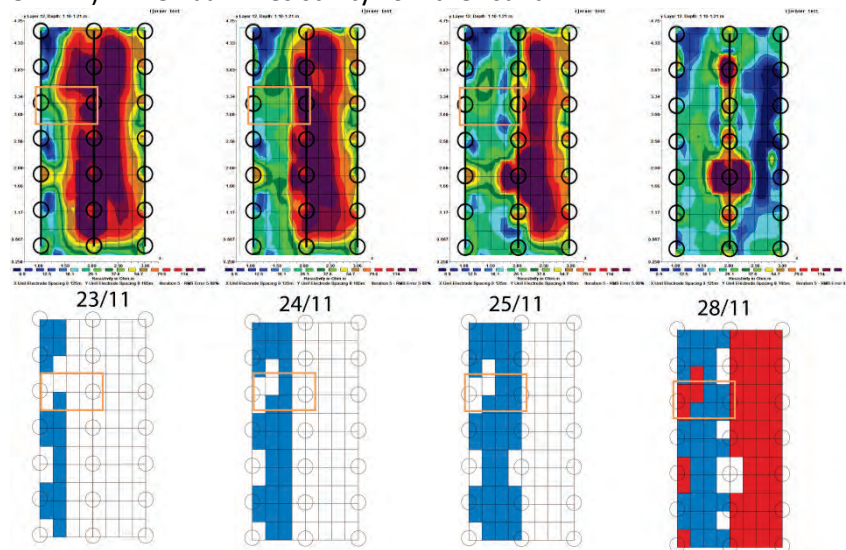
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keywords: 4D ERT, monitoring, time-lapse

In this work we present an optimized 3D array setup to image injection of iron fluid in a heterogeneous medium. During the injection phase, the water content of the pore space will be replaced with iron. We first measure the bulk resistivity of the sand sample saturated with tap water and we found that is about 80 Ohmm (fluid conductivity was 22 Ohmm). The bulk resistivity of the sand

were replaced with bags filled with iron fluid (blue blocks in figure) at various steps. For every simulation step, we measured a cycle of 63201 measurements of various arrays (pole-tripole, circular dipole-dipole, bipole-bipole and inhole) and different measuring planes (on x-x, x-y, z-z, x-z). Numerical analysis on the sensitivity combined with the actual physical measurements allowed us to reduce the number of measurements to 3479 and still be able to image accurately the fluid injection.



saturated with iron is about 3 Ohmm. We identify a contrast of about 30 times. Before the actual injection, we perform measurements in a tank filled with water and sand bags. For the tank experiment, 21 boreholes were installed in an electrical insulated tank of 7x5.2.5 m. We used 3 rows of 7 boreholes each row. Each row has distance of 1m from the subsequent row. Every borehole within the same row has distance of 0.66m. Each borehole has 11 electrodes, with 0.22m spacing. Total number of electrodes is 231. In order to simulate the injection, sand bags (white blocks in figure)

Figure: Inversion results of the corresponding tank simulation. White blocks indicate the location of sand bags (high resistivity) while blue and red blocs indicate sands filled with iron fluid.

## Considerations regarding surface to borehole ERT

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We developed a geoelectrical borehole tool for near-surface measurements, allowing for highly resolved tomographic resistivity distributions in soils. They can be used as an indicator for the water distribution on a small scale and help identifying thin hydraulic barriers. The tool consists of 20 ring electrodes distributed over one meter on a plastic rod and is pushed into the ground ensuring good electrical contact. It is operated in combination with surface electrodes whenever possible for recovering 2D structures, while the whole setup is characterized by its small electrode distances.

This feature, allowing for a high resolution, also poses a challenge in terms of data processing and modeling, as the spatial extent of the electrodes is no longer negligible.

We verify that the ring electrodes (and even the surface electrodes) can not be represented by dimensionless point electrodes as they are usually assumed in standard ERT inversion codes. We utilize another way of representing electrodes with a finite spatial extent, the conductive cell model, in a 3D inversion. This allows for an exact replication of the actual data acquisition conditions, as the whole electrode surface is involved in the measurement. The accuracy of the approach is evaluated for a couple of artificial model cases using a crossed-bipoles configuration. Moreover, we apply the approach to laboratory data from a well-defined layered box model, using only the borehole tool.\

The developed inversion procedure reconstructs the artificial model cases quite accurately and recovers the laboratory model realistically.

## Development of new underground exploration method

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Many accidents, including sink-hole, have happened under construction because of unexpected underground utilities, despite of performing the site investigation. To solve these problems, new geophysical exploration method, different from previous ones, is developed. An electric field analysis is performed with underground utilities, the world's first. After measuring the electrical resistance values by applying a voltage to the sensor installed on the ground surface, buried location, direction, and size of the cylindrical underground material are predicted by using the developed algorithm. This technology is 5 times deep in depth of exploration, 6 times shorter in exploration times and 20 times shorter in analysis time than existing technology. This technology is listed in 5.4.4. of KEPCO cable tunnel design guidelines and applied in several sites, such as substations and cable tunnels. So, it is contributed to timely completion and stabilized power supply due to accident prevention of underground project.

## High-speed geoelectrical monitoring of artificial rain experiments at a slope using a large-scale rainfall simulator

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keywords: high-speed geoelectrical monitoring, slope disaster, large-scale rainfall simulator

Measuring the temporal variation of water content in a slope is important for preventing slope disasters. We conducted repeated monthly geoelectrical surveys since February 2011 on one slope of an embankment in the large-scale rainfall simulator of the National Research Institute for Earth Science and Disaster Resilience (NIED). The slope from the crest to the ground is approximately 12 m in length and its angle is approximately 35 degrees. Thirty-seven electrodes are established permanently at 0.5-m intervals along the 18-m long survey line including the slope. Measurements of near-surface soil water content and temperature have been conducted every 10 minutes at five places along the slope. The embankment is usually outdoors and observations in natural weather have been performed. The results of the repeated geoelectrical surveys show that short-term changes in resistivity correspond to changes in water content caused by rainfall.

This fact suggests that a large short-term increase in water content that causes a slope disaster is detectable by a decrease in resistivity. In order to confirm this, we applied artificial rain to the embankment, controlling the total amount and intensity of rainfall using the mobile simulator. In this experiment, a high-speed resistivity profiling system which can provide 576 (24x24) data in about 10 seconds was used for the resistivity monitoring on the survey line. The resistivity measurements were carried out at intervals of 1 or 2 minutes simultaneously with the measurement of soil moisture content during the artificial rainfalls. A series of resistivity sections were analysed to each observational data. The changes of resistivity sections corresponded to rapid changes in soil moisture content. The result shows that the high-speed geoelectrical monitoring is effective for observing soil moisture changes caused by heavy rain in real time.

## KEYNOTE LECTURE: Recent developments using ERT-derived temperature for monitoring and characterizing aquifers

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Groundwater temperature may be of use as a state variable proxy for aquifer heat storage, highlighting preferential flow paths, or contaminant remediation monitoring. However, its estimation often relies on scarce temperature data collected in boreholes. Electrical resistivity monitoring may provide more exhaustive spatial information of the bulk properties of interest than samples from boreholes. One advantage of the bulk resistivity-temperature relationship is its relative simplicity: the fractional change is often found to be around 0.02 per degree centigrade, and represents mainly the variation of electrical resistivity due to the viscosity effect. However, in presence of chemical and kinetics effects, the variation may also depend on the duration of the test and may neglect reactions occurring between the pore water and the solid matrix. Such effects are not expected to be important for low temperature systems (<30 °C), at least for short experiments. In this contribution, we use different field experiments, from 2D to 3D, under natural and forced flow conditions to review developments for ERT to map and monitor the temperature distribution within aquifers, to characterize aquifers in terms of heterogeneity and to better understand processes. We show how temperature time-series measurements might be used to constrain the ERT inverse problem in space and time and how combined ERT-derived and direct estimation of temperature may be used together with hydrogeological modelling to provide predictions of the groundwater temperature field.

## KEYNOTE LECTURE: Characterization and monitoring of the riparian and hyporheic zones

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The hyporheic and riparian zones (HRZ) are the areas located beneath and adjacent to rivers and streams, where the interactions between surface water and groundwater take place. This complex physical domain allows the transport of several substances (e.g., water, nutrients, and pollution) from a stream to the unconfined aquifer below, and vice versa, thus playing a fundamental role in the river ecosystems. The importance of the HRZ makes its characterization a goal shared by several disciplines, which range from hydraulics and ecology to biogeochemistry. Regardless of the field of study, the main aim is always to completely describe the structures and the processes that distinguish this zone. Furthermore, flow and transport models are nowadays key instruments to efficiently characterize the HRZ, given their ability of simulating surface water-groundwater exchange phenomena at a local scale. In order to achieve these common goals, many disciplines use invasive techniques that permit punctual *in situ* surveys and/or sample analysis. Point measurements may be precise, but their capability to sample in space and time with sufficient resolution to avoid aliasing is very questionable.

The resulting picture of the real processes is thus, often, strongly biased. There is no doubt that non-invasive techniques can play a major role in this research area. Electrical Resistivity Tomography (ERT) has been applied in cross-well configuration or with a superficial electrodes deployment. Distributed Temperature Sensing (DTS) usage in hydro-geophysics has been developing since the last decade, revealing a wide applicability to the typical issues of this field of study. In this work, we present the general challenges concerning the hydro-geophysical characterization of the HRZ, and the case study of the Vermigliana Creek in the Northern Italian Alps, where a combination of ERT and DTS apparatuses has been installed below the river bed, and time-lapse measurements over several seasons as well as short-term response measurements help cast light on the surface water-ground water interactions.

## Joint assessment of soil hydraulic properties by constraining geoelectrical tomography measurements with X-ray Computed Tomography pore architecture information

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keywords: Keywords: Electrical Resistivity Tomography; X-ray Computed Tomography; Hydraulic properties; Non-invasive soil core study; Time-lapse monitoring

Developing a better understanding of hydraulic properties of soils is of significant importance for such diverse fields as agriculture, soil and ecosystems management, vadose zone hydrology, contaminant transport, civil engineering and geotechnics and the tourism and leisure industries. We propose a new method of investigating soil hydraulic properties by the joint appraisal of two advanced tomography technologies: Electrical Resistivity Tomography (ERT) and X-ray Computed Tomography (CT). Both methods are non-invasive and allow properties measurements without disturbing the structural integrity of the sample. The method implies contemporaneous moisture dynamics measurements in soil columns. ERT enables the continuous time-lapse measurement of the 4D resistivity profile. This allows monitoring and modelling the fluid preferential pathways inside the column. X-ray CT has the ability to determine the pore structure and matrix architecture of the samples.

The information obtained from the X-ray scanner is used to refine the mesh used to reconstruct the 4D resistivity profile hence constraining the model. Synthetic modelling has been run integrating spatial information extracted from X-ray scans into ERT inversion models. Obtained constrained models as such have been compared with unconstrained scenarios. The results suggest that the constrained models provide a higher accuracy and resolution. This innovative methodology of mapping and monitoring fluids, which combines the advantages of two established techniques, holds promise for soil science application and related fields.



## Infiltration of treated wastewater in a soil-based constructed wetland: usage of time-lapse ERT to monitor saline tracer injection.

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keywords: Time-lapse ERT, soil-constructed wetland, waste water.

Soil-based constructed wetland, with infiltration in soil of secondary treated effluents is a low-cost technique to reduce the flux of pollutants discharged to surface receiving water bodies. More than 500 soil-based constructed wetlands have been built over the last ten years in France. Nevertheless, these systems are usually designed with empirical rules, with a limited knowledge on the behavior of the hydraulic parameters (i.e. infiltration capacity) versus time when treated effluent is applied. Indeed, depending on the hydraulic load and the quality of the effluents, in particular the organic matter content, the infiltration of treated effluent can lead to biological, chemical or mechanical clogging. The evaluation of the presence or absence of clogging effects is essential, in particular for defining water supply strategies to minimize clogging. The use of conventional hydrological measurements, such as water content measurements or permeability tests, have the advantage of being precise measurements, but these measurements are limited in space and the installation of these sensors is destructive for the soil. In these systems, it is also possible to estimate the incoming and outgoing water fluxes, the difference being affected the infiltration and evaporation fluxes.

But between these two measurement scales, there is a lack of measurement tools at the intermediate scale to fully understand and monitor the phenomena. Geophysics, in particular recent development in electric resistivity tomography (ERT), allows obtaining distributed information on the waste water fluxes in porous media. Thanks to time-lapse monitoring of infiltration of water or combined with saline tracer in a saturated medium, we have monitored 4 saline tracer tests between 2014 and 2016. We have first designed a specific apparatus to investigate very shallow resistivity variation for small borehole under de soil-based constructed wetland. The objective of this abstract is to demonstrate the advantage of discontinuous time-lapse ERT saline tracer injection monitoring for studying soil clogging effect in soil-based constructed wetland. Four time lapse electrical were performed between 2015 and 2017, which show the evolution of clogging over time. This new information leads to improve the design and the operation rules, like with the used of the soil for waste water treatment.

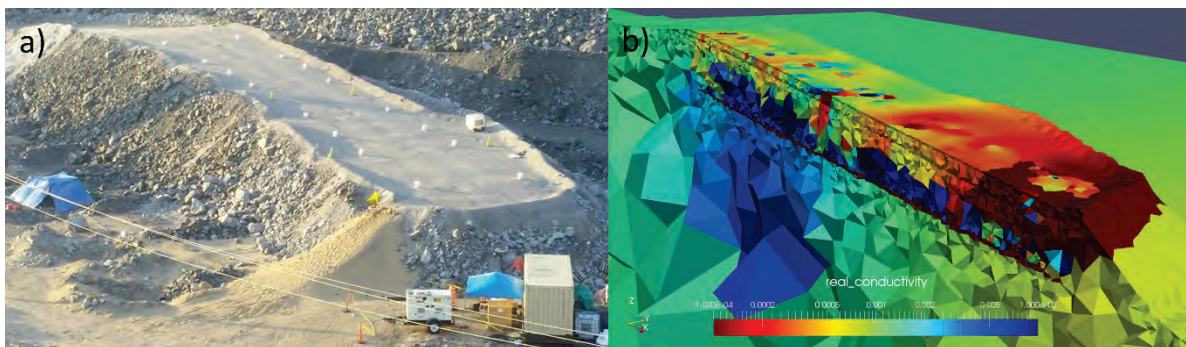
## Hydrogeophysical monitoring of water infiltration in an experimental waste rock pile using 3D time-lapse Electrical Resistivity Tomography

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Hydrogeological behaviour of heterogeneous and non-saturated media can be complex and challenging to assess, especially where classical hydrogeological instrumentation can't be directly applied - such as in the core of waste rock piles. In this paper, the authors will present the results of several 3D ERT surveys carried out in 2016 and 2017 for time-lapse monitoring of water infiltration events in an experimental waste rock pile. This 60 m-long, 10 m-wide, 7 m-high pile was built according to a new waste rock disposal method at the Rio Tinto Fer et Titane hemi-ilmenite Lac Tio mine (Havre St. Pierre, QC). This pile includes inclined layers of relatively fine-grained compacted materials (sand and crushed anorthosite) on the surface, which creates capillary barrier effects that divert water from the reactive core, thus limiting metal leaching and contamination of the

conductivity of the leachates. In addition, 192 circular electrodes are buried in the pile (96 at the top and 96 at the bottom) according to a regular 2m-spaced grid. These 192 electrodes are used to carry time-lapse measurements every hour with an optimized protocol of 1000 configurations uploaded on the Terrameter LS (ABEM) to monitor internal flow of water sprinkled on the pile with a water truck. Time-lapse 3D ERT data were inverted using E4D (Johnson et al., 2010) to yield the 3D model of bulk resistivity over time before, during and after artificial infiltration events. While resistivity results show consistent variations due to moisture distribution, conversion of bulk resistivity into volumetric water content is not straightforward. This challenge is related in part to the interaction between water and the conductive water rock in the core of the pile (ilmenite). Laboratory column measurements have also been conducted to assess the relationship between bulk conductivity, water conductivity and moisture content with waste rock samples from the pile. The 3D images of water content will also be compared with hydrogeological measurements and modelling.



effluent. The pile has been instrumented with probes to monitor moisture content and pore water pressure near the surface and at the base. Six lysimeters collect percolating water, and serve to measure water flow and assess chemical composition and electrical

Figure: a) Photography of the experimental waste rock pile instrumented with 192 geophysical electrodes; b) 3D resistivity model of the pile: red areas correspond to the resistive sand and anorthosite while blue areas correspond to conductive ilmenite-rich waste rock.

## Long-time resistivity monitoring of a freshwater/saltwater transition zone using vertical electrode systems

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In September 2009 two vertical electrode systems (CLIWAT 1 and CLIWAT 2) were installed in the water catchment areas Waterdelle and Ostland at the North Sea island Borkum to monitor possible changes of the transition zone between the freshwater lens and the underlying saltwater in depths between 44 m and 65 m below ground level. The installation and the first measurements were carried out in the framework of the EU Interreg project Climate & Water (see <http://cliwat.eu/> and Sulzbacher et al., 2012).

Each of the two vertical electrode systems is about 20 m long and includes 78 stainless steel ring electrodes; the spacing between adjacent electrodes is 0.25 m. These systems are used for DC multi-electrode measurements. The measurements are carried out automatically several times per day using a modification of the commercial resistivity meter 4point light 10W (see [www.l-gm.de](http://www.l-gm.de)). The power is supplied by batteries recharged by solar panels. Since December 2009 the data are regularly transmitted to Hannover by telemetry.

For the measurements the Wenner-alpha array is used. Each multi-electrode measurement includes 975 different four-point arrays. In the beginning the measurements were strongly influenced by moisture effects and showed a lot of outliers, but the use of newly developed active electrode switchboxes increased the quality of the data very much. In recent years a maintenance of the system at the surface was necessary once to twice a year only.

At both locations the data show a clear decrease of the apparent resistivity from

about 80-90  $\Omega\text{m}$  in depths around 45 m to about 1-2  $\Omega\text{m}$  around 65 m depth (spacing  $a = 0.25$  m). This decrease indicates the transition zone between freshwater and saltwater. The depth of the transition zone as well as the kind of decrease of the apparent resistivity is very stable since 2010. Only within the first year large changes occurred, but these were caused by the readjustment of the local conditions (disturbed by drilling) to the undisturbed situation.

Temporal changes are only visible if single depths are considered. They are especially large in CLIWAT 2 (Ostland) in depths around 55 m. Here a sand layer confined by clay layers is found. In 2015 Miriam Ibenthal used a vertical 2D density-dependent groundwater flow model to explain the long-term resistivity measurements and showed within her master thesis at the University of Göttingen that these temporal changes can be explained by variations of the groundwater level, changing groundwater recharge rates and changing pumping rates of the nearby located drinking water supply wells (Ibenthal, 2015).

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## Monitoring infiltration and subsurface stormflow in layered slope deposits with 3D ERT and hydrometric measurements

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Understanding the nature and dynamics of water infiltration into slope deposits is essential to understand the processes of hillslope catchments and thus for prediction of floods. Our monitoring test site is located in the Eastern Ore Mountains and consists of three periglacial sediment layers. Classic hydrometric data (i.e. matric potential) provide important temporally dense information, but they cannot be obtained in sufficient spatial density to understand water flow. We used 3D ERT for monitoring controlled artificial infiltration of water being taken from the nearby spring, once in a dry and once in a wet precondition. About 300 electrodes were installed in 10cm grids. In order to reduce measuring speed with regard to the fast processes, we optimized a combined dipole-dipole and gradient setup with almost 3000 data every 35 minutes. The computed 3D models are clearly able to image water transport through the individual layers. Comparison with hydrometric point data proves the applicability of the approach and the necessary resolution reached.

Infiltration through the uppermost layer is dominated by vertical preferential flow, whereas water movement in deeper layers is mainly downslope matrix flow. Subsurface stormflow occurs in form of organic layer interflow and at the interface to the first basal layer. Main driving factor for it is a capillary barrier effect at the interface to the second basal layer, preventing water from entering the deepest layer under unsaturated conditions. However, as saturation increases, the barrier breaks down and water reaches the hydraulically conductive base layer where additional stormflow may occur. As a result, ERT is able to provide important insight for understanding water movement in slope deposits.

## Spatialization of subsurface properties and states using geophysical and geostatistical methods

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The knowledge of the spatial heterogeneities of the subsurface is major information in many disciplines such as pedology, geology, hydrogeology and geochemistry, and at different scales. However, the lack of coordination between the various tools, disciplines and methods describing each subsurface element does not allow efficiently addressing the hydrological behavior of the soil surface. The spatial heterogeneity can have a significant effect in a study of subsurface processes of groundwater flow and pollutant transfer. In this study, we demonstrated the potential of geophysical methods to provide new momentum to the characterization of soil water content heterogeneities as proxy. More specifically, we hypothesize that a geostatistical framework based on BME (Bayesian Maximum Entropy) to assimilate geophysical (considered as uncertain measurement) and hydrological (considered as certain measurement) data can provide *in fine* a representative distribution in space (and time) of subsurface properties.

The BME is a modern spatio-temporal geostatistical method allowing through Bayesian process the integration of reliable datasets with the spatial dataset of different levels of uncertainty. This methodology is applied to a field dataset carried out at Boissy le Châtel plot, in Orgeval carchment (East of Paris, France). Two years of high frequency monitoring experiment allowed to acquire an important datasets composed with: (i) 546 ERT profiles with a pro Syscal resistivitymeter (Dipole-dipole and gradient array)) and (ii) hourly soil water content using 12 buried TDR probes. The measurements of Electrical Resistance Tomography (ERT) allow an indirect and uncertain distribution of the soil

water content, because it is subject to errors of measurement inversion and ERT conversion. Despite these inconvenient, the estimation of water content, although indirect and tarnished by errors, can significantly improve the estimation of the water content distribution, when its associated uncertainty are correctly estimated and are rigorously assimilated during calculations. The two datasets were integrated into specialization framework based on the BME method to predict the soil water content distribution.

The results indicate that the BME method creates more reliable model of water content distribution. This approach seems to be a powerful method integrating ERT and TDR measurements to improve the distribution of water content. The effectiveness of this method depends mainly on the estimation of the structure and amplitude of the data uncertainties. The identification and assimilation of these uncertainties is the difficult point, especially when the ERT measurement artifacts are important.

## KEYNOTE LECTURE: Monitoring crop root systems using electrical impedance tomography

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keywords: crop root systems, SIP, EIT

In recent years, interest in using geophysical methods for the non-invasive investigation of plant roots has reemerged and led to a wave of studies based on geophysical methods developed for hydrogeophysical applications. We here propose to use low-frequency (mHz to kHz) electrical polarization measurements to infer structural and functional information on crop root systems. Based on the polarization of electrical double layers (EDLs) at various biological membranes, we hypothesize that the magnitude of polarization relates to the overall surface area of EDLs in root systems. Furthermore, based on fundamental assumptions on EDL polarization, we assume that characteristic relaxation times can be linked to characteristic length scales of the polarized structures. Combined with the knowledge that nutrient dynamics and other physiological reactions influence the structure of EDLs in bio matter this provides us with a unique link to characterize and monitor not only the structure, but also the physiological function of root systems in-situ.

To highlight this potential of multi-frequency electrical impedance tomography (EIT) for root research we then present recent time-lapse imaging results from controlled laboratory experiments. In this context we discuss current shortcomings and challenges of measuring root systems on the laboratory scale. Following this, we present the setup and preliminary analysis of a full-season field monitoring experiment using multi-frequency EIT, installed in a maize test field. We discuss approaches to analyze and interpret such results, as well as the technical framework necessary to manage and analyze the huge amounts of data.

We conclude that electrical polarization measurements offer unique possibilities for the non-invasive characterization and monitoring of crop root systems, both in the laboratory and the field scale. Improvements in data acquisition techniques and analysis procedures required to succeed in the biogeophysical field are beneficial to the whole electrical monitoring community, besides offering an additional, urgently needed non-invasive investigation method for the root research community.

## Agroforestry in temperate regions: where does the water go? Electrical resistivity tomography as a tool to help us find out.

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keywords: ERT, agroforestry, tree-crop-soil interactions, monitoring

Recently, agroforestry systems have been recognized to provide an opportunity for “ecological intensification”, thereby increasing yield outcome while simultaneously minimizing negative impacts on the environment. Mixtures of trees and crops have the potential to capture more resources of light, water and nutrients than monocultures of trees or crops (Cannell et al. 1996). Nevertheless, few studies are available focusing on the impact of trees on soil moisture dynamics in cropped soil in temperate regions. In this study, we monitored the soil water dynamics in a corn field bordered by poplar trees in Ieper, Belgium using Electrical resistivity tomography (ERT) and classical soil tension sensors (Watermark) during the entire growing season of 2016 (May-September). We installed four ERT transects of 30 m long with an electrode spacing of 50cm. Three transects were placed in a part of the field bordered by trees and one reference transect was located in a part of the field without trees.

Next to each transect, Watermark sensors were installed to estimate the soil water tension. The data allow us to monitor the influence of the trees on the soil water depletion by the crop. We quantified the effect in space and time of mature poplar trees on soil moisture dynamics in an agricultural field sown with maize during one growing season and confirmed the ability of electrical resistivity tomography to study tree-crop interactions for water under field conditions and we delimited an area of influence of the tree on the crop using a segmented linear regression technique. With our study, we show the potential of ERT to quantify tree-crop-soil interactions for water in agroforestry systems.

## A forward model for electrical conduction in soil-root continuum: a virtual rhizotron study.

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Solomon Ehosioko<sup>2</sup>, Nolwenn Lesparre<sup>2</sup>,  
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keywords: Soil-root modeling, soil water monitoring, ERT, bio-pedo relationship.

Electrical Resistivity Tomography monitoring of soil-root system water fluxes have received growing interest in the past decades. Some studies suggest that roots can be more electrically conductive than soil. We suggest that ERT data taken in agricultural fields is impacted by plant roots and might contaminate estimates of soil water content based on bare soil petrophysical relations. To understand how do roots impact electrical current flow and thus ERT data, a numerical electrical model was coupled with a mechanistic maize-soil water flow model. All the maize roots with a radius larger than 0.05 cm were explicitly accounted for in the finite element mesh and associated to their specific electrical properties. Root growth and water uptake processes continuously affected the EC contrast between soil and root. We demonstrated that high contrasts between root and soil EC lead to errors in the estimation of soil water content, which could

be diminished by using an appropriate biopedophysical correction term. The effective EC (bulk properties) of the medium computed using simulated plate electrodes at rhizotron boundaries reveal directional anisotropy induced by root processes and is more pronounced in sand medium when compared to loam. The percentage change in bulk EC due to change in direction ( $EC_{horizontal}$  vs.  $EC_{vertical}$ ) starts at ~30 % in sand and ~3 % in loam when root is young and increases up to ~500% in sand and ~20% in loam at day 22 when root is three weeks old. Directions in which there is more anisotropy contains more information on the root processes and hence they can be used as prior information for ERT injection scheme to retrieve better information.

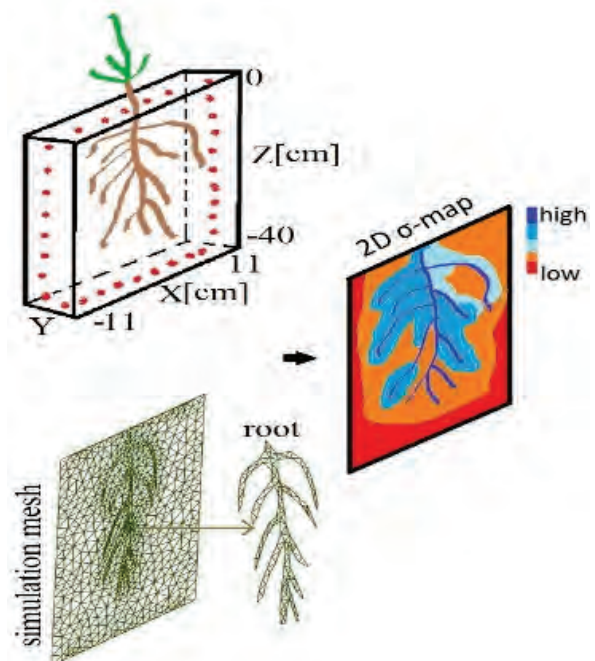


Figure: Schematic of plant-soil virtual rhizotron model



## Developing an electrode design for EIT field measurements on crop root systems

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keywords: electrodes, bentonite, EIT, SIP, crop roots

The root system is an important component of the biosphere, linking the soil to the vegetation-atmosphere environment. To improve crop breeding, production and management, it is essential to better understand root-soil interactions and associated processes. Especially root architecture, growth and activity play a key role in nutrient uptake of crops. To date, studies of root systems are scarce compared to those of shoots due to challenges associated with investigating the hidden roots in the soil. Furthermore, the variable structure of the root system and the small diameter of fine roots pose an additional challenge for their observation. Hence, the development of non-invasive methods for studying plant roots in situ is important.

The spectral induced polarization (SIP) method is more and more used for environmental and near-surface applications in the vadose zone. Especially the method of electrical impedance tomography (EIT) that is used to image the subsurface distribution of electrical conduction and polarization properties is capable of characterizing and monitoring root extension and physiological processes. Within the context of the establishment of EIT as a tool for root system characterization and monitoring at the field

scale, we here present a newly developed electrode design to monitor crop root systems on the field scale during an entire growing season. Electrodes used in a farmed field should influence the soil and crops as little as possible and they need to be non-polarizable to prevent polarization effects when using the required narrow electrode spacing. Hence, the use of available non-polarizable electrodes containing lead or other contaminating materials is undesirable. Here, we propose a novel electrode design consisting of a PVC tube with a metal stick and bentonite as the filling electrolyte. The clay-filled electrode is able to maintain a high moisture content for extended time periods and therefore allows good contact to the soil while minimizing polarization effects.

The new electrode design has been tested during three test series that were conducted between 2015 and 2017. In the first test we compared the new bentonite electrodes to two well known electrode types (stainless steel and Pb/Pb-Cl) in parallel measurements. The results show a comparability of the newly developed electrodes to the stainless steel electrodes, both provided stable phase signals and not too high magnitudes during the 35 days. In the second test, the electrodes were installed in a field experiment for five months for EIT monitoring during a growing season. In the summer season, the soil got very dry and so did the bentonite in the electrodes that led to high transfer resistances and low current injection, which resulted in inaccurate EIT measurements. In a next step, electrodes with a more stable bentonite mixture were evaluated.

{Results and conclusion on next page}

The results for this electrode design showed that even for a very dry environment (sand box) the electrodes provide a longer stability and accurate EIT measurements. After saturating the sand again, the electrodes apparently absorb the water indicating that drying of the electrodes is reversible. For this reason, electrodes tested in a field experiment in a lawn showed a consistently high quality of measurements because intermittent rainfall rewetted the bentonite.

It was concluded from the test measurements and the field experience that the newly developed electrode design is practicable for the use in EIT field measurements on crop root systems. During long drought periods, it is advisable to extend the current electrode design with a drip irrigation system to maintain a wet and thus intact bentonite filling. Without such a system, the electrodes will eventually dry and become too resistive for accurate measurements, especially in summer.

## Geoelectrical investigations at a planned ICDP drill site in the geodynamic active Eger Rift to understand subsurface CO<sub>2</sub> migration processes

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keywords: migration of geogenic CO<sub>2</sub>, mofettes, ERT

The western Eger rift area (West Bohemia/CZ and Vogtland/D) is characterized by ongoing magmatic processes in the intra-continental lithospheric mantle. These processes take place in absence of any presently active volcanism at the surface. However, they are expressed by a series of geodynamic phenomena like occurrence of repeated earthquake swarms and surface exhalation of mantle-derived and CO<sub>2</sub>-enriched fluids in mofettes and mineral springs.

The focus of the recently started ICDP project “Drilling the Eger Rift” is to understand the processes underlying the generation of swarm earthquakes in relation to the fluid/CO<sub>2</sub> ascent and movement in the subsurface (“fluid triggered lithospheric activity”) supported by a proposed network of boreholes which serve different monitoring aspects (seismological, fluid, microbiological).

During the last decade, intensive geoelectrical investigations (ERT, SP), combined with other geophysical and soil gas methods, had been conducted especially in the area of the Hartoušov-Bublak mofette field (Flechsig et al., 2008; Kämpf et al., 2013; Nickschick et al., 2015 and 2017) to get insight in fluid movements and their tectonic control. Distinct resistivity anomalies in the

subsurface below the strong degassing areas have been revealed. These anomalous areas are most likely related to the force behind fluids’ ascent and consecutive sediment alteration and/or transport linked with the migration of the CO<sub>2</sub>-rich fluids on deep seated faults. ERT (and gravity surveys) also support the theory of a significant change in the lithological composition between eastern and western flank along the PPZ fault zone, that it is still active up to this day. This fault zone of several tens of kilometres seems to play a major role in the regional tectonic frame (Nickschick et al., 2015).

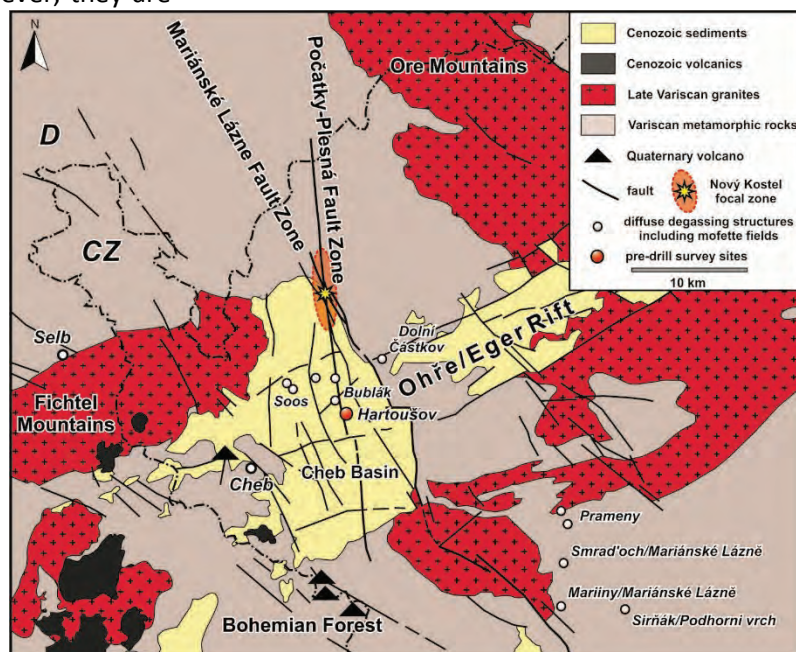


Figure: Geological map of the Cheb Basin and surrounding with locations of degassing areas of magmatic CO<sub>2</sub>, Quaternary volcanoes and the recent swarm earthquake focal zone near Novy Kostel (based on Flechsig et al. 2008 and Bussert et al., 2017).

### REFERENCES

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## Demonstration of applicability of geoelectrical imaging as monitoring tool for the complete life-cycle of a CO<sub>2</sub> storage reservoir

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keywords: CO<sub>2</sub> storage, crosshole and surface-downhole ERT, case study

For any CO<sub>2</sub> storage site, an appropriate monitoring program is a key requirement, which needs to address the following main objectives:

Support of safe and efficient storage operations (operational monitoring) Quantitative imaging of CO<sub>2</sub> plume development (migration monitoring) Control of brine displacement as a consequence of injection-related pressure increase (safety monitoring) The application of geoelectrical measurements for CO<sub>2</sub> storage monitoring was first introduced at the Nagaoka, Ketzin and Cranfield test sites. The usage of this method is motivated by the significant resistivity contrast of conductive brine and electrically insulating CO<sub>2</sub>. At the Ketzin pilot site, geoelectrical monitoring contributed to all of the above mentioned monitoring aspects (operational/migration/safety) and comprises crosshole and large-scale surface-downhole measurements (Bergmann et al., 2016). The following phases of the CO<sub>2</sub> injection and post-injection operation were successfully monitored by geoelectrical surveys:

During the initial phase of CO<sub>2</sub> injection, which includes the arrivals of CO<sub>2</sub> at the monitoring wells, ERT measurements display the rapid evolution of a CO<sub>2</sub>-related resistivity signature and its transient behavior. In addition to the increase in CO<sub>2</sub> saturation, this signature is driven by the increasing reservoir pressure.

Various injection regimes (i.e. variable injection rates, shut-in and re-start periods) led to a transition from a steady-state CO<sub>2</sub>/brine contact towards a decreasing CO<sub>2</sub> plume thickness. This is further conditioned by the brine backflush, corresponding solubility trapping and halite precipitation (Baumann et al., 2014).

The post-injection phase shows the buoyancy-driven behavior of the plume and its spreading with significantly reduced vertical thickness. From controlled CO<sub>2</sub> release and brine injection experiments, the cone-shaped CO<sub>2</sub>/brine front has been investigated in order to study the capability of such withdrawal/injection measures for potential CO<sub>2</sub> plume management. A very promising development is the recently studied, joint hydrogeophysical evaluation of reservoir and geoelectrical data (Wiese et al., submitted).

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## Integrating ERT and other near-surface geophysical techniques for the investigation of a maar structure near Neualbenreuth (Eastern Bavaria, Germany)

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keywords: maar, ERT, Neualbenreuth

With the existence of the Quaternary Mýtina Maar at the Germany Czech border that was proven in 2007, further geophysical prospecting for a maar structure nearby was carried out at a morphological depression 4 km SE of the Mýtina Maar and close to the village of Neualbenreuth (NE-Bavaria, Germany, Figure). Several ERT-profiles were measured across the area of interest in a concentric arrangement and clearly revealed a zone of 350-400 m diameter with low resistivity material of 50-250 Ohmm encircled by high-resistive rocks of at least 2000 Ohmm in the subsurface. Additional results from refraction seismics and gravity surveying supported the interpretation of a bowl-shaped depression in the quartzitic bedrock of at least 100 m depth that is filled with low velocity and low density material.

In 2015, drilling successfully recovered a drill core from an area the geological depression was considered to have its deepest center. A widely continuous stack of laminated organic poor sediments that are characteristically for maar-lake sediments could be established from core analysis to a depth of at least 100 m. This undermined the majority of results from integrated geophysical surveying that had been carried out before and gave an additional and fundamental piece of evidence for the existence of a maar structure.

With the Cheb Basin as an area of earthquake swarm and hidden magmatic activity being located only ca. 30 km from Neualbenreuth, the presented results argue for future geophysical prospecting in search of other maar volcanoes, considering the potential for future hazard (volcanic/phreatomagmatic eruptions) in Eastern Bavaria and the Cheb Basin area.

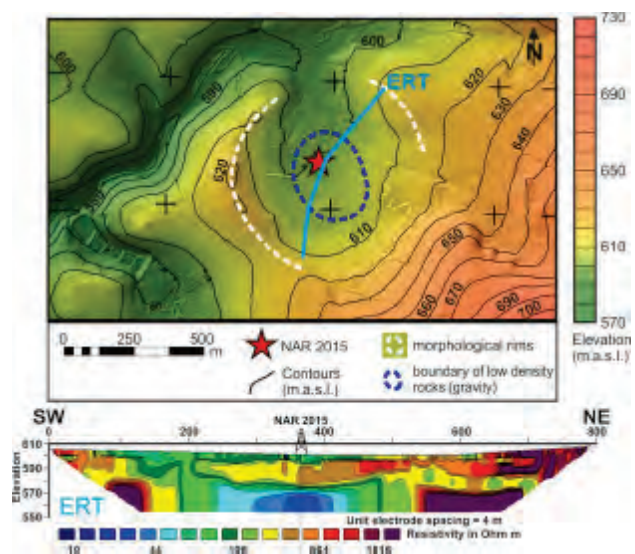


Figure: Digital elevation model with morphological rim of the inferred maar structure, zone of low density rocks, drill hole NAR 1 and outline of a single characteristic ERT-profile (top). ERT-profile that shows the distribution of low resistivity material surrounded by high resistive rocks in the subsurface (bottom).

## KEYNOTE LECTURE: Advanced ERT inversion strategies with BERT &amp; pyGIMLI

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The quality of both static and dynamic inversion results depends on the density and quality of the data, but also on the availability of additional information on the present state and ongoing processes. BERT (Boundless Electrical Resistivity Tomography) is an open software system for inversion of ERT data and makes use of the flexible numerical pyGIMLI framework providing several abstract modelling, inversion and regularization frames. The talk gives an overview on the possibilities by presenting several cases and outlines the current state of development and future ways.

There is a variety of different transformations and regularization techniques to decrease the ambiguity of the inversion process to geologically plausible models and changes. Besides classical methods, there is the ability of account for properties by geostatistic regularization. Based on the pyGIMLI region technique, one can subdivide the subsurface into units to control their properties individually. This allows, e.g., for adding structural constraints from reflection methods or boreholes. It also enables to use parameter information in boreholes to improve the results in their neighborhood.

BERT is not restricted to point electrodes that are not always an accurate assumption, it also supports arbitrarily shaped facial or line electrodes using the Complete (CEM) and Shunt (SEM) Electrode Models. There is also the possibility of transdimensional inversion, i.e., reducing the dimension of the inversion

to 2D, 1D or 1.5D while retaining the full three-dimensionality of the forward problem. The modelling domain can also be formulated in a structural way. Spectral Induced Polarization (SIP) data of different frequencies can be inverted simultaneously using spectral constraints, just like laterally constrained or fully discretized temporal inversions.

Besides the latter, different time-lapse strategies can be followed, from individual over reference model and difference inversion to temporal discretization. Additionally, one can couple ERT with flow and transport models to enable a fully coupled hydrogeophysical inversion for hydraulic conductivity. There are also Python frameworks for different kinds of joint inversion like structurally coupled inversion of data from unrelated methods or petrophysical joint inversion taking into account existing relations between the target parameters.

We exemplify all those strategies and how to use them by illustrative examples from various recent case studies, starting from the classical command line operation to managing classes in Python. Committing to the idea of reproducible science, we are documenting examples in the tutorial and on the documentation websites. Furthermore, we provide all data sets and scripts from published papers in our software repositories on github and gitlab to enable users to benefit and go beyond them, and inviting user to contribute inside of a growing user community.

## KEYNOTE LECTURE: Data Processing and 4D Inversion of ERT monitoring data

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keywords: ERT, processing, 4D inversion

Geoelectric monitoring has been widely used in environmental, hydrogeological and engineering problems. In these applications, we have frequently misinterpreted the ground condition changes due to the inversion artefacts and thus to the false anomalies in the difference images. To alleviate the problems, great care must be taken in every aspect of the ERT monitoring: 1) collection of high quality data, 2) careful data processing, and 3) appropriate inversion.

Since geophysical responses to temporal changes of subsurface properties are very weak, high quality data is prerequisite condition to a successful ERT monitoring. Careful examination and assessment of data reliability are also required since data are always contaminated by noise. Usual procedure of data processing relies on eye-inspection and and/or through inversions in a trial-and-error manner. This approach for enhancing the data quality is hard to be systematically applied, consumes great efforts and time, and occasionally filters out good data as well. In this presentation, processing of ERT monitoring data is discussed, where editing of data in the space and time domains, filtering of anomalous data, and evaluation of electrode status and electrode filtering are discussed. Especially, data reliabilities in this procedure can be used as weighting factors to the actual inversion to obtain reliable inversion results.

In the inversion of ERT monitoring data, there are many well-known studies to reconstruct time-lapse images of subsurface. One of the most rigorous approaches among them is the

four dimensional (4D) inversion approach, where the subsurface model and the entire monitoring data sets are defined in a space–time domain. These definitions enable us to simultaneously invert multiple monitoring data sets measured at different times, and to introduce the regularizations in both space and time domains to effectively reduce inversion artefacts. Several successful case histories support the superiority of 4D inversion approach.

## Effects of near surface resistivity changes on time lapse ERT inversion

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keywords: injection test, near surface resistivity changes, time lapse ERT, ERT inversion

Time lapse Electrical Resistivity Tomography (ERT) to deduce hydraulic properties of aquifers is widely used in hydrogeology. A major problem while using surface measurement configurations are near surface changes in resistivity over time. Changes in deep aquifer regions we aim to monitor with time lapse ERT might be masked by near surface changes over the monitoring period. We report here on three approaches to overcome such artifacts. First, we applied the different approaches on artificial data and, in a second step, on ERT field data obtained during a fresh water injection test.

We distinguish between two main sources of disturbance: The first one are known surface features like e.g. surface ditches used for drainage with varying water fillings and therefore varying resistivities over time. The second source are unknown changes due to soil-atmosphere interactions, e.g. water accumulation in slight surface depressions. Additional to these main sources, random noise influences the data.

To deal with the near surface changes, we tried three approaches:

First, we simply excluded the electrodes nearby the ditch to reduce its influence. The results seem to be reliable, but we lose sensitivity in depth of the aquifer. The resolution of the injected plume seems to be decreased. Resistivity changes at other locations are not addressed by this approach. Nevertheless, changes within the aquifer, which we link to our injection, are more distinct, both in the artificial and field data.

Second, we included the shape of the ditch into the inversion mesh and inverted for the values on a very refined mesh. This requires a very long calculation time but the result shows less artifacts at the surface below the ditch. Similar to our first approach, we could replicate the synthetic result on our field data. However, near surface changes at other locations still affect the inversion result of deeper regions.

In a third approach, we inverted the data sets with region dependent regularization factors to allow small scale changes near the surface and to apply more smoothing in the aquifer where we expect the large and slowly moving injection plume. The synthetic results show small scale changes of the first layers which do not influence the inversion result below them as strong as before. The changes in depth are less masked and the simulated injection body is better resolved. Though, predefining the individual regions prior to the inversion procedure requires already a detailed knowledge of the investigated subsurface. Therefore, applying the approach on field data takes some careful adjusting to improve the time lapse inversion results.

We suggest to simply exclude or downweight heavily disturbed near surface data points during the inversion of time lapse monitoring data. If more knowledge of the subsurface is already available, a region based inversion could improve the results. All known surface features should be included into the inversion mesh or at least be represented by locally refined mesh to avoid artifacts.



### 3D resistivity inversion using a nonlinear partial derivative

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keywords: 3D, inversion, nonlinear

Inappropriate treatment of nonlinearity has been the roots of many unresolved issues on geophysical inversion. We therefore propose a novel approach, which provides better partial derivatives beyond the first-order sensitivity matrix (i.e. linear Fréchet derivative) thereby improving both the convergence behaviour and the resolving power of the inversion.

The essence of our approach lies in building a nonlinear partial derivative (NLPD), which is the key player of nonlinear inversion. We show that the NLPD operator provides means to include high order sensitivity terms which are ignored in conventional linearized inversion, therefore paves the way to a nonlinear sensitivity matrix.

While constructing this nonlinear sensitivity matrix, our approach introduces (1) the evaluation of the so-called contrast sources and (2) the update of fields within the computation domain using these contrast sources, which will affect the sensitivity matrix to behave nonlinear.

Numerical examples on synthetic datasets are presented to demonstrate the merits and effectiveness of our algorithm on geoelectric data.

## Interpretation of resistivity data based on inversion with structural constraints for the detection of cavities during construction

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keywords: ground subsidence, resistivity inversion, structural constraint

Seoul, South Korea, has suffered frequent appearances of ground subsidence, which are seriously threatening public safety. More serious geotechnical hazards are caused by not only large scale land subsidence but also mine collapse or construction of tunnel, subway or large building. To reduce those serious hazards, this study focuses on applying geophysical exploration to detect underground cavities mainly at depths less than 10 m, which eventually cause ground subsidence. Among several geophysical exploration method, electrical resistivity methods can play the most powerful role because the methods have been widely used to map subsurface structures.

Inversion of resistivity data is the key in interpreting the resistivity structure, but is a non-unique problem resulting in ambiguous interpretation. To lessen the ambiguities, we describe and apply an inversion strategy with constraining structures using a priori information, which can be obtained from other geophysical or geology surveys and thus be pre-interpreted to generate a layered structure or a target area. Using the pre-interpreted structure, we construct a base-model for inversion and apply constraint with bounding ranges of the value of resistivity in each layer. The effectiveness of the structural constraints are tested for synthetic data.

Comparing results from conventional and proposed inversion strategies, we can confirm that the proposed inversion with structural constraints yields more reasonable resistivity images than the conventional inversion. Further, we apply the structural constraint strategy to time-lapse inversion of resistivity monitoring data in order to detect the appearance of ground cavities during construction process. Since the process can cause geologic changes, time-lapse inversion gives more reliable results when considering interpreted structures from 3D inversion of resistivity data obtained before starting the construction process.

### ACKNOWLEDGEMENTS

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## Electrical Resistivity Tomography regularisation for piecewise smooth models

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keywords: regularisation, inversion,

The regularisation terms used in the inversion of geophysical data affects the structure visible in the solution. Where the subsurface is smooth or piecewise constant, the  $L_2$  and  $L_1$  norms of the model gradient effectively introduce this information into the inversion. However, where the subsurface is heterogenous, containing of both sharp and gradational changes, these established regularisation terms produce unrepresentative solutions. This has implications in infrastructure monitoring, where smooth wetting fronts or contaminant plumes appear alongside the sharp contrasts of engineered structures, as well as in lithological layering partially affected by weathering.

The Total Generalised Variation (TGV) functional is a convex, higher order generalisation of the  $L_1$  gradient norm, favouring piecewise smooth solutions. We use second order TGV regularisation to solve the electrical resistivity tomography inverse problem. Our alternating-minimisation algorithm decouples the second order calculations from the main Gauss-Newton iterations, allowing efficient performance. We will demonstrate the improved performance of TGV over  $L_1$  and  $L_2$  regularisation in the case of piecewise smooth models.

## Towards unified and reproducible processing of geoelectrical data

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keywords: Geoelectrical data processing, Reproducible research, Python

The multitude of geoelectric measurement devices and inversion codes in use is mirrored in a multitude of individually tailored data importing and processing routines. The majority of scientific advancements in data processing (e.g., filtering schemes, error estimation) is therefore not directly transferable between use cases, especially when measurement devices and inversion codes change. Reproducibility may be further impeded by the use of commercial software such as MATLAB and Microsoft Excel.

To accelerate and concentrate scientific advancement and ensure reproducibility of processing workflows, a unified framework for geoelectrical data processing is required. Based on the free and platform-compatible programming language Python, we present a working prototype of such a unified interface and demonstrate its functionality and ease of use by means of classical processing workflow of geoelectrical time-lapse data (i.e., import, filtering, error estimation, visualization, data export). Encompassing all functionality in a journaling system, which keeps track of all actions applied to the data sets, thereby making the processing testable and reproducible. The framework is designed to be as non-intrusive as possible, only to provide functionality without forcing the user to follow a specific processing workflow. A variety of importers and exporters is provided, so that the processing steps applied to the data set do not depend on the measurement device and the inversion code used thereafter.

We believe that the approach presented could foster exchange of best practices and new techniques among academic groups and practitioners, and that a common data import, processing, and export framework can ease the transition to fully reproducible research. We welcome any feedback that could help in establishing such a tool in the geoelectrical community.

## 4D inversion for automated near real-time ERT monitoring applications

Paul Wilkinson<sup>1</sup>, Cornelia Inauen<sup>1</sup>, Philip Meldrum<sup>1</sup>, Oliver Kuras<sup>1</sup>, Sebastian Uhlemann<sup>1,2</sup>, Giulio Curioni<sup>3</sup>, Jonathan Chambers<sup>1</sup>

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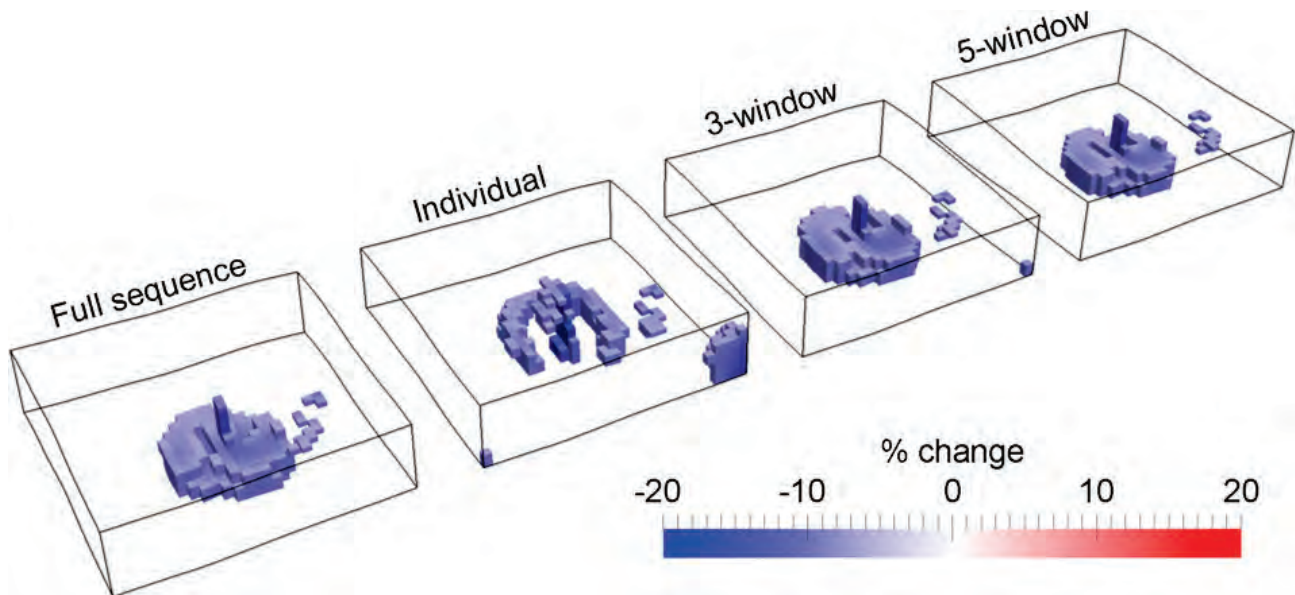
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keywords: 4D inversion, monitoring, automation

4D inversions for time-lapse ERT monitoring data have been developed in recent years that apply regularization in both the spatial and temporal dimensions. Such methods have advantages over other approaches (standalone inversion, difference inversion, or constraints against previous models) in

Temporally constrained 4D inverse methods might appear unsuitable in the context of automated ERT monitoring since they normally operate on the full sequence of monitoring data, which would preclude the delivery of inverse results until data far in the future of an interesting event had been acquired. But in this study we demonstrate, using real data from field monitoring installations, that applying 4D methods to short duration time windows (comprising e.g. 3 or 5 time-steps) produces inverse models very close to those obtained by inverting the full time sequence (containing many tens to hundreds of time-steps). This permits the advantages of temporal regularization to be applied in a near real-time monitoring context, with only a minimal delay in reporting results.



that subsurface changes during data acquisition can be taken into account; changing noise conditions can be accommodated; change artefacts and non-uniqueness are reduced; no time-directional bias is introduced; and baseline/preceding data does not have to be assumed to be more accurate than subsequent data.

Figure 1: Resistivity changes caused by a controlled water leak in a monitoring experiment (cut-off at -10%). 4D temporally regularized inversions using moving windows of length 3 and 5 show much greater similarity to the full sequence inversion than individual standalone inversions without temporal constraints.

### Implementing positivity constraints in 4-D resistivity time-lapse inversion

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- (\*) Corresponding Author

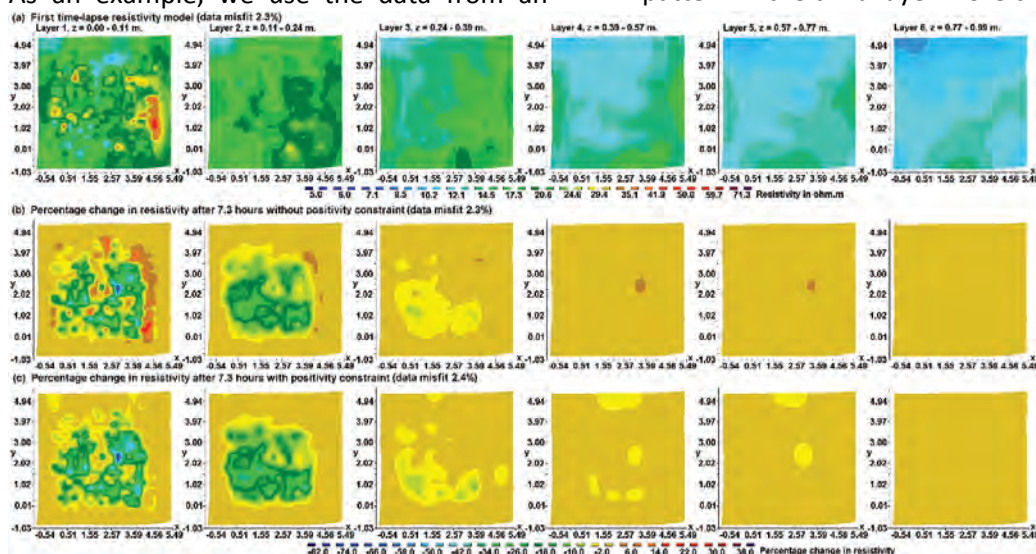
The 4-D inversion technique is a robust method for the inversion of data from time-lapse 3-D resistivity surveys. The smoothness-constrained least-squares equation used is as follows.

$$\begin{aligned} \left[ \mathbf{J}_i^T \mathbf{R}_d \mathbf{J}_i + (\lambda_i \mathbf{W}^T \mathbf{R}_m \mathbf{W} + \alpha_i \mathbf{M}^T \mathbf{R}_t \mathbf{M}) \right] \Delta \mathbf{r}_i = \\ = \mathbf{J}_i^T \mathbf{R}_d \mathbf{g}_i - (\lambda_i \mathbf{W}^T \mathbf{R}_m \mathbf{W} + \alpha_i \mathbf{M}^T \mathbf{R}_t \mathbf{M}) \mathbf{r}_{i-1} \end{aligned}$$

$\mathbf{J}$  is the Jacobian matrix,  $\lambda$  and  $\alpha$  are the spatial and temporal damping factor vectors.  $\mathbf{g}$  is the data misfit vector,  $\mathbf{r}$  is the model parameter vector and  $\mathbf{W}$  is the spatial roughness filter.  $\mathbf{R}_d$ ,  $\mathbf{R}_m$  and  $\mathbf{R}_t$  are weighting matrices used by the L1-norm inversion method. While the method reduces artefacts by using a temporal roughness filter  $\mathbf{M}$ , it does not constrain the direction of the changes with time.

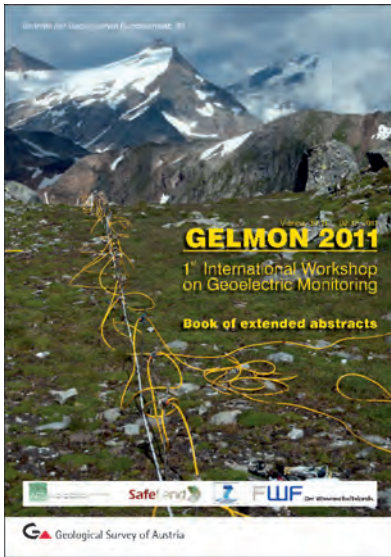
As an example, we use the data from an

resistivity inverse model from the initial data set. The infiltration started 1.3 hours later lasting until 6.7 hours. Eight time-lapse data sets were collected. Figure 1b shows the percentage resistivity model change between the initial data set and one collected at 7.3 hours. It shows a large region with negative changes in the top two layers, but there is band to the right of the infiltration zone in the top layer with increases of up to 30% which is an artefact. To incorporate a positivity constraint into the inversion algorithm, we first used the model from the standard time-lapse algorithm. For the model cells that show an increase in the resistivity with time, a truncation procedure was used where the resistivities of the different time models were reset to the mean value (corresponding to zero change with time). We then used the method of transformations in the inversion algorithm to ensure that the resistivity of the later time models are always less than the first model. Figure 1c shows the results where the zones with increased resistivity values are eliminated. It also shows the in-filtration pattern in the third layer more clearly.

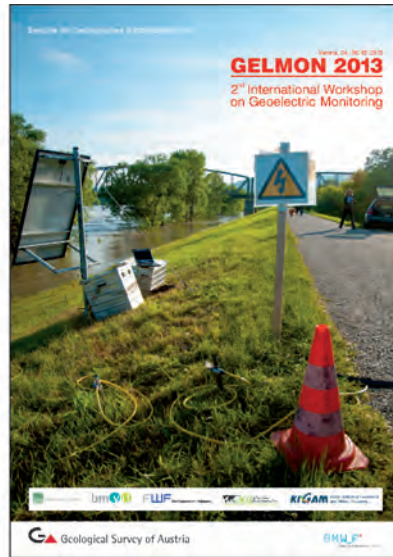


infiltration experiment at the Hollin Hill (U.K.) landslide research site where saline solution was sprinkled on the surface to study the effects of fissuring on hydrological processes and landslide initiation. Figure 1a shows the

Figure 1: (a) Resistivity model for first data set shown as layers. Percentage change in resistivity from the inverse model after 7.3 hours (b) without and (c) with positivity constraint.



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